# A Global Framework for the Protection of Space-Launch Operators and Developers from the Liability and Risks of Chemical Propellants

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## Abstract

Since the late 1950s, launch vehicles, fueled by chemical propellant, have been utilized to send payloads into space for Earth remote sensing, telecommunications, interplanetary exploration and crewed transport. The manufacturing, handling, storage, and transport of chemical propellants is done in accordance with industrial safety standards and environmental regulations. Since 1987, emissions of ozone-depleting pollutants are highly regulated by international agreement through the Montreal Protocol on Substances That Deplete the Ozone Layer. Combustion products from launch vehicles affect the global stratosphere. Even with recent advances in reusability and the introduction of large launch vehicles and new launch sites around the globe, rocket launches occur irregularly so that concerns about the damage done to the ozone layer by rocket emissions have long been neglected by the international community and have been not been subjected to regulatory attention.

Present day rocket launches inject approximately 11000 tons of chlorine, alumna and carbon soot into the atmosphere. These accumulations promote chemical reactions and absorption and scattering of sunlight that modifies the composition and flow of radiation in the stratosphere. Ultimately, these processes reduce stratospheric ozone, warm the stratosphere, and cool the Earth's surface. Current estimates put direct loss of ozone between 0.01% and 0.1%. Taking into consideration that the current ozone loss from the globally banned 'ozone depleting substances' is 3%, it is clear that, should launch frequencies increase by an order of 10, they will be on the same scale as these regulated ground emissions.

Today, the space industry is estimated to be at 450 billion USD, but the development of mass manufacturing techniques and reusable components is expected to bring down the cost of space access, and Morgan Stanley has estimated that the global space industry will be worth 1 trillion USD by the year 2040. The space-launch sector is evolving rapidly, and the associated growing launch rates, new propellants, larger, reusable launch vehicles, and the emergence of other stratospheric polluters, raises concerns for the current international requirements to manage global climate change. Concern also exists beyond the launch emissions, and consideration must be made for the full propellant lifecycle, including accidents or failures. Chemical propellants can be toxic and explosive, and concern must be given to local environment/ecology surrounding launch-sites and storage facilities, as well as propellent-handling personnel.

There is an uncertainty in regulations due to the present incomplete understanding regarding rocket emission impacts from a global perspective. Little is known about particle

accumulations and their contributions to stratospheric ozone depletion and thermal perturbations because of a lack of consistent models and focused research in the literature. The few studies that have appeared recently only identify gaps in the current understanding rather than address the problem. Lack of accurate information inevitably invites distorted competitive claims and unwarranted and overly restrictive regulation.

This work uses previous stratospheric plume measurements from in situ and remote sensing instrumentation, laboratory measurements and simulations to generate an improved and consistent model of combustion, plume chemistry and kinetics, and a global atmosphere model for plume dispersion and radiative transfer. Global projections and worst-case scenarios are taken as metrics to validate the proposed framework. This includes case studies of the Ariane 5 (AP/Al/HTPB. $LH_2$/LOX and MMH/$N_2O_4$), Vega (HTPB and UDMH/$N_2O_4$), Soyuz (Kerosene/LOX), Atlas V (HTPB, Kerosene/LOX and $LH_2$/LOX), Falcon 9/Heavy (RP-1 Kerosene/LOX) and the projected hypothetical case of the Skylon spaceplane (Air and $LH_2$/LOX).

In parallel with the rapid development in launch technologies: industry, nations, space agencies, and stakeholders should encourage, facilitate, and fund research on rocket emissions and engagement with international regulators to define these metrics for better understanding, and monitoring the effects. Therefore, globally, there is an increasing necessity to establish harmonized safety requirements and a system of recognition to better fit commercial space launches. There have been many efforts from organizations such as the International Association for the Advancement of Space Safety (IAASS) that have been working on this effort; in addition to State policies such as the United States' Toxic Substances Control Act. However, because different levels of space safety exist, this paper will focus on a niche issue of space safety in the form of risks associated with rocket propellants.

The purpose of this paper is to provide a global framework to help the U.S., European, and Asia-Pacific commercial operators and developers protect themselves from liability and risk associated with rocket propellants. This work places emphasis on the protection of human lives, environment, and properties from accidents or mishaps by focusing on comprehensive safety guidelines. The first section of this paper provides a brief technical background on the use of rocket propellants, as well as case studies and the aforementioned numerical models, highlighting the risks associated with these chemicals. The second section presents a comparative analysis between U.S., European, and Asia-Pacific regulation on rocket propellants. The findings from this section are then adapted into the third section which concludes by presenting a regulatory framework that sets up safety standards to be adopted industry-wide.