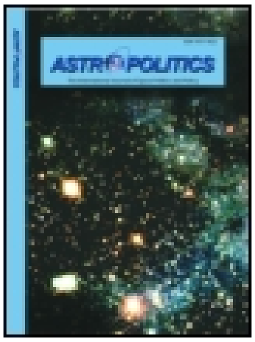

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Limits on the Space Launch Market Related to Stratospheric Ozone Depletion

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Solid rocket motors (SRMs) and liquid rocket engines (LREs) deplete the global ozone layer in various capacities. We estimate global ozone depletion from rockets as a function of payload launch rate and relative mix of SRM and LRE rocket emissions. Currently, global rocket launches deplete the ozone layer ∼0.03%, an insignificant fraction of the depletion caused by other ozone depletion substances (ODSs). As the space industry grows and ODSs fade from the stratosphere, ozone depletion from rockets could become significant. This raises the possibility of regulation of space launch systems in the name of ozone protection. Large uncertainties in our understanding of ozone loss caused by rocket engines leave open the possibility that launch systems might be limited to as little as several tens of kilotons per year, comparable to the launch requirements of proposed space systems such as spaceplanes, space solar power, and space reflectors to mitigate climate change. The potential for limitations on launch systems due to idiosyncratic regulation to protect the ozone layer present a risk to space industrial development. The risk is particularly acute with regard to the economic rationale to develop low-cost, high flight rate launch systems.

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Combustion emissions from rocket launches change the composition of the atmosphere. The changes can be divided into transient changes near the launch site that affect air quality in the lowermost troposphere and long-term global changes in the composition of the stratosphere. In this paper, we are concerned with the long-term impact of rocket emissions on the global ozone layer. Ozone depletion has been a critical concern of nations across the globe for many decades, and large-scale industrial processes that alter stratospheric composition are assessed with respect to the amount of ozone depletion they would cause. When an assessment suggests unacceptably large ozone loss for a particular process, regulatory actions to limit or modify that process might be enacted to protect the ozone layer.[1] In this paper, we consider rocket combustion emissions in the context of ozone layer protection over the next several decades. Our calculations are not a formal assessment, but are a preliminary evaluation to identify the main areas of concern for the space industry. These concerns include risks associated with overly conservative regulation and a suggestion for new research in order to reduce the likelihood of such regulation.

Cicerone and Stedman[2] first considered rocket emissions as a source of ozone depletion. Subsequent studies have shown consistently that at current launch rates, ozone depletion from rocket exhaust is insignificant compared to other sources of ozone loss.[3] If launch rates and ozone depletion from other sources remain at current levels, this assessment will not change. The potential exists that the demand for launch services could increase significantly in the future.[4] Large (factors of ten or more) increases in launch demand could come about for a variety of reasons, including national decisions regarding security, enhanced space exploration, market forces associated with significant reductions in launch costs, or the emergence of new markets such as space tourism, manufacturing, or solar power. Analysts generally assume that if the cost of access to orbit is reduced sufficiently, then large, new markets will emerge for space industry and the launch market. This development would be considered revolutionary, and it is not clear when or if, this might occur. Nevertheless, if space transport follows the "normal" development path of transportation technology enters a period of continual expansion, it would be necessary to reconsider the environmental consequences of large rockets, launched often. In this paper, we consider the implication of such significant increase in demand for orbital launches on the global ozone layer.

We do not consider greenhouse gas emissions from rockets. Climate change is to some extent a separable problem from ozone depletion. While rocket engines emit gases identified as contributing to climate change, the amount emitted globally is trivial compared to other sources and is likely to remain so. Annual CO_2 emissions from rockets, for example, are about several kilotons (kt) compared to emissions of several hundred kt from aircraft which, in turn, is only a few percent from all CO_2 sources.[5] Space launch emissions, even for the large growth scenarios discussed here, will not likely be significant in future greenhouse gas regulatory schemes. As a cautionary tale, we point out that even though aircraft are responsible for a few percent of all CO_2 emissions, the airline industry must contend with considerable attention and likely regulation or carbon taxation.[6] The message to the space industry should be clear: policy and media attention on high visibility propulsion emissions are often framed in ways that overemphasize the relative contribution.[7]

If rockets are a minuscule contributor to the problem of climate change, they do have a significant potential to become a significant contributor to the problem of stratospheric ozone depletion. This follows from three unique characteristics of rocket emissions:

1. Rocket combustion products are the only human-produced source of ozone-destroying compounds injected directly into the middle and upper stratosphere. The stratosphere is relatively isolated from the troposphere so that emissions from individual launches accumulate in the stratosphere.[8] Ozone loss caused by rockets should be considered as the cumulative effect of several years of all launches, from all space organizations across the planet.
2. Stratospheric ozone levels are controlled by catalytic chemical reactions driven by only trace amounts of reactive gases and particles.[9] Stratospheric concentrations of these reactive compounds are typically about one-thousandth that of ozone. Deposition of relatively small absolute amounts of these reactive compounds can significantly modify ozone levels.
3. Rocket engines are known to emit many of the reactive gases and particles that drive ozone destroying catalytic reactions.[10] This is true for all propellant types. Even water vapor emissions, widely considered inert, contribute to ozone depletion. Rocket engines cause more or less ozone loss according to propellant type, but every type of rocket engine causes some loss; no rocket engine is perfectly "green" in this sense.

Since 1987, the ozone layer has been protected by international agreements[11] that limit the production and use of substances that have been determined to cause ozone depletion. The Montreal Protocol on Substances That Deplete the Ozone Layer (and subsequent amendments), regulates the worldwide production and use of ozone depleting substances (ODSs), including the well-known chlorofluorocarbons (CFCs) and other halogen gases. The Montreal Protocol is widely considered a significant success and the global phase out of ODSs mandated by the Protocol is expected to allow the ozone layer to recover to pre-ODS levels by about 2040. In support of the Montreal Protocol, the stratospheric science community issues a quadrennial summary, the Scientific Assessment of Ozone Depletion,[12] describing the state of knowledge of stratospheric composition, the factors causing ozone depletion, and projections of the future ozone layer. The Quadrennial Ozone Assessments have occasionally addressed ozone depletion caused by rocket emissions and have determined that the current loss is "small" in comparison to other sources of ozone loss so that rocket emissions are not a part of the regulatory framework that protects the ozone layer. Later we discuss the threshold level of ozone loss that might be considered "not small," as well as the level that might be considered "too large."

The recovery of the ozone layer,[13] while a favorable development, is motivation to be concerned about ozone depletion caused by rocket emissions over the next several decades. The eventual elimination of the major sources of ozone loss (that is, ODSs) raises the question: Will sources of ozone loss currently considered small, such as rocket emissions, eventually be scrutinized more closely by the stratospheric protection community?[14] This would particularly apply to rocket emissions if demand for launch services increases in coming decades, just as other sources of ozone loss decrease due to the success of the Montreal Protocol. In addition, revisions in our understanding of emissions, stratospheric processes, or the introduction of new propellants on a large scale (hybrid rockets, for example) may cause changes in the estimated ozone loss for a given launch rate.

In this paper, we examine the problem of rockets and ozone depletion from several new points of view. For the first time, we consider the problem in a long-term context that includes significant, sustainable,[15] growth in the space industry and evolving regulatory actions associated with the recovery of the ozone layer from past pollution. We apply the first plausible estimates of ozone loss caused by liquid propellant rockets, which will certainly play the major role in a significant expansion of the launch industry. We develop a parameterization of the steady-state global ozone loss caused by solid and liquid propellant rocket emissions and relate the ozone loss to amount of payload delivered to Low Earth Orbit (LEO). The model is limited by uncertainties in the actual composition of rocket emissions, and the stratospheric processes that bring about the ozone loss; and it can only be used to draw conclusions of an order of magnitude. Nevertheless, the model is useful to examine long-term trends and investigate rocket emission ozone loss within the context of scenarios of large increases in launch rates, the recovery of the ozone layer, and conceptual analysis of the econometric effect of caps on rocket emissions that might be enacted to protect the ozone layer. We draw a number of conclusions for the global launch industry that have implications for policymakers for both strategic space transport planning and future protection of the ozone layer. Finally, we also identify the most important areas where new research could reduce the model uncertainties and so increase the ability to reliably plan for future space systems development.

STRATOSPHERIC OZONE AND REGULATORY PROTECTION

Ozone Chemistry

A detailed account of stratospheric chemistry is beyond the scope of this paper however, a few critical concepts need to be explained in order to justify our parameterization of rocket ozone loss. The stratospheric ozone (O_3) layer generally resides between 20–30 km altitudes, absorbing harmful solar ultraviolet radiation before it reaches the Earth's surface. Chemical and dynamical processes that are well understood determine the vertical and horizontal distributions of stratospheric ozone. The ozone layer results from a long-term balance between the vertical profile of ozone production, the vertical profile of ozone destruction, and the global circulation of stratospheric air.

The ozone destruction side of the balance is dominated by reactive trace gases known as radicals. The highly reactive radicals—oxides of nitrogen, hydrogen, bromine, and chlorine referred to as NOx, HOx, BrOx, and ClOx—control global ozone levels by tilting the long-term balance between ozone production and destruction in favor of the latter. Moreover, because the radical reactions are catalytic, only trace amounts, a few parts per billion, are able to control much greater amounts of stratospheric ozone. A single radical molecule emitted into the stratosphere, for example, can destroy up to $\sim 10^5$ ozone molecules before being deactivated and transported out of the stratosphere. Radicals react with ozone on very short time scales, minutes to hours, so that direct injection into the stratosphere over a limited area (a rocket plume, for example) will cause a prompt, localized, ozone "hole." [16]

Particles also play an important role in ozone destruction. Chemical reactions particle surfaces activate radicals from their reservoirs, shifting the balance toward lower ozone levels. The strong potential for particles to reduce ozone is demonstrated in the springtime south polar stratosphere, where photochemical reactions on ice particles efficiently liberate ClO_x from reservoirs[17] and so play a role in the formation of the infamous "Ozone Hole." Such reactions are known occur on the surface of alumina and, possibly, soot particles.[18] Particles with diameter less than about 1 micron (μm) remain suspended in the stratosphere for several years[19] and become mixed globally by the stratospheric circulation. This means that repeated injections of submicron particles into the stratosphere, as from global (~weekly) rocket launches for example, result in an accumulation of particles. The accumulated particle surfaces increase the rates that radicals "leak" from their reservoirs and so reduce ozone levels globally.

NOx, HOx, BrOx, and ClOx radicals are produced from source gases and reservoir gases. The sources and reservoirs can be thought of as a sort of chemical storage for the radicals, which leak photochemically from storage into the stratosphere, increasing the rate of ozone destruction. The concentrations of the sources and particularly reservoirs are determined by a steady state between fluxes across the tropopause, production from radical-radical reactions, loss from photolysis and radical-reservoir reactions, and direct injection from rocket engine emissions. H_2O, emitted by all rocket engines, is one of the most critical source gases.[20] H_2O is the source gas for HOx radicals but also contributes to the formation of the ice particles that cause the polar ozone hole. Small changes in middle atmosphere water vapor and temperature can cause large changes in stratospheric cloudiness. Ozone loss from water vapor emissions is highly nonlinear and difficult to predict.

As a foundation for further discussion, we proceed with the understanding that all types of rocket engines, solid rocket motors (SRMs) and liquid rocket engines (LREs), emit compounds that are known to reduce ozone to various degrees, depending on their various compositions. Rockets engines inject all of the types of compounds mentioned above associated with ozone loss—radicals, their sources and reservoirs, and reactive particles—throughout all levels of the stratosphere. They are the only ozone destroying, human-produced, compounds that are emitted into the stratosphere this way.

OZONE MEASUREMENT AND PROTECTION

Long-term global trends in global stratospheric ozone, the interest of this paper, are often considered using the quantity AAGTO, the averaged global total ozone. The AAGTO averages out spatial and temporal variability of stratospheric ozone into a single quantity to represent the total quantity of ozone in the stratosphere. The AAGTO, informally known as "global total ozone," is often the metric reported by models to compare predictions of the response of the stratosphere to different emission scenarios. Stratospheric models generally agree that the present day AAGTO (global total ozone) is about 4% smaller than the AAGTO in the era before significant ODS use, usually taken as 1980.

For this paper, we identify the term "global ozone loss" with a decrease in predicted AAGTO (or equivalently, the decrease in global total ozone) associated with a constant annual rate of rocket emissions. We further equate the term "global ozone loss" with the commonly used term "ozone depletion" in that it refers to the overall decrease in the total quantity of ozone in the stratosphere. We use ΔO_3 to represent the percentage global ozone loss, or ozone depletion, caused by human-produce compounds. As a matter of convenience, ΔO_3 is numerically positive but refers to a decrease in the total number of ozone molecules in the stratosphere. Because of the global phase-out of ODSs mandated by Montreal Protocol regulations, the ozone layer is expected to recover to pre-ODS levels by about 2040. Figure 1 shows how ΔO_3 is expected to approach zero as the ozone layer recovers.[21] The Montreal Protocol is widely seen as a great success; ΔO_3 would have reached

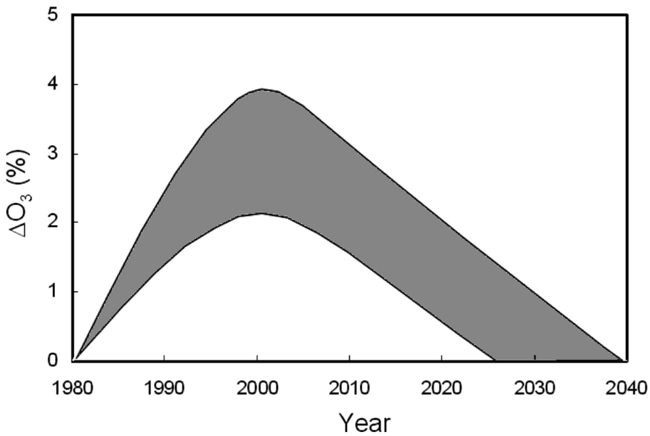

FIGURE 1 Anticipated recovery of global ozone assuming that the schedule of ODS phase-out required by the Montreal Protocol is carried out as currently planned. The shaded region represents the uncertainty over the details of the ozone layer recovery.

40% by 2010, with widespread and serious negative effects from increased solar ultraviolet radiation, without the regulation.

The formalism for determining which gases must be phased-out is highly developed: widely accepted computer models of stratospheric composition and circulation are used to predict ΔO_3 per unit mass of a gas released at the earth's surface, and this result is used to determine the substance's Ozone Depletion Potential (ODP), its ability to cause steady-state global ozone loss compared to a well-understood reference gas (CFC-11). If there is widespread agreement among the various computer simulations of ozone response to a chemical perturbation that the ODP of a particular compound exceeds a critical value (0.2 or higher), then it is scheduled for reduction and elimination by the stratospheric protection community. The models used to calculate ODPs—and so identify compounds for phase-out—are updated routinely by the scientific and regulatory communities. Innovations have included using a time dependant ODP or evaluating the increase in effective equivalent chlorine (EECl) burden caused by a substance rather than simply calculating the steady state ODP.[22] For most gases released at the earth's surface, the regulatory process is fairly well defined and has been operating successfully for 25 years.

The Montreal Protocol formalism is not entirely free of ambiguity and controversy. Models do not always agree on the predicted ODP and so it is not always clear if the ODP of a particular substance exceeds the 0.2 trigger for phase-out. In addition, because Protocol signatories can request critical use exemptions (CUEs) and delay phase-out schedules, some compounds with an ODP unambiguously greater than 0.2 can nevertheless see continued use, delaying the final phase-out of an ODS. The case of methyl bromide (CH_3Br) is relevant and instructive.[23] An agricultural fumigant in widespread use, methyl bromide is the major source gas for the BrOx radical and has an ODP between 0.4–0.8. Accordingly, the gas was scheduled for global phase-out. Various considerations have caused some Protocol signatories to request continued use of methyl bromide, under the CUE process. One of the arguments for continued use is that despite its large ODP, the global ozone loss ΔO_3 caused by methyl bromide is "small," compared to other causes of ozone depletion. This line of argument, if accepted, might be seen set a precedent for an alternate regulatory scheme for ozone protection wherein, for some industrial compounds, the ODP value is less important than ΔO_3. The methyl bromide case suggests that 0.2% might reasonably be adopted as the upper limit of acceptable ΔO_3, regardless of a compound's ODP, if the compound in question has unique and significant economic value.

ASSESSMENT OF ROCKET PROPULSION EMISSIONS

The Montreal Protocol assessment process is even less certain for compounds that are known to affect the ozone layer but do not fit into the ODP formalism, which is limited to gases released at the Earth's surface.[24] For compounds injected directly into the stratosphere, such as aircraft and rocket emissions, assessments are done with models that predict ΔO_3 for a range of "emissions scenarios." Scenarios are model inputs that follow from specification of the composition, altitude and latitude distribution, and absolute quantity (e.g., fleet flight rate) of the emission. The predicted fleet ΔO_3 is evaluated relative to the predicted ozone loss from other industrial sources. This process is not formally defined and the ambiguity invariably leads to subjective and vague assessments such as "small" or "large," "insignificant" or "significant," and "major" and "minor." As we have noted for methyl bromide, formal regulatory definitions of these terms have not been determined. The level of global ozone loss ΔO_3 that would be considered significant enough to require phase-out or use limitation, that is to say an international benchmark that would invoke regulatory action, has not been specified. Assessments of aerospace combustion emissions are complicated further by uncertainty over who would have regulatory authority, the Montreal Protocol or the International Civil Aviation Organization (ICAO), which recommends environmental standards for aircraft emissions.

Subjective assessments have advantages and disadvantages for the regulatory process, especially for poorly understood emissions without feasible alternatives. The indeterminacy of subjective assessments provides flexibility, an important advantage for successful regulation. A disadvantage of subjective assessments is that the associated uncertainties, under the rubric of ozone protection, can lead to distortions of design or investment decisions. This could possibly even include exploitation of the uncertainty by proponents of one system in competition with another.

The case of supersonic transport (SST) aircraft emissions[25] is illustrative as a cautionary tale regarding lack of knowledge, exploitation of the uncertainties, and the resulting idiosyncratic behavior of the policy apparatus. Early research suggested that SSTs could cause a large global ozone loss and this claim was used by various factions to argue against full-scale SST development. Decades after the SST was cancelled, knowledge of turbine emissions and stratospheric processes improved to show how SST ozone loss concerns could be successfully mitigated with technology (low emission engines) and operations (cruise altitude). However, the lay perception has remained that the SST was cancelled because of "environmental" issues. (As an aside, global emissions from subsonic aircraft are predicted to cause a small *increase* in global total ozone and so are not of special concern from an ozone protection standpoint.)

The point here is that the SST debate demonstrated how the reality of a public policy issue often equals the public perception. If the uncertainty in some environmental effect is only potentially large or the associated policy ambiguous, then the effect becomes a policy problem. Space launch systems represent a situation similar to that of SSTs with respect to ozone layer protection.[26] Ozone loss from rocket emissions could be large in some scenarios and rockets are not included in the present assessment and regulatory regime. Formal metrics such as ODP and EECl are not meaningful for rockets. These metrics do not account for direct emission into the stratosphere, particles, or gases other than chlorine or bromine compounds. Thus, as for SSTs in the past, computer models are used to predict the change in global total ozone for a particular rocket fleet scenario and are informally evaluated in a qualitative and subjective sense.

Compared to SST emissions however, the level of research applied to predict ozone loss from rocket emissions has been minuscule and out of balance with reality. Consider that the global space launch industry is well established and likely to grow while the SST industry is nil and unlikely to grow at all. The 2002 WMO Ozone Assessment briefly mentions (1) that SRM emissions at current launch rates likely have a "small" impact on ozone and (2) that LRE emissions may have some additional impact that is largely unknown. The wording of the 2002 Assessment implies that 0.1% can be taken as the threshold for "small" ozone loss, even less than the 0.2% implied by some arguments in the ongoing methyl bromide discussion.

In this work, we are interested in quantitatively evaluating different scenarios of launch activity so for the purpose of discussion we need to define the threshold that differentiates between "small" or "large" ozone loss, even if there is currently no such designation formally. We consider 1% an unambiguous upper limit that defines unacceptably large ΔO_3. The upper limit could be smaller however. Following the methyl bromide arguments, the upper limit on ΔO_3 might be as low as 0.2%. We also note, for some environmental concerns the ICAO standard is "no worse than Concorde" the only supersonic transport to see operational status. Concorde's ΔO_3 at the peak of fleet operations was certainly small,[27] less than 0.01%. As we show below, the present day impact of many of the world's rocket systems likely exceeds the "Concorde" standard with regard to ozone loss. In order to compare different future launch market scenarios, we assume two values of ΔO_3, 1% and 0.2%, that represent a possible upper bound that defines the limit of "acceptable" ozone loss. If the predicted global ozone loss ΔO_3 does not exceed 0.2%, we assume regulatory concerns would be nil. In contrast, if predicted ΔO_3 exceeds 1%, we assume that regulatory factors would almost certainly limit launch operations. For launch systems, this regulation could take a number of forms such as caps on launch rates or limits on propellant type combinations. We emphasize that these trigger limits of 0.2% and 1% are theoretical and completely particular to this work; our purpose here is to foster discussion regarding the matter and show how a regulatory limit on global ozone loss from launch systems could affect space launch development.

STRATOSPHERIC IMPACT OF ROCKET EXHAUST

Overview and Methodology

A full description of the complex processes that mix, transport, and chemically process rocket emissions into the global stratosphere is beyond the scope of this work However, it is of interest to briefly review the available information on rocket emissions and how the ozone layer is affected. With this background, we present approximate descriptions of the global ozone loss ΔO_3 for rocket emissions based on available data and models. The available information is sparse and approximate; so our analysis must be considered in the context of large uncertainties. This is particularly so for liquid propellant engines. The alternative to our work is to make no progress at all. Accordingly, in addition to our conclusions, we highlight the many areas where further research is required.

To first order, rocket engine exhaust consists of chemically inert compounds (N_2 and CO_2), radicals (NO, OH, Cl), radical sources and reservoirs (HCl, H_2O), intermediate underoxidized compounds (H_2, CO) and alumina or soot. The relative combinations of these compounds in the exhaust depend on propellant type; four main propellant types are in wide use, one solid, and three liquid. We must distinguish between rocket exhaust (hot gases and particles at the nozzle exit) and rocket emissions (the cold plume wake that mixes into the stratosphere). In the lower stratosphere, fuel rich rocket exhaust is modified in the hot plume by intense secondary combustion reactions driven by atmospheric oxygen mixing into the plume. This "afterburning" governs the conversion of H_2 to H_2O, CO, and soot to CO_2, and net production of ozone destroying radicals.[28] Afterburning is vigorous in the lower stratosphere, lessens with altitude, and stops in the upper stratosphere and so rocket emissions are highly variable with altitude. Afterburning is not well understood—especially with respect to the minor components that most affect ozone.

Table 1 shows the first order emission compositions for the four main propellant types. Parentheses show the common names for the different propellant types. Table 1 acknowledges afterburning by reporting H_2 and CO in the exhaust as converted to H_2O and CO_2, respectively, and net production of radicals. We emphasize that plume models have never been validated with respect to the net emission of radicals, soot, or the details of the alumina particles sizes. One recent measurement suggests that the models in fact underestimate the production of NO in the Space Shuttle SRMs or LREs.

The emissions presented in Table 1 cause prompt and deep ozone loss (approaching 100%) in the immediate plume wake, caused by the radical emissions, over areas of hundreds of square miles lasting several days after launch. These stratospheric "ozone mini-holes" have been well observed in situ by high altitude aircraft plume sampling campaigns. It is not known if the cumulative effect of the small "ozone holes" is significant compared to the global steady-state chemical effects of the emissions.

Beyond the prompt plume wake ozone destruction, second order processing of rocket combustion products occurs during the weeks and months after launch. The plumes are transported and mixed into the global stratosphere and lose their identity as distinct air masses. This intermediate mesoscale phase would be characterized by complex plume-atmosphere interactions among radicals, reservoirs, and sinks. Significant influences from alumina or soot particles are expected, possibly involving the creation of new H_2O related particles. The details of this processing will be highly variable according to altitude and even time of day of launch and certainly has a large influence on the steady-state global ozone loss. A few chance observations of aged plumes confirm the importance of the mesoscale processing. No studies have been done on this aspect of rocket emissions.

TABLE 1 Approximate Emission for the Four Main Propellant Types Given as Mass Fraction for each Component.

	Inert N_2	Inert CO_2+CO	OH source H_2O+H_2	Radicals ClOx, HOx, NOx	Radical reservoirs HCl	Particles Alumina soot
NH_4ClO_4/Al (solid)	0.08	0.27	0.48	0.1	0.15	0.33
LOX/H_2O (cryogenic)	—	—	1.24	0.02	—	—
LOX/RP-1 (kerosene)	—	0.88	0.30	0.02	—	0.05
UDMH/N_2O_4 (hypergolic)	0.29	0.63	0.25	0.02	—	Trace

Note: The Total Mass Fraction Exceeds Unity because of the assumption that air mixed into the plume oxidizes CO and H_2.

One should now appreciate that rocket emissions are complex, variable, and not well understood. Global models of the stratospheric response to rocket emissions have not taken into account at all the influence of afterburning and mesoscale processing. This is because a rigorous analysis of these effects has never been done. The information in Table 1 should not be taken to predict the emission of a given rocket engine type. Rather, the main points of Table 1 are that (1) SRMs emit relatively large quantities of gases and particles that deplete ozone; (2) LREs emit smaller amounts of gases and particles that potentially deplete ozone; and (3) all rocket engines emit water vapor that will deplete ozone.

For our purposes, we make the problem tractable, at least to first order, by making several simplifications:

1. We ignore the prompt plume wake ozone "mini-holes" and the mesoscale mixing and processing. We only consider the situation presented in published models of rocket emissions, the long-term, cumulative, steady-state ozone loss ΔO_3 from all rocket launches.
2. We assume that ozone loss caused by SRMs is separable from ozone loss caused by LREs. As Table 1 shows, SRMs emit much greater amounts of reactive chemicals and particles. Thus, we can be certain (despite the relative lack of LRE models) that SRM emissions will affect ozone much more significantly than emissions from any of the three LRE types.
3. We consider LREs together as a class so that the ozone loss they cause can be described with a single parameter, representing the "characteristic" LRE impact. Each LRE type certainly reduces ozone uniquely and unequally, but all LREs cause some ozone loss that is an order of magnitude smaller than SRM ozone loss. This approximation is rough, but it is consistent with the sparse LRE emissions data, plume data, and model predictions.
4. We describe the ozone loss for SRMs and the LREs based on generalizations deduced from published models that describe perturbations to the global stratosphere from rockets and supporting plume measurements. While significant progress was made on the problem of rocket emissions in the 1990s, little additional work has been done since the 2002 WMO Ozone Assessment. The literature is sparse. Published calculations of ΔO_3 for rocket emissions are very limited—none account for variability associated with afterburning, mixed propellant types, chemical processing between the early plume wake and steady-state phases, and LRE emissions, in general.
5. We assume that the steady-state ozone loss ΔO_3 from rockets can be approximated by the linear addition of the long-term steady-state effects of all launches on a global basis. This simplification ignores several second order effects such as the effect of launching from different latitudes, seasons, times of day, and the changing background stratosphere.

6. We only consider rocket propulsion systems currently in wide use. We do not consider proposed propellant combinations such as LOX/methane, hybrid systems, or hypersonic propulsion systems. These are a small part of the present day global emissions. They are likely to be more significant in coming decades however. Airbreathing hypersonic systems in particular are of great interest for ozone loss since they would emit much of their combustion products directly into the peak of the ozone layer at altitudes near 20 miles and are often discussed as the first stage of proposed high flight rate, reusable launch systems.[29] A hypersonic-based launch system would deposit a larger fraction of the total combustion products into the stratosphere than rocket systems. Much research and development is currently being invested into hypersonic systems, without much regard to their impact on the ozone layer.

We emphasize the uncertainty in specification of rocket emissions and their effects on the stratosphere. This is especially true for the cryogenic and kerosene systems that are usually assumed harmless to the ozone layer.[30] Significant data collected in LRE plumes strongly suggest that LRE emissions contain significant amounts of reactive NO, OH, and particles; furthermore, they cause the formation of ice particles in the middle and upper atmosphere.[31] These data indicate that the assumption that "LREs are green"[32] as far as ozone is concerned are not correct.

PARAMETERIZATION OF GLOBAL OZONE LOSS ΔO_3

With the problem simplified, we write an expression for the global ozone loss ΔO_3 from rockets as the sum of the effects of SRM and LRE combustion emissions as

$$\Delta O_3 = \delta_S M_S + \delta_L M_L \tag{1}$$

where ΔO_3 is the steady-state percent decrease in global total ozone for an atmosphere with rocket emissions compared to one without. M_S and M_L are the annual stratospheric emission (kiloton) from SRMs and LREs, respectively. δ_S and δ_L are ozone loss coefficients that relate ΔO_3 and emission mass for SRMs and LREs, respectively. For convenience, we assume that the units of M and δ are kilotons (kt) and percent per kiloton (% per kt) of rocket combustion emitted into the stratosphere. M_S and M_L are assumed annual values. Both terms on the right-hand side implicitly include the effects of both gas and particle emissions of the two propellant types. The parameters δ_S and δ_L are admittedly not as sophisticated as the standard metrics for ozone depleting substances such as ODP or EECl but they can reasonably applied understand trends and comparisons to the major sources of ozone loss such as halogens. Indeed, one of the goals of this work is to argue the need for the creation of a more robust and considered formalism to assess rocket emissions.

We estimate the values for δ_S and δ_L by summarizing previous research on the emissions from rocket engines and the response of the stratosphere to those emissions. For some cases, the relevant research has not been done, and so we make use of general arguments to estimate the correct values for δ_S and δ_L. The emissions M_S and M_L are either specified explicitly or estimated as a function of LEO payload. The ozone loss coefficients δ_S and δ_L are acknowledged only an approximate description of the relationship between rocket emissions and global total ozone loss. Our definition of δ_S and δ_L averages out a number of second order variables including latitudinal and seasonal details of launches and nonlinear effects in stratospheric chemistry and dynamics. δ_S and δ_L are too coarse to be considered as an ODP analogue for rockets. As we point out below, much work lies ahead in order to derive a comprehensive and sensible way to compare the global total ozone loss from different rockets.

Some work has been done to model the effects of SRM emissions and so we have some confidence in our assumed value for δ_S of 1.5×10^{-2} % per kt. This value follows from a number of detailed steady-state stratospheric models that include SRM chlorine gas and alumina particle emissions.[33] The ozone loss from chlorine emissions from SRMs is well understood, however, the ozone loss from alumina particles is only poorly understood. Chemical reactions on alumina particles promote production of ClOx from its reservoirs, similar to reactions on certain ice particles that contribute to the south polar ozone hole. While the chemistry is known, the steady-state alumina loading is not. Only alumina particles smaller than ~1 μm remain in the stratosphere for years and contribute to the steady-state ozone loss. The fraction of SRM alumina particles that meet this criteria been variously reported as between 1% and 30%.[34] Here we assume the alumina sub-micron mass fraction equals 5%, in the middle of the range of possible values. The models show that for a mass fraction of 5%, the alumina and chlorine contribute about equally to SRM ozone loss. Our assumed value for δ_S of 1.5×10^{-2}% per kt can be considered moderately conservative.

Little work has been done to model LRE emissions or their effects on ozone. We have only moderate confidence in our assumed value for δ_L of 3×10^{-4} % per kt. This value follows from a detailed model of hypergolic emissions where the global ozone loss, almost completely due to NO emissions, approximately equaled 2% of the ozone loss from SRM emissions, suitably scaled by propellant mass.[35] We assume that all three LRE types can be characterized under the assumption that the ozone loss coefficient δ_L equals 2% of δ_S. This assumption is speculative, though plausible. OH and NO emissions from kerosene and cryogenic engines are unknown but are plausibly present at the percent level with after burning and are certainly present at the tens of percent level without afterburning. Soot from kerosene engines might also contribute to ozone loss. We will say that the actual ozone loss factor for LREs is not likely to exceed our assumed value greatly, but neither can we rule this out because of the nearly complete lack of data and models. In the event that additional data and model results show that after burning kerosene and cryogenic engines do not emit significant amounts of NO, OH, or chemically active particles, then the ozone loss would be determined by H_2O vapor alone. In that case, our calculations would overestimate ozone loss by about a factor of ten.

It is convenient to restate equation (1) in terms of the total annual mass of rocket exhaust emitted into the stratosphere M_T and the ratio f where:

$$M_T = M_S + M_L$$
$$f = \frac{M_S}{M_T} \qquad (2)$$

where f represents the fraction of total stratospheric emission from SRMs. We then write the global ozone loss as

$$\Delta O_3 = M_T(f\delta_S + (1-f)\delta_L) \qquad (3)$$

GLOBAL OZONE LOSS FOR VARIOUS LAUNCH FLEET SCENARIOS

Ozone Loss and Rate of Orbital Payload Delivery

We are interested in the global ozone loss caused by the total emissions from all launches from the earth's surface and so "fleet" refers to the total of all rocket types worldwide. The assumed values for δ_S and δ_L are used in equation (1) to calculate the global steady-state ozone as a function of the exhaust mass emitted annually above the tropopause. Figure 2 shows global ozone loss ΔO_3 for an SRM fleet and an LRE fleet; ΔO_3 from mixed fleets would lie between the two extremes. The ozone losses in Figure 2 require about three years of roughly constant emissions to develop as exhaust gases and particles to reach a steady state with stratospheric processes, a requirement that the global launch industry meets. Presently, SRMs contribute about one third of annual global rocket emissions and so they dominate current ozone loss. In recent years, the average of annual SRM emissions is about 3 kilotons per year so that Figure 2 shows that current launch related ozone loss is about 0.03%, well below the 0.2% loss threshold we assigned earlier to designate small (or equivalently, minor) ΔO_3. The figure makes clear that even the 1% loss threshold we assigned for unacceptably large ozone loss can be reached for sufficiently large emissions of either SRMs or LREs.

In order to understand how rocket ozone loss relates to the annual, global weight of material placed into orbit, we must account for the relationship

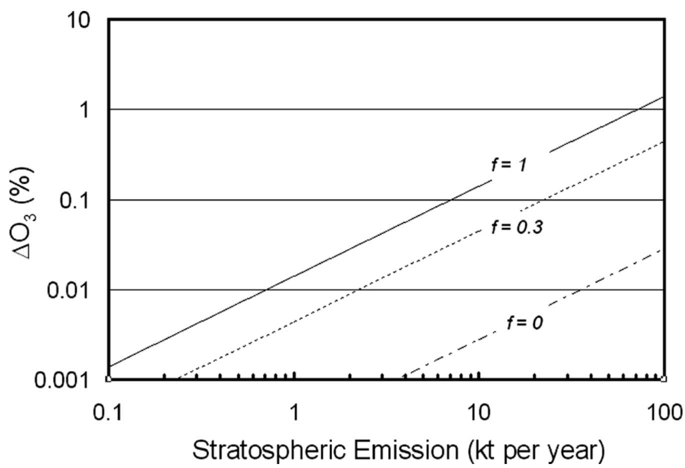

FIGURE 2 Global ozone loss ΔO_3 (%) as a function of annual rocket emission into the stratosphere (kt per year) for different values of *f*, the fraction of total stratospheric emissions from SRMs.

between launch emissions and payload weight. While each launch vehicle will have slightly different relationships between payload and emissions, detailed studies of several specific launch vehicles show that an approximate relationship between stratospheric emission M_S or M_L and first and second stage propellant masses M_1 and M_2 is given by

$$M_{S,L} = \frac{1}{3}M_1 + M_2. \tag{4}$$

Figure 3 shows estimated stratospheric emission as a function of LEO payload mass for a variety of launch vehicles (active and inactive). The relative mix of SRM and LRE propellant burned in the stratosphere for each of these vehicles is highly variable, from purely SRM to purely LRE. Since the engines used by the various launch vehicles have different efficiencies (e.g., specific impulse) and each launch vehicle has been designed for different missions (LEO, GEO transfer, high inclination, reusability) and has different launch site latitude, the definition of payload in this context is somewhat arbitrary. In addition, a given launch vehicle can take on different stage configurations (e.g., strap-on stages) so that the relationship shown is only approximate.

Application of the ideal rocket equation for a 5 kt payload, two stage vehicle with specific impulse of 300 sec and structural mass fraction of 0.1, along with equation (4), and consistent with the overall level of approximation for this discussion allows us to write

$$M = 12\, M_{\mathrm{LEO}}, \tag{5}$$

where M is the total stratospheric emission, and M_{LEO} is the LEO payload. Figure 3 shows that this relationship is consistent with estimated emission

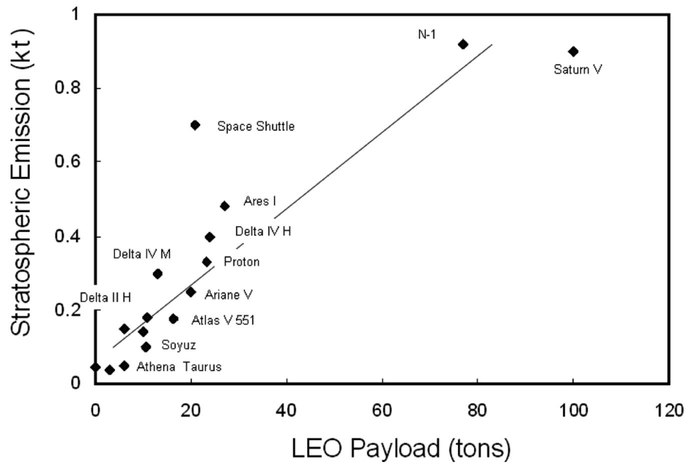

FIGURE 3 Stratospheric propulsion emission as a function of LEO payload for fourteen different launch vehicles. The line indicates stratospheric emission estimated according to equation (5).

across a variety of launch vehicles and so represents the relationship between LEO payload and stratospheric emission in a robust, if coarse, manner. Note that for the Space Shuttle, we assume the useful payload rather than the total mass of the Orbiter with payload placed into orbit. This means that the Space Shuttle emits several times more stratospheric emission per payload mass than the general trend for other launchers. Greater stratospheric emission for reusable launch vehicles (RLVs) compared to expendable vehicles would be characteristic of RLV systems in general and so in this sense RLVs are more harmful to ozone than expendables.

We can combine equations (3) and (5) to write an expression for global total ozone loss ΔO_3 as a function of mass placed into low earth orbit (LEO) M_{LEO} as

$$\Delta O_3 = 12\ M_{LEO}(f\delta_S + (1-f)\delta_L). \quad (6)$$

We apply equation (6) to investigate how much global ozone loss the current global launch market causes, how this fits into other sources of ozone loss, and how this might change in the future as the space industry grows. Figure 4 shows the range of global ozone loss for mixed SRM and LRE systems as a function of payload delivered to LEO. In recent years, the global launch industry has annually lifted nearly 1 kt into LEO and about one quarter of the stratospheric emission has been from SRMs. (Note that GEO payloads typically require about six times their final GEO weight to be placed into LEO parking orbits.) Like Figure 2, Figure 4 shows that the current ozone loss from the global launch fleet is about 0.03% with almost all of this is due to the SRM component of the exhaust. As discussed above the stratospheric protection community has deemed this level of ozone loss "not significant."[6]

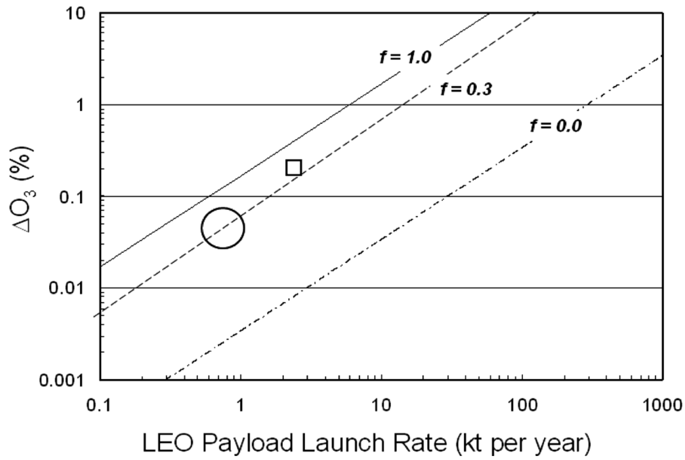

FIGURE 4 Steady-state ozone loss as a function of LEO payload rate for different values of *f*, the fraction of stratospheric emission from SRMs. The square shows the situation that would have emerged for the original Space Shuttle design goal. The circle illustrates the approximate situation for the global launch business in recent years.

Interestingly, Figure 4 shows the situation that would have developed had the Space Shuttle met its original goal of weekly launches. In this case, ΔO_3 from Space Shuttle launches would have approached the 0.2% limit for small ozone loss. Designed and built prior to the era of international protection of stratospheric ozone and when the impact of SRM emissions on ozone was not understood, global ozone loss was not a factor in Space Shuttle design or operations planning. If weekly launches of the Space Shuttle were proposed now, it is not clear how the stratospheric protection community would respond. We point this out to emphasize that, as new discoveries improve our understanding of rocket emissions and stratospheric processes, ozone depletion considerations might influence launch systems design and operations during the typical multi-decade life of launch systems.

Global fleet launch rates sufficiently large to exceed the 0.2% threshold for any propellant type mix are not likely without revolutionary changes in the space industry. We cannot know when or how such changes might come about though serious planning and discussions are ongoing.[36] Various proposals for very large space infrastructure projects, space tourism, or RLVs with very high launch rates have been seriously proposed and significant resources have been invested. All of these proposals would result in large launch vehicles with very high launch rates (i.e., daily) and so it is of interest to evaluate them based on their impact on the ozone layer. One often discussed concept is the use of Solar Power Satellite (SPS) systems for electricity production. A recent study[37] indicates that the required annual launch demand for an economically viable SPS system would be about 25 kt per year, over many years, perhaps indefinitely. Figure 4 shows that this SPS launch system would be constrained to use liquid propellant systems in order to ensure that ΔO_3 remains below the 0.2% threshold; an SPS launch system could not make significant use of SRMs in the stratosphere. Since we are able to define LRE ozone loss in only approximate term, we cannot rule out that even an all liquid propellant fleet at SPS launch rates might result in significant global total ozone loss, depending on the actual effect of a specific LRE type. The ambiguity of SPS launch illustrates the need for an improved understanding of rocket emissions of all types. With the current knowledge gaps, we cannot predict with any confidence which (indeed, any) large launch or space systems are plausible with respect to ozone depletion.

THE CARRYING CAPACITY OF THE STRATOSPHERE

Figure 4 raises the notion that the stratosphere is characterized by a "carrying capacity" that represents an upper limit to the amount of material that can be placed into earth orbit using conventional rocket propulsion without causing excessive ozone loss. We have argued that the upper limit of acceptable ΔO_3 could reasonably be considered 0.2–1%, though we reiterate that there is no formally defined value or even a regulatory formalism to determine "too much ozone loss" for a particular global industrial process or system. For a value of ΔO_3 considered excessive as small as 0.2% our results show that upper limits on material that can be placed into earth orbit by conventional chemical propulsion systems are about 1 and 28 kt per year for SRM and LRE launch systems, respectively. Our ability to calculate the actual carrying capacity of the stratosphere is controlled by several poorly known parameters, the global ozone loss parameters δ for each propellant type and the maximum value of global ozone loss ΔO_3 allotted to launch systems by regulatory actions.

In the event that an upper limit on ΔO_3 is ever assigned to the global launch industry, the limit would necessarily be globally distributed, perhaps on a national basis. Any given nation then would have to operate under a limit that would be even smaller than the global limit. The carrying capacity of a given nation then would be determined by the mix of propellant types used by its launch systems. It is unlikely that the carrying capacity will be approached in the near or even intermediate future but it could be approached after several decades of significant launch market growth, especially for the scenarios of revolutionary changes in the space industry. The details of the true carrying capacity of the stratosphere for a given propellant (or combinations of propellants) will change as new models and data become available, however Figure 4 shows us that it is not possible, within the context of protecting the ozone layer from excessive loss, for the launch market to grow arbitrarily large. Given the anticipated recovery of the ozone layer, the potential for large scale space infrastructure projects, and the potential growth in non-traditional space markets (tourism, for example), policy makers should begin to consider how a vigorously growing launch market might affect the ozone layer. Further, they need to define a formalism for evaluating rocket emissions without prejudice with respect to any one nation's launch systems.

OZONE LOSS FOR VARIOUS LAUNCH MARKET SCENARIOS

In order to predict the relative contribution of rocket emissions to global total ozone loss from all sources, especially in view of the declining influence of ODSs (Figure 1), we must assume a scenario of future demand for launch capacity. Predicting launch demand, even in the near term, has proven difficult. Widespread expectations of a surge in commercial launch demand in the 1990s where overoptimistic and the demand did not materialize. Studies of long-term (e.g., decades) launch demand have been based on various approaches including historical comparisons to other transportation systems such as railroads or aircraft and economic analysis of emerging market demand based on price and demand relationships One simple approach is to assume that the relative mix of SRM and LRE propulsion systems will not change significantly over time and apply a constant growth rate to the current value of global ozone loss of 0.03%.

Figure 5 shows the sum of global ozone loss from ODSs (declining leg) and space launch (increasing legs) for illustrative rates of launch demand increases: zero, doubling each decade, and tripling every decade. If such trends appear and persist over the next several decades, around 2035 rocket emissions would represent an ozone depletion mechanism comparable to the declining ODSs. Figure 5 makes the point that, while currently insignificant compared to ODSs, the very success of the Montreal Protocol increase the relative ozone depletion from rocket emissions.

A more sophisticated approach to predicting launch market growth links launch price ($ per pound launched into LEO) to the quantity of material launched into LEO (kt launched per year) and so allows us to predict how ΔO_3 from rockets might change as a function of launch price. A detailed econometric analysis of the launch market is beyond the scope of this paper; however, we can illustrate some basic notions of how limitation on the launch market associated with ozone depletion might affect the space economy. The organizing principal is that as launch price declines, new demand will appear and, over a sufficiently long time, launch capacity and demand are in equilibrium with an appropriate law of supply and demand. However, as we have seen launch rates cannot rise arbitrarily high without causing too much ozone loss. Thus, ozone depletion from rocket emissions could be considered a market externality that has the potential to lead to inefficient allocation of investments or failure of the launch market.

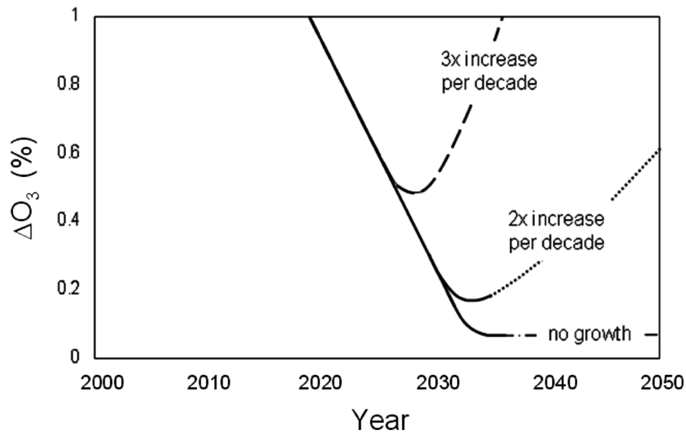

FIGURE 5 Global ozone loss from 2005–2050 for different launch growth scenarios. The solid line show declining ozone loss from past ODS emissions. The dash-dot, dot, and dashed lines show increasing or stabilizing ozone loss from launch emissions for the cases of no growth, doubling per decade, and tripling per decade, respectively.

SRMs cause so much ozone loss that if all launches were on SRMs, the market could not likely grow at all beyond the current situation, and so SRMs are not likely to play a major role when proposing large increases in payload delivered to orbit. Whether large growth comes about with expendable or reusable systems they will almost certainly have to be LRE systems, at least from an ozone loss point of view. Accordingly, we do not consider SRMs any further in this paper and concentrate our attention on LRE emissions for the remainder of this paper.

One measure of market performance is total revenue. In this case, we mean the combined revenue (in dollar terms) for launch providers worldwide, though it could mean an individual country or whatever organization is allotted the particular level of ozone loss (e.g., 0.2% or 1%). Assuming for the moment that launch price *P* and launch demand *Q* are independent, we write an expression for the total launch market revenue *R*, given by

$$R = QP, \tag{7}$$

where *P* is launch cost ($ per pound to LEO); and *Q* is identified with M_T, the total mass of payloads launched into LEO. The carrying capacity concept implies that there is an upper limit on Q, which in turn implies an upper limit to total revenue *R* for a given price *P*

$$R_{max} \leq PQ_{\mathrm{max.}} \tag{8}$$

This limit on total launch market revenue R_{max} is shown in Figure 6 for an LRE-based launch fleet with $Q_{\max}$ determined for 0.2% and 1% maximum allowable ΔO_3. Figure 6 shows that for a launch price of 100 $ per lb, the

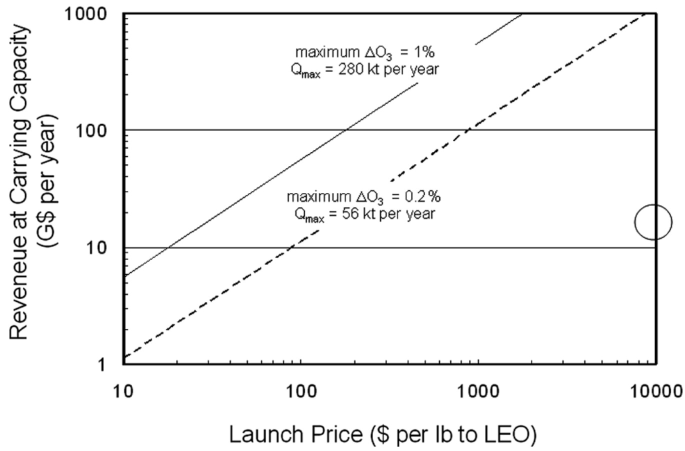

FIGURE 6 Revenue R (G$) as a function of launch price P ($ per lb) for an LRE based system (i.e., $f = 0$.) The solid and dashed lines show the maximum possible revenue for maximum permissible global ozone loss ΔO_3 of 1% and 0.2%, respectively. The current global launch market economic condition of 10,000 $ per lb and 20 G$ is indicated.

maximum possible total revenue for a launch industry based on LRE systems equals about 15 and 70 G$, respectively. Also noted in Figure 6 is the approximate present day market condition with launch price of about 10,000 $ per lb and gross revenue of about 14 G$.

In real-world markets operating near supply and demand equilibrium, Q can be related to P with an assumed specification of market elasticity E describing how demand changes with changing price. Various studies of the relationship between price P and quantity Q for the launch market have been done and one common result is that, at least near the current price of about 10,000 $ per lb, the launch demand is not very elastic with respect to changes in price.[38] The studies often conclude than the launch market is inelastic until some threshold price is reached, below which the demand for payload quantity will (perhaps) strongly increase as price decreases. The threshold price and the rate of demand increase below the threshold are only speculation but the notion of a demand elasticity threshold seems widely accepted. Using these concepts, we relate launch quantity demand and price as

$$Q = Q_0 P^{-E}, \tag{9}$$

where E is the elasticity of the launch market, and the constant Q_0 is determined assuming that Q does not increase until price falls below 2,000 $ per lb. E has the usual definition of fractional change in quantity per fractional change in price; $E = 1$ corresponds to an inelastic market. For discussion purposes we assume three levels of market elasticity, low, medium,

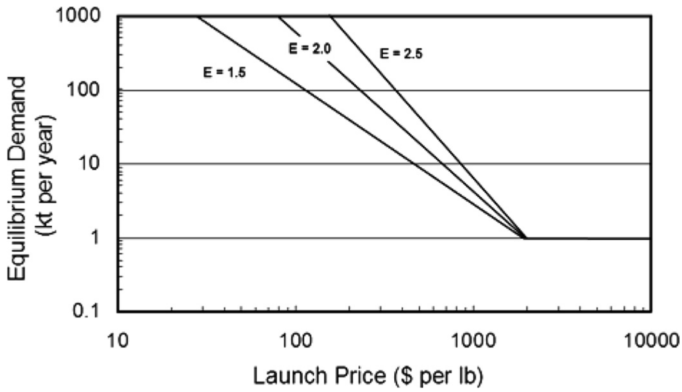

FIGURE 7 Equilibrium demand for launch quantity Q as a function of launch price P for three scenarios of launch market elasticity. Values of E equal to 1.5, 2, and 2.5 correspond to low, medium, and high elasticity, respectively. An inelastic market ($E = 1$) is assumed between 2,000 and 10,000 $ per lb.

and high elasticity $E = 1.5$, 2, and 2.5 respectively. Figure 7 shows the resulting equilibrium relationship between Q and P. This analysis does not address how the market gets to equilibrium, only that it does by the usual market forces and the assumption of equilibrium provides a reference for discussion. The values of E we assume are speculative but follow the results of other studies. One RLV cost study, for example, assumes elasticity between our high and medium cases. Another study assumes a demand curve that resembles our low case.

We are interested in how the market limitations implied by Figure 6 relate to total revenue. Figure 8 shows total launch market revenue as a function of launch price for LREs, with the limits associated with 1% and 0.2% global ozone loss limitation indicated. Ignoring the global ozone loss limitations for the moment, Figure 8 shows that revenue decreases until the 2,000 $ per lb elasticity threshold is reached. This conundrum of a "trough" in launch market revenue has been previously cited in launch market studies. It means that the launch market will have to "jump over" a trough in revenue, near the price of 2,000 $ per lb, through technology investments that would be unprofitable for a long period of time. Investors financing such a jump would need high confidence that a predictable launch market, with known limitations including regulatory ones, will be found on the low price side of the trough.

Figure 8 shows that for LRE systems, total revenue can respond favorably for some combinations of elasticity and global ozone loss limits. However, the stratospheric carrying capacity limits how much revenue recovery is possible. For example, for a global ozone loss limit of 1% and medium elasticity, revenue can increase by a factor about 3 for a price of about 100 $ per lb. On the other hand, if the global ozone loss limit is only 0.2%, revenue can barely recover to the present day value of about 10 G$.

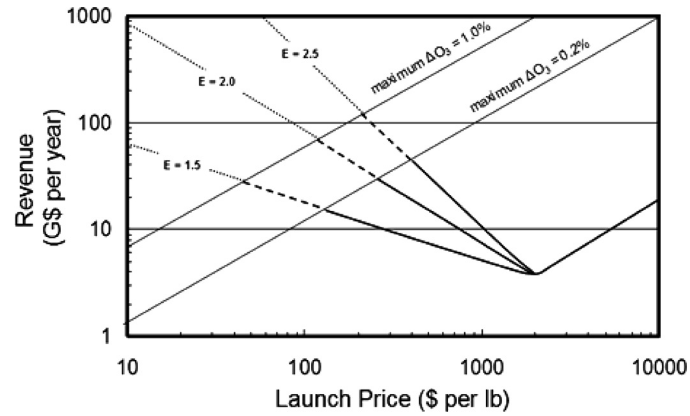

FIGURE 8 Total revenue *R*(G$) as a function of launch price *P*($ per lb) at demand-price equilibrium. *R*(*P*) is shown for elasticity *E* values of 1.5, 2.0, and 2.5. The heavy solid, dashed, and dotted lines show *R*(*P*) for $\Delta O_3<0.2\%$, $1\%<\Delta O_3<0.2\%$, and $\Delta O_3>1\%$, respectively.

Our results have important implications for the development of the space and launch industry. Analysis of future launch markets (reusable launch systems particularly) implicitly assume that the only limitations on launch rates are technological or economic. Studies of launch economics typically assume that launch rates are free to rise to meet any quantity demand if launch costs can be reduced sufficiently to spur demand. Indeed, these analyses usually show that launch demand must increase by orders of magnitude in order to justify the development of a reusable system. Our analysis shows however that considerations of stratospheric ozone depletion represent a very significant factor that should be considered in econometric analysis of large-scale space systems.

While a detailed econometric analysis is beyond the scope of this work, reflecting on the development of a low-cost launch system against an evolving ozone regulatory environment illustrates our point. Our putative launch system is consistent with the scale of future launch systems often presented for econometric analysis. We suppose that a corporation decides to commit the financial resources to develop a low-cost launch system that could profitably operate in a launch market with medium quantity demand elasticity, $E = 2$. The objective of this new launch system is to "jump" across the trough in revenue and profitably operate at a price of 100 $ per lb, demand of 400 kt per year (10,000 flights per year), generating revenue of 80 G$ per year. Development would take about ten years and a positive return on investment would take even longer. The decision to proceed with decades long development and investment critically depends on (among other things) an assumption that normal market forces will freely respond to a low-cost launch service and modulate demand over several decade life-cycle of a launch system.

Consider, however, the implication of unanticipated ozone protection regulation for our conjectural launch system. Suppose that as the system becomes operational, new international regulations are adopted to strengthen protection of the ozone layer. Suppose that new regulations restrict the global total ozone loss ΔO_3 resulting from any particular industrial activity, including space launch, to not exceed 1%. Figure 8 shows that under this regulatory regime, the new launch system would be limited to launching only about 278 kt into orbit per year, much less than the design assumption of 400 kt per year. The new launch system could not reach the design economic state. To realize the design revenue of 80 G$, the launch price would have to rise to about 145 $ per lb, violating the original design assumption. If our conjectural launch system is limited by the lower maximum ΔO_3 equal to 0.2% (perhaps because a global launch limit of 1% is divided among the world's various national launch agencies) then the economic situation becomes very distorted. In this case, the new launch system is limited to launching 30 kt per year so that price must increase to about 1,300 $ per lb to realize the design revenue of 80 G$. This price is so high so as to completely obviate the need to invest resources to develop the 100 $ per lb system in the first place.

This launch market thought experiment clearly demonstrates that for plausible values of the two main uncertainties of concern, the amount of ozone loss caused by LRE exhaust (the value of δ_L) and the magnitude of maximum allowable global ozone loss (a cap on launches, for example) could have a significant impact on the economic viability of possible large-scale, low-cost launch systems. We emphasize that the value we assume for δ_L is only one plausible value from a range of possible values. It is also plausible, though perhaps less likely, that the actual value of δ_L is much smaller than the value we have assumed; we simply do not have sufficient data. For the best case with δ_L equal to the lower limit from H_2O emissions alone and an ozone loss limit of 1%, the launch limit is about 2500 kt per year. At this level, it is difficult to imagine that ozone loss regulation would play any role in space development. However, for the worst case with δ_L equal to the upper limit and an ozone loss limit of 0.2%, only about 30 kt could be placed into orbit per year, a level certain to have a strong influence on the economic and technological basis for large scale space systems.

Our work shows that the commonly held assumption that LRE emissions have no environmental impact is not accurate. LREs, particularly kerosene and cryogenic systems, are often described as "environmentally friendly" or "green" propellants[52] and this is generally true compared to SRMs. SRM emissions are a fairly well known cause of global total ozone loss. We reiterate the point that emissions from all rocket propellant types cause some global total ozone loss, even if only from water vapor emissions. Further, even LRE ozone loss will be considered significant by the regulatory apparatus charged with protecting the ozone layer at high enough flight rates. Analysis of proposed launch systems or emerging space markets such as tourism or space power generation commonly assume that the only limit to the potential number of launches or the amount of material that can be launched into orbit is economic. This is not necessarily true. We have shown that protection of the ozone layer presents a potentially serious limit to growth of the space transportation market and that this limit might be low enough so as to influence the economic value of investments in new launch systems. The problem is that we do not have sufficient information on the actual effects of rocket emissions on ozone to eliminate this possibility. Challenges to the growth and sustainability of space exploration[51] need to consider the risk of overly conservative limits related to ozone depletion that might arise out of a lack of accurate information on rocket emissions.

How do rockets currently compare to existing aerospace propulsion emissions? We are sure that rockets cause ozone loss. We are relatively sure that global aircraft emissions currently cause a small increase in global ozone,[39] making a comparison between them with regard to ozone depletion is not strictly meaningful. Rockets cause a few percent of all ozone depletion, about the same relative impact that aircraft have on radiative forcing of the atmosphere.[40] And as we noted, there is great policy pressure for aircraft to reduce their greenhouse gas emissions, possibly at great cost to the industry.[41]

How do rockets currently compare to other ODS sources? As we have noted, ozone loss from rockets is currently small compared to all ODSs on a global basis. However, can also compare rockets, a specific industrial process, to specific applications of ODSs that require exemptions from Montreal Protocol phase-outs. One example is Metered Dose Inhalers (MDIs), hand-held medical devices that historically used CFCs as a propellant. United States companies have been granted Essential Use Exemptions for CFC use in MDIs in recent years. In 2008, the exemption, obtained after much diplomatic negotiation, was for 0.03 kt[42] of CFCs. Now the annual emission of United States SRMs is about 3 kt into the stratosphere and while there is no common metric for comparison, there is little doubt that the integrated impact from SRMs was larger than the integrated impact from the CFCs covered under the MDI exemption.

In these two examples, we see that policies to protect the global atmosphere might be seen as having contradictory or inconsistent positions. A small contributor to climate change (air transport), might be regulated, while a small to ozone depletion (rockets) is not regulated. Montreal Protocol exemptions are required for one activity (CFC-based MDIs) while another activity with larger ozone loss (SRMs) is not subject to any regulatory attention. Indeed, new SRM-based launch vehicles are being developed by the European Space Agency and NASA so that SRM ozone depletion might even expand even as the CFC exemptions continue.

POLICY IMPLICATIONS

The purpose of space policy is to provide long-term direction for the space industrial base in order to support national interests and promote growth. Space policy should characterize opportunities and risks, with regard to the growth of the space transportation industry, as well as recommend steps to increase opportunity and reduce risk. We have demonstrated that the international imperative to protect the ozone layer presents a long-term risk to the space launch industry in coming decades. Should the space industry enter a phase of rapid growth, ozone loss caused by high launch rates could become large enough to attract the attention of the regulatory apparatus protecting stratospheric ozone. The risk of limitation on launch systems due to ozone depletion is certainly many decades away. Nevertheless, the risk is not zero, applies to all rocket engine types, and the timescale is no longer than typical launch systems design and life cycle timescales.

This risk of launch limitations comes about for two reasons: uncertainty of impact and uncertainty of regulation. The range of uncertainty regarding ozone loss from liquid propellant rocket engines is too large to support clear assessment of future launch systems. Plausible assumptions within the ranges of uncertainties can lead to the conclusion that excessive ozone loss might limit payload delivery rates to a level only a factor 30 greater than current rates. Meanwhile new rocket propulsion systems that could affect the ozone layer such as hybrid propellants and hypersonic propulsion are being developed and promoted without regard to ozone impacts. The level of ozone loss from rocket emissions, globally or nationally, that would be considered unacceptably large is also very uncertain. The international organizations that regulate ozone depleting substances and the environmental effects of aerospace systems have not addressed the issue in a quantitative way that planners can apply to analysis of space launch growth. Together, these uncertainties make it so that we cannot know what sort of space transportation infrastructure, launch rates and propulsion systems, will be acceptable several decades from now.

Even though the Montreal Protocol does not define the ODP for aerospace combustion emissions, some estimates of an equivalent SRM ODP have been proposed and depending on any of several assumptions in the model, the value can exceed 0.2 SRM emissions, and are therefore, in some sense, similar to methyl bromide in that the calculated ODP likely exceeds 0.2—the value that triggers regulatory action. Continued use of methyl bromide might indicate the success of arguments that as long as a compound's ΔO_3 is "small" compared to other sources, then continued use may be appropriate, irrespective of the calculated ODP. Such arguments might be applied SRM emissions in the future. The inherent weakness of this kind of argument is that if the comparison ΔO_3 shrinks or is eliminated then "small" may become "large."

We wish to make clear that this work is not calling for limitation of any kind on the launch market. Rather we wish to point out that our current level of technical and regulatory understanding allows that such limitations are likely to emerge at some point in this century. Nor is this work considered overly alarmist regarding ozone depletion from rocket exhaust. Rather we wish to point out some of the long-term sensitivities and vulnerabilities of the space industry to ozone depletion considerations. Policy and investment decisions typically rely on the assumption that the future is likely to be similar to the recent past and our shows one way that this assumption could fail.

Current United States policy regarding ozone loss from rockets is to accept that the Montreal Protocol does not require any action because rocket emissions are not on the list of proscribed substances. New space systems must only consider ozone loss as part of an Environmental Impact Analysis (EIS) required by the National Environmental Policy Act (NEPA). Under NEPA, which has no enforcement mechanism, each space system is considered independent of each other and there is no formal cumulative analysis. For example, one space system may require several launches over a number of years. The ozone loss from these few launches is, of course, insignificant and so the EIS for that system contains a finding of no significant stratospheric impact. Under NEPA, each system considers only its own contribution to ozone loss as insignificant and there is no accounting for the cumulative loss of all systems or programs, either nationally or globally. In addition, the EIS process does not require a peer reviewed consensus in the scientific community regarding predicted ozone loss as the Montreal Protocol does; NEPA only requires a period of public comment. Finally, a final EIS of record is not required until a system is essentially ready for deployment (long after development investments have been made) and so does not require consideration of the effects of proposed or in development systems whose ozone impact is in the (perhaps far) future.

The policies of other space faring countries regarding ozone loss from rocket emission are not as clear, except insofar as the Montreal Protocol does not require any action. In the early and mid 1990s, the impact of SRMs was much more uncertain than now and the issue was occasionally raised at the Meeting of the Parties to the Montreal Protocol, but it has not been subject to recent attention. The recent lack of attention is due mainly to the fact that SRM emissions are much better understood than in the 1990s; the estimated upper limit on δ_S has been reduced by a factor of about ten since then. However, if the issue of rocket emissions becomes significant, the Parties to the Montreal Protocol might attempt to cap ozone loss from rocket emissions. It is not at all clear how such a cap might be configured or specified. The Montreal Protocol allocates ODS production and consumption on a "country" basis but this approach would be entirely inadequate for rocket emissions. Space launch is a globally integrated activity whereby a rocket produced in one country, launches from a site in a second country, using propellant produced in a third country, and carries the payload of a fourth country. A "by country" approach would be difficult to implement for rockets.

A related concern, illustrating the possibly contentious nature of the problem, is that the relative mixes of SRM and LRE emissions vary widely from country to country. The Russian Proton (hypergolic) and European Ariane V (SRM and cryogenic), for example, launched about the same orbital payload in 2007. However, the Ariane V likely causes about 25 times more (steady state) ozone loss than the Proton. Disparities such as this, coupled with the lack of validated models and undefined assessment metrics, raises the potential for economic competition to become conflated with regulatory actions.

The implications of our work for policy makers are two-fold:

1. Space policy should help establish the way for launch market development unfettered by uncertain regulatory concerns. The confused experience of the supersonic transport, where science and policy were not synchronized with engineering systems development, should be avoided for emerging space transportation technologies. Policy should establish the goal of obtaining a sufficiently robust scientific understanding of rocket emissions and their impact on stratospheric ozone to support analysis and development of large space systems. This includes in particular reusable launch vehicles, new propellants, and hypersonic systems. In order to achieve this goal, space policy should encourage research efforts to identify and close knowledge gaps regarding rocket emissions. Our work shows that some guidance is required from the technical side of the equation on the composition and impact of rocket emissions.
2. Policymakers in the stratospheric protection community should begin to consider how to assess rocket emissions formally, in comparison to each other and in comparison to other substances that deplete the ozone layer. It is unlikely that rocket emissions could be brought under any existing metric definition. Even the most fundamental definition of such a metric is not clear. The explicit coupling between economic gain (payload) and loss of ozone complicates the problem. Since each country places different emphasis on SRMs and LREs, a globally acceptable metric is needed before putative space industry growth raises rocket emissions above the minor category as far as ozone loss in concerned. Our work shows that some guidance is required from the ozone protection policy side of the equation on the level of acceptable ozone loss.

Policy makers in the space travel and stratospheric protection communities might begin to consider how the launch industry can best fit into whatever regulatory regime emerges as the earth's ozone layer recovers and the global demand for access to earth orbit grows. One direction that ozone protection could take is an emissions trading scheme in which each national space agency is allocated a certain quantity of ΔO_3 and can sell unused allocations or buy allocations as needed. Another direction would be an "ozone loss tax" on launch providers or payload providers. Systems such as these are already emerging in response to climate change with air transport providers possibly subject to a "carbon tax" that would have major impacts on their profitability and aircraft fleets.[43] In a future paper we will address potential methods to apportion or regulate launch ozone loss including accounting of ozone loss by launch provider and payload provider, especially in comparison to current ODS special use exemptions and possible ODS trading schemes.

Refinement in our understanding of ozone loss from rocket propulsion is critical for understanding the political economy of large scale growth in space transport. A systematic effort to accomplish this can be implemented at modest cost. A program of stratospheric plume measurements, plume wake and stratosphere model investigations, and laboratory measurements on alumina and soot particles can be effectively coordinated within existing NASA, NOAA, and USAF research efforts and research infrastructures. This notion was proven in the 1990s first by the Rocket Impacts on Stratospheric Ozone (RISO)[44] and Atmospheric Chemistry of Combustion Emissions Near the Tropopause (ACCENT)[45] efforts and most recently by the Plume Ultrafast Measurements Acquisition (PUMA) effort.[46] Prior to RISO, ACCENT, and PUMA, uncertainties regarding ozone loss from SRMs were much greater than present day uncertainties regarding LREs and these efforts returned high-value emissions data at relatively low cost. Renewed and vigorous rocket emissions research would have the goal of reducing the uncertainties of LRE ozone loss to the same level as SRMs and provide a predictive capability for evaluating the ozone loss associated with emerging propulsion technologies.

SUMMARY

Space travel's impact on stratospheric ozone can be relatively significant in comparison to other industrial activities because rockets uniquely emit ozone destroying compounds throughout the stratosphere. Both solid and liquid fueled rockets cause ozone loss. Based on existing data, models, and general principals of rocket combustion and stratospheric chemistry we constructed a simple description of the relationship between rocket combustion emissions and ozone depletion and then related ozone depletion to the mass of payload placed into LEO. Because stratospheric rocket emissions are not fully understood, our description is necessarily uncertain, especially with respect to liquid propellant engines. Even so, we draw several conclusions and provide guidance for future work.

Present day global ozone loss caused by rocket emissions is dominated by SRM emissions and is almost certainly less than 0.1%, insignificant relative to other sources of ozone loss at the present time. The relative impact of rocket emissions will likely increase over the next several decades as the requirements of a growing space industry grow and the ozone layer recovers from past use of ozone depleting substances that have been now banned by international agreements.

Global ozone loss associated with space development scenarios that assume large increases of payload delivered to orbit could be significant, even using liquid propellants. Growth of a factor of one hundred could cause several percent global ozone losses, likely large enough to trigger attention by the international stratospheric protection community. Regulation of launches might take the form of limitation of the number of types of launches or mass of payloads and might apply globally or nationally. Such limits would present significant distortions in what is usually assumed to be an emerging free market for launch services. One implication of launch limits associated with ozone depletion is to increase the difficulty of recovering large investment to reduce launch cost through increased launch rates. Because of the large uncertainty over the impacts of liquid propellant rockets on ozone, and the lack of a clear process to assess the ozone loss caused by rocket emissions, the potential for limitation on space transportation cannot be eliminated. This potential presents a long-term risk that space development could be hampered by overly aggressive ozone protection efforts that might arise from a lack of information on rocket emissions. Policy makers in both the space development and stratospheric protection communities should begin to better understand ozone loss from rocket emissions, how to quantify those losses, and how to manage the loss if the space transport business grows significantly in the future.

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NOTES

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