Beyond the Burning:
Researching and Implementing Policy Solutions for Sustainable Debris Ablation

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TN-02 Literature Review

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1 Introduction

This project seeks to establish a comprehensive research framework aimed at mitigating the environmental risks associated with atmospheric ablation of end-of-life spacecraft. By integrating a deep understanding of current atmospheric ablation research with a broad perspective encompassing technical, geopolitical, and socio-ecological factors, we will develop a robust research program with cascading short, medium, and long-term goals. Our focus will be on identifying and addressing critical knowledge gaps and challenges within the field of atmospheric ablation modelling and prediction. This holistic approach will enable us to explore the multifaceted implications of atmospheric ablation and pave the way for the UK to assume a leadership role in space sustainability.

1.1 Scope

This document, TN-02, successfully meets the requirements outlined in Milestone 1 (MS1) by conducting a comprehensive review of existing knowledge in atmospheric ablation and space policy, encompassing both academic literature (white and grey) and legal frameworks. By critically assessing the state-of-the-art in atmospheric modelling, testing capabilities, and policy frameworks, TN-02 identifies key technical challenges and research gaps needed to develop evidence-based space policy for sustainable space utilisation.

1.2 Applicable Documents

Applicable documents are identified as ADn, where "n" denotes the document number from the table below.

Ref.	Document ID	Title	Rev.
[AD1]	G23A.001.PP.01	Project proposal	N/A
[AD2]	G23A.001.GFA.01	Fully executed Grant Funding Agreement	N/A
[AD3]	G23A.001.TN.01	A research strategy for evidence-based space policy development	N/A

1.3 Reference Documents

Reference documents are identified as RDn, where "n" denotes the document number from the table below.

Ref.	Document ID	Title	Rev.	Date
[RD1]	ST/SPACE/61/Rev.2	International Space Law: United Nations Instruments	2	2017
[RD2]	IADC-02-01	IADC Space Debris Mitigation Guidelines	2	March/2020

[RD3]	United NationsOffice for Outer Space Affairs	Long-term sustainability of outer space activities: implementation experiences, opportunities for capacity-building and challenges.	1	June/2024

1.4 Acronyms and Abbreviations

Tag	Description
BNNT	Boron nitride nanotube
CFRP	Carbon fibre reinforced polymer
EoL	End-of-Life
GEM	Gibbs Energy Minimisation
GO	Graphene oxide
LEO	Low Earth Orbits
MEO	Medium Earth orbits
MLI	Multi-layer insulation
TPS	Thermal protection system
VLEO	Very Low Earth Orbits

2 Review of Atmospheric Ablation Modelling and Tests

2.1 Atmospheric Re-entry Flow

Satellites falling into Earth's atmosphere can be treated in the same way as re-entry vehicles. Any object, including satellites, space debris, meteoroids, or re-entry vehicles, experiences extreme heat due to the conversion of kinetic energy into thermal energy when they are entering the atmosphere. After the bow shock wave, a high temperature region forms in front of the re-entry object, whose features are the excitation of vibrational degrees of freedom and induces nonequilibrium chemical processes. At this region, the time scale associated with the vibrational and chemical reactions is comparable to the characteristic flow time scale. This phenomenon is commonly known as thermo-chemical non-equilibrium, and this introduces several complexities to the flow features. Therefore, choosing adequate non-equilibrium models is crucial to accurately predict the aerothermal load on the re-entry object. However, the complex coupling of thermo-chemical nonequilibrium on the flow physics has always been a challenging aspect of hypersonic flows.

When a spacecraft or an object enters the Earth's atmosphere, it will encounter a variety of flow regimes from free molecular to continuum. The adaption of numerical techniques differs based on flow regimes, which is characterized by the Knudsen number [1]. This number is the ratio of the mean free path of a gas molecule (rarefaction scale), λ, to the characteristic length scale, L.

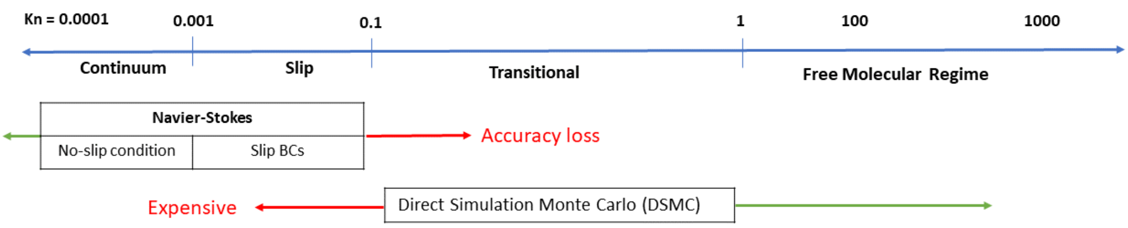


Figure 1. Classification of flow regimes

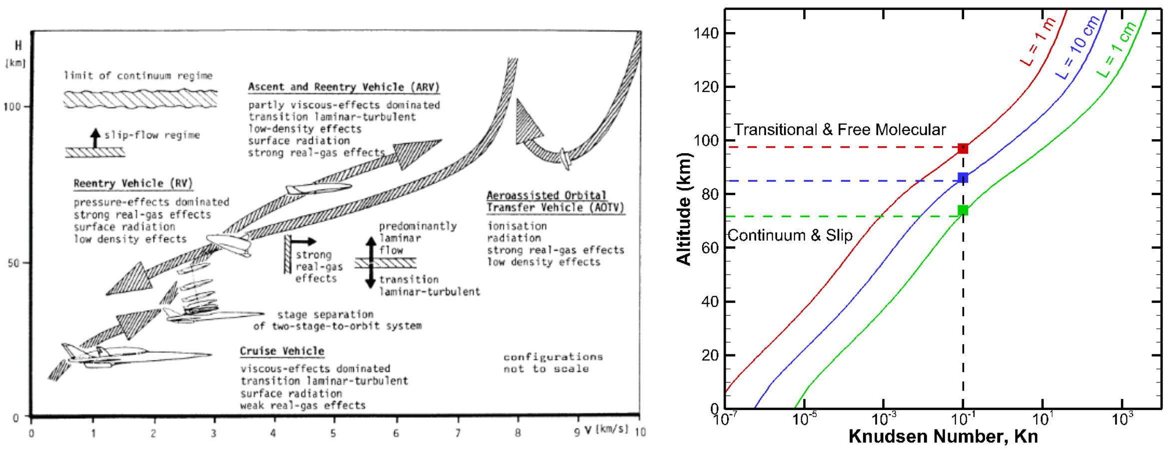
2.1.1 Flow Regimes

- Free Molecular Flow (Kn > 10): In this regime, the gas-surface collisions dominate, while gas-gas interactions are rare and often neglected [2]. The freestream gas can be assumed to follow the Maxwell-Boltzmann distribution function. Based on this, surface forces, moments, and energy are determined using gas-surface interaction models.
- Transitional Flow (0.1 < Kn < 10): Here, gas collisions cannot be neglected, however, the continuum assumption is also invalid. The kinetic particle-based, Direct Simulation Monte Carlo (DSMC) method [3] is typically employed to model the flow. However, DSMC becomes computationally expensive as the Knudsen number approaches slip and continuum regimes.
- Slip Regime (0.01 < Kn < 0.1): In this regime, the no-slip boundary condition is not strictly valid, as the non-equilibrium start to appear near surfaces. However, the Navier-

Stokes equations can still be used to model the flow behaviour with appropriate boundary conditions by considering velocity slip and temperature jump corrections.

- Continuum (Kn < 0.01): The continuum assumption is valid in this regime, and the famous Navier-Stokes equations provide an excellent approximation for gas flow and are generally used for flow modelling with no-slip boundary conditions.

For a typical spacecraft re-entry, the intense heating occurs in the continuum regime, usually below altitudes 75 km (see Fig. 2.a). Therefore, the CFD models are preferred for the re-entry flow analysis. Unlike spacecraft, satellites vary widely in size, from small CubeSats to large communication satellites (see Fig. 2.b). This necessitates the choice of different numerical techniques for their re-entry simulations. For example, at an altitude of 90 km, an object of 10 cm (1U CubeSat) falls into the transitional regime, where DSMC needs to be used, whereas a large object of 1 m falls into the slip regime, where Navier-Stokes equations with slip models can be used. However, in any method, the chemical reactions and internal energy relaxation need to be addressed accurately, which are detailed in Section 2.1.5.



(a) (b)

Figure 2. (a) Illustration of various high speed flow regimes encountered by re-entry vehicles Classification of flow regimes; (b) Flow regimes for different sized objects.

2.1.2 Computational Methods

2.1.2.1 Molecular Dynamics (MD)

As there are negligible gas-gas interactions in comparison to gas-surface collisions in the free molecular regime, the chemical reactions are very rare, hence can be neglected. However, any reactions involving the surface such as oxidation need to be considered. Objects with a minimum size, such as very small sized debris, fall into this regime.

2.1.2.2 DSMC

The DSMC (Direct Simulation of Monte Carlo) method is a particle-based method that gives solution to the Boltzmann equation. This method deals with simulated molecules, each representing a large number of actual molecules. The physics of the system is governed through molecular movements and collisions between simulated molecules and between simulated molecules and surfaces. The macroscopic flow properties, i.e., the collective behaviour of molecules, are obtained by statistically sampling the molecular data. For accuracy, the DSMC method requires that the cell size and time step be less than the mean free path and mean collision time of the gas, respectively; and that at least 15-20 simulated particles be used per cell.

The internal energy relaxations and chemical reactions are modelled through collisions via acceptance-rejection algorithm. The Larsen- Borgnakke or quantum-kinetic (Q-K) model is commonly used for internal energy relaxations with proportion of inelastic collisions undergoes internal energy redistribution. The chemical reactions in the DSMC method are typically modelled based on total collision energy (TCE) model [3]. The microscopic information on the probability of chemical reactions, which is a function of energies of two colliding particles, is obtained from reaction rates. The Arrhenius form of the same is given below.

$$K(T) = AT^{B} \exp\left(-\frac{E_a}{k_B T}\right) \quad (1)$$

where $K(T)$ is the reaction rate, T is the temperature of colliding molecules which is a function of their relative velocities and internal energy states, E_a is the activation energy, k_B is the Boltzmann constant, and A , B are constants. The accuracy of reaction rates, which are essential inputs for these simulations, significantly influences the validity of the results. Therefore, precise estimation of reaction rates is crucial. The DSMC simulations face challenges when handling chemical reactions involving trace species (mainly electrons and ions) due to their low densities, which can lead to statistical errors. Addressing this issue requires either accepting increased statistical noise or significantly increasing the number of simulated particles, which comes at the cost of higher computational expense.

Several DSMC solvers are developed by different academic and research institutions, but most of the license are limited to them. Some of the renowned DSMC solvers along with their developers and features are tabulated in Table 1. Bird developed a series of initial DSMC solvers namely DS1V, DS2V and DS3V, respectively for one-, two- and three-dimensional problems [3]. DS1V is mainly used to test any newly developed DSMC codes for verification purpose. DS2V is 2D/axisymmetric code that includes a graphical user interface (GUI) and adaptive mesh refinement techniques. DS3V is a 3D version without GUI. SPARTA and dsmcFOAM are two major open-source DSMC solvers. Some of the other well-known DSMC solvers are explained below.

A. SPARTA

The Stochastic Parallel Rarefied-gas Time-accurate Analyzer (SPARTA) [4] is an open-source, 1-D/2-D/axisymmetric/3-D DSMC solver with a Cartesian mesh. Written in C++, SPARTA uses distributed-memory message-passing parallelism (MPI) for parallelization. It allows the user to choose from two different chemistry models, TCE and Q-K, to model chemical reactions, including dissociation, recombination, exchange, and ionization reactions. It supports collision models such as hard sphere (HS), variable hard sphere (VHS), and variable soft sphere (VSS). One of SPARTA's key features is the implementation of surface chemistry reactions. Other performance features include on-the-fly grid adaptation, grid cell weighting of particles, and static and dynamic load-balancing of grid cells/particles. SPARTA is distributed under the terms of the GNU Public License for both academic and commercial use. The manual provides detailed instructions for creating input script, commands, as well as for pre-processing and post-processing procedures.

B. dsmcFOAM

dsmcFOAM [5] is a DSMC solver developed within the framework of the open-source CFD solver OpenFOAM. It is written in object-oriented C++ modules, similar to OpenFOAM, and is open source under the GNU General Public License. It uses automatic sub-cell generation to promote nearest neighbour collisions, the VHS model for elastic collisions, and the L-B model for internal energy redistribution. It is parallelized using an MPI-based domain-decomposition approach built upon the parallel capability provided by OpenFOAM. The solver is available in 1-D, 2-D, and 3-D versions, but the axisymmetric version is not yet included. The initial version doesn't contain reactions, but chemical reactions and electronic energy modes were later added, resulting in dsmcFOAM+ [6]. One of the advantages of dsmcFOAM is that it uses the same grid as the regular OpenFOAM that solves CFD, making it easier to couple with the OpenFOAM CFD package. The coupling has recently been achieved through a domain decomposition technique using the state-based information exchange technique [7].

C. DAC

The DSMC Analysis Code (DAC) [8] is an axi-symmetric and 3-D DSMC solver developed at NASA Johnson Space Centre. The preprocessor in the DAC uses a two-level embedded Cartesian grid that locally satisfies the necessary conditions for a DSMC simulation. It employs a dynamic load-balancing algorithm and has been tested for many large cases, including one with over 100 million simulated molecules. In addition to regular specular and diffuse boundary conditions, catalytic recombination reactions are also implemented. Elastic collisions are modelled using the VHS model, while internal energy exchange is modelled using the L-B model. The Q-K model is used for chemical reactions, and charge-neutral ionization and electronic energy level models are implemented to calculate radiative heating.

D. SMILE

Statistical Modeling In Low-Density Environment (SMILE) [9] was one of the earliest DSMC codes available, developed by the Laboratory of Computational Aerodynamics at ITAM, Novosibirsk, Russia. The basic SMILE code was originally written in FORTRAN and later rewritten in C++ using object-oriented programming concepts, resulting in SMILE++. It is a 2D/axisymmetric/3D solver that includes various physio-chemical models, chemical reactions, and parallel capabilities. Various surface reactions such as adsorption, desorption, dissociative adsorption, Eley-Rideal, and Langmuir-Hinshelwood recombination were added later to SMILE++ [10].

E. MONACO

MONACO is an advanced in-house DSMC solver developed at the University of Michigan, USA, capable of handling both 2D and 3D simulations in an object-oriented framework [11]. It includes several sophisticated models for elastic collisions, such as the VHS and VSS models, and incorporates various energy exchange probability models for inelastic collisions. For chemical reactions, MONACO employs the TCE model. Notable features of MONACO include adaptive mesh refinement, different subsonic boundary conditions, and multiple gas-surface interaction models. Additionally, MONACO is coupled with LeMANS, another in-house CFD solver, creating a hybrid framework that solves the Navier-Stokes equations in the regions of near equilibrium and applies DSMC in non-equilibrium regions.

Table 1. Some of the renowned DSMC solvers along with their developers and features.

Name	Dimension	Institution	Country	Features
DS1V DS2V DS3V [3]	1D 2D 3D	University of Sydney	Australia	Initial DSMC solvers, primarily used for code validation, GUI enabled in DS2V version.
SPARTA [4]	1D 2D 3D	Sandia National Laboratories	USA	Open-source, surface chemistry reactions, on-the-fly grid adaptation, grid cell weighting of particles, static and dynamic load-balancing of grid cells/particles.
dsmcFOAM [5][6][7]	1D 2D 3D	University of Strathclyde	UK	Open-source built on and uses same grid as OpenFOAM, coupled with OpenFOAM CFD package.
DAC [8]	2D/3D	Johnson Space Centre, NASA	USA	Dynamic load-balancing algorithm, catalytic recombination reactions, accounts for radiative heating.
SMILE [9] [10]	2D/3D	Laboratory of Computational Aerodynamics at ITAM, Novosibirsk	Russia	Considers adsorption, desorption, dissociative adsorption, Eley-Rideal, and Langmuir-Hinshelwood recombination.
MONACO [11]	2D/3D	University of Michigan	USA	Adaptive mesh refinement, different subsonic boundary conditions and coupled with LeMANS, an in-house hypersonic CFD package.

2.1.2.3 CFD

As a significant part of the re-entry trajectory falls under the continuum regime (see Figure 2(a)), the CFD based on Navier-Stokes-Fourier laws become a design tool. There are few research codes that have the capability of solving complex nonequilibrium flows, a few examples are DPLR, LAURA, LeMANS, and HANSA. A brief description of these solvers is detailed below and tabulated in Table 2.

Table 2. Some of the renowned CFD solvers along with their developers and features.

Name	Institution	Country	Features
DPLR	NASA Ames Research centre	USA	• 2D/axisymmetric/3D structured FVM solver, distributed memory parallelism via MPI. • Assumes single vibrational temperature for all species. • Dissociation is based on Park's two-temperature model and translational temperature is used for other reactions.
LeMANS	University of Michigan	USA	• 2D/axisymmetric/3D structured FVM solver, Accounts for rotational, vibrational and free electron non-equilibrium, assumes single vibrational temperature for all species. • Considers free electron temperature for ionisation reactions.
LAURA	Langley Research Centre, NASA	USA	• Uses TVD scheme and uses RANS models for turbulence, considers shock-layer radiation and surface ablation. • Radiation calculations are handled by the HARA radiation code, which was also developed at NASA and distributed with LAURA.
HANSA	University of Southampton	USA	• 2D/axisymmetric structured/unstructured FVM solver developed from LeMANS, integrated with MHD module. Accounts for rotational, multi-species vibrational and free electron non-equilibrium. • Reactions considers translational, rotational, multi-species vibrational and free electron non-equilibrium modes.
COOLFluiD	Von Karman Institute for	Belgium	• 2D/3D parallel open-source solver with different numerical methods and physical models.

fluid dynamics	• Thermodynamics, transport and chemical properties are computed by an interfaced thermochemical library.

A. DPLR

Data-Parallel Line Relaxation (DPLR) is a 2D/axisymmetric/3D structured, finite volume Navier-Stokes CFD code, which was developed by NASA Ames Research Centre for the computation of supersonic and hypersonic flows in chemical and thermal nonequilibrium [12]. Written in Fortran 90, DPLR employs distributed memory parallelism via MPI. The code features implicit boundary conditions, generalized multi-block topologies, grid alignment to flow features, and supports comprehensive chemical kinetics and thermodynamic property databases. It uses Park's two-temperature model to describe thermal nonequilibrium, distinguishing between the translational-rotational state and the vibrational-electronic-electron state of the gas. DPLR assumes a strong coupling of vibrational modes, represented by a single vibrational temperature. DPLR handles turbulence through k-ω or k-ω shear stress transport (SST) modelling. Additionally, it is loosely coupled with material response and shock layer radiation codes. This code is currently available only to contractors working on relevant US government projects.

B. LeMANS

LeMANS is an in-house, parallel, unstructured 2D/axisymmstric/3D, finite-volume CFD code developed at the University of Michigan for the simulation of weakly ionized hypersonic flows in thermo-chemical non-equilibrium conditions [13]. The code assumes that the translational and rotational energy modes of all species can be described by their respective temperatures T and T_r, as is the free electron temperature, T_e. A single temperature, T_{ve}, describes the vibrational and electronic energy modes for all species assuming fast vibrational-vibrational energy relaxation. Stokes' hypothesis is used to model the viscous stresses with a Newtonian fluid assumption. Species mass diffusion fluxes are modelled using a modified version of Fick's law. Two models are used to compute the mixture transport properties: the first model employs Wilke's semi-empirical mixing rule, with species viscosities derived from Blottner's model and thermal conductivities from Eucken's relation; the second utilizes Gupta's mixing rule, calculating viscosities and thermal conductivities from non-coulombic/coulombic collision cross-section data. Heat fluxes for all energy modes are modelled according to Fourier's law. The source terms of the species conservation equations are handled using a standard finite-rate chemistry model for reacting air, using Park's two-temperature model to account for thermal nonequilibrium effects on reaction rates. A blowing boundary condition is implemented to account for ablation modelling. LeMANS employs a modified Steger-Warming Flux Vector Splitting scheme to discretize the numerical fluxes between cells, which has low dissipation and is appropriate near boundary layers. A point implicit method is employed for the time march, but it switches to a line implicit method for faster convergence after a few hundred iterations. LeMANS has been validated against several experimental data and other similar codes such as DPLR and LAURA.

C. LAURA

Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) is a CFD tool developed at NASA Langley Research Centre that solves the Navier-Stokes equations using a cellcentred formulation on a structured multi-block grid system [14]. LAURA employs the symmetric total variation diminishing (TVD) scheme and point integration for source terms arising from thermo-chemical nonequilibrium, along with several Reynolds-Averaged Navier-Stokes (RANS) turbulence models. The code is equipped with multiple features to simulate phenomena in high-energy flows, including thermo-chemical nonequilibrium, shock-layer radiation, surface ablation, and species ionization. Radiation calculations are handled by the HARA radiation code, which was also developed at NASA and distributed with LAURA, enabling accurate simulation of radiative heat transfer.

LAURA has been crucial in assessing aerothermal environments during entry, descent, and landing phases in various NASA missions, including Mars Pathfinder, FIRE II, the Orion capsule, and the Galileo Probe simulations. Despite its development several decades ago, LAURA has undergone continuous improvements. Recent enhancements include an automated uncertainty quantification workflow for radiative heat transfer, options for specifying surface roughness and turbulent transition locations in algebraic turbulence models, improved grid and solution interpolation techniques, and optimized MPI communication routines to boost parallel efficiency.

D. HANSA

HANSA is a state-of-the-art CFD code developed by the University of Southampton for simulating thermo-chemical non-equilibrium hypersonic flows. It is an in-house, parallel, 2D/axisymmetric structured/unstructured solver that uses a finite volume method with an integrated MHD module to simulate MHD applications in non-equilibrium weakly ionised flows, such as plasma communication and MHD heat shields [15]. Since HANSA is developed from LeMANS, it shares similar schemes and basic thermo-chemical non-equilibrium models. For example, the Modified Steger-Warming (MSW) vector splitting approach is used to compute inviscid fluxes, except at the shock where the original Steger-Warming method is used, whereas viscous fluxes are computed using properties at the cell centres. A point implicit algorithm is applied for time integration. HANSA has been validated against several experimental data, and code validation studies performed against SPARTA-DSMC and LeMANS. Even though HANSA was developed from LeMANS, the thermal non-equilibrium model has been extended with multi-vibrational models, allowing species-based vibrational temperatures to be used to model the reactions. A single temperature is assumed for vibrational-electronic modes for each species, with the assumption of faster energy transfer between electronic and vibrational modes. Therefore, HANSA has the capability of addressing thermal non-equilibrium by considering translational, rotational, species-based vibrational-electronic, and free electron temperatures.

E. COOLFluiD

COOLFluiD (https://github.com/andrealani/COOLFluiD/wiki) is a large open source CFD platform for simulating flows and plasmas primarily developed at the Von Karman Institute for fluid dynamics (VKI). It includes multiple 2D/3D parallel solvers with different numerical methods and physical models. A variant of AUM+up scheme and limited Least Square solution reconstruction algorithms are used to discretize the convective fluxes for the fluid, while a scaled CIR scheme is used for Maxwell equations. A fully implicit Backward Euler method is used for converging to a steady state. The resulting discretized liner system is solved by the GMRES algorithms and Additive Schwarz preconditioner from PETSc (https://www.mcs.anl.gov/petsc/). Thermodynamics, transport and chemical properties are computed by an interfaced thermochemical library (e.g. MUTATION++ for neutral mixtures and PLATO for ionized mixtures) for the simulation.

2.1.3 Physical and Computational Models

Thermodynamic and chemical equilibrium are reached through molecular collisions. The time required to achieve thermal/chemical equilibrium through collisions is called the thermal/chemical relaxation time. In hypersonic flows, particularly in the presence of strong shocks, the time scale associated with the bulk motion of the flow can be comparable to the thermal and chemical relaxation time. This situation is referred to as a thermochemical non-equilibrium condition. CFD models chemical non-equilibrium using species conservation equations and thermal non-equilibrium through internal energy relaxation equations. DSMC, on the other hand, model these phenomena by simulating molecular collisions and energy exchange using the acceptance-rejection method. Since peak heating occurs in the continuum regime, the following sections will detail thermal and chemical non-equilibrium models within the CFD framework. It is worth noting that the underlying physical principles are identical across methods, only the implementation details vary.

Figure 3 illustrates the temperature ranges for vibrational excitation and various chemical reactions of air reviewed by Park [16]. Vibrational excitation of molecules begins at approximately 800 K. Oxygen (O_2) dissociation starts at 2500 K, followed by nitrogen (N_2) dissociation at 4000 K. Exchange reactions involving nitric oxide (NO) predominate within the temperature range of 2500 K to 9000 K. At very high temperatures, above 9000 K, ionization takes place, leading to the formation of ions such as N^+, O^+, and electrons (e^-). The accuracy of any numerical model depends upon the accurate modelling of these thermo-chemical non-equilibrium process.

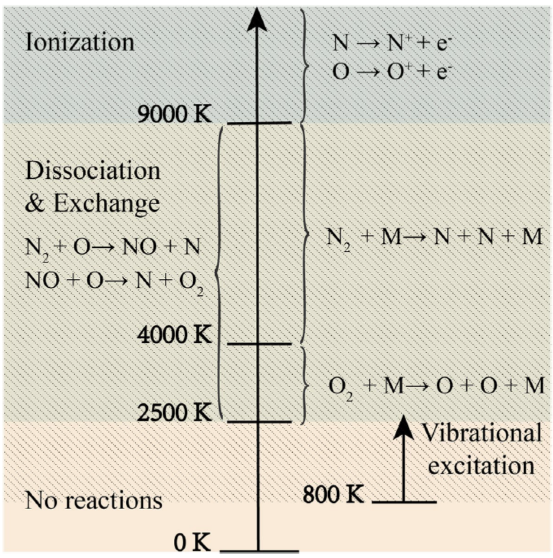


Figure 3. Temperature ranges of vibrational excitation ad chemical reactions for hypersonic flows [17].

2.1.3.1 Thermal Non-equilibrium

Under equilibrium conditions, a single temperature suffices to characterize its internal energy. However, in a typical hypersonic environment, a strong shockwave can induce thermodynamic non-equilibrium. This departure from equilibrium necessitates the definition of multiple temperatures to describe different energy modes. As the translational temperature of the gas increases after the shock, the translational energy is transferred to elevate the rotational and vibrational states of molecules from lower to higher states. Consequently, the rotational and vibrational states of molecules tend to be distributed at new temperatures according to Boltzmann distribution that differ from the translational temperature [18]. The temperatures characterizing the rotational and vibrational population distributions during this nonequilibrium period are referred to as rotational and vibrational temperatures, respectively. Rotational relaxation occurs simultaneously with translational relaxation up to Mach 12.9 [19], [20], implying that a single temperature can adequately characterize both rotational and translational energy modes. Due to very slow relaxation rates, vibrational temperature must be treated separately.

A. Vibrational energy non-equilibrium

The expression for the rate of change of vibrational energy of a gas through collisions is given by the famous *Landau-Teller* formula [1]:

$$S_{vib-tra} = \sum_s \rho_s \frac{(e_{v,s}(T) - e_{v,s}(T_v))}{\tau_{v,s}} \tag{2}$$

where

$$\tau_{v,s} = <\tau_{v,s}> + \tau_{p,s} \tag{3}$$

where T is the translational temperature, T_v is the vibrational temperature, ρ is density, $e_{v,s}$ is vibrational energy and $\tau_{v,s}$ is the vibrational relaxation time. The Landau-Teller expression is valid only for di-atomic molecules that are harmonic oscillator, which is based on three assumptions: 1) it considers only a single quantum jump between different energy levels, 2) the transitions rates are proportional to the quantum number and 3) the levels are populated according to the Boltzmann distribution. Multiple quanta jump between the energy levels can be modelled using anharmonic oscillator model, but probability of such event is mostly small. Therefore, Landau-Teller formula is typically used in hypersonic codes. The molar averaged Landau-Teller relaxation time is given as:

$$<\tau_{v,s}> = \frac{\sum_r X_r}{\sum_r (\frac{X_r}{\tau_{s,r}})} \tag{4}$$

where X_r is the molar fraction of species r. The Landau-Teller inter-species relaxation time, $\tau_{s,r}$, is modelled using curve fits, famously called as Millikan and White correlation [21] is given as:

$$\tau_{s,r} = \frac{101325}{p} \exp\left[A_{s,r}\left(T^{-0.33} - B_{s,r}\right) - 18.42\right] \tag{5}$$

where

$$A_{s,r} = 0.00116\, \mu_{sr}^{0.5}\, \theta_{sr}^{1.33}$$

$$B_{s,r} = 0.015\, \mu_{sr}^{0.25}$$

$$\mu_{s,r} = \frac{M_s M_r}{M_s + M_r}$$

The Millikan-White correlation was obtained using a limited number of collision pairs and under-predicts the relaxation time at high temperatures. Park [22] made a correction to the M-W correlation, also known as the collision limited relaxation time, as

$$\tau_{s,r} = \frac{1}{N\,\sigma_s\,c_s} \tag{6}$$

where N is the number density of the mixture, c_s is the average molecular speed of the species, σ_s is the limiting cross section given by:

$$\sigma_s = 10^{-20}\left(\frac{50000}{T}\right)^2 \tag{7}$$

When an electronically excited molecule collides with another molecule, a portion of its electronic excitation energy can be transferred to the vibrational energy of the colliding molecule. For some molecular species such as N_2, this energy exchange can be sufficiently rapid [18] to justify the use of a single temperature to represent both electronic and vibrational modes. Many hypersonic solvers employ this approximation for computational efficiency.

Most of the hypersonic CFD codes assume rapid vibrational-vibrational energy exchange between diatomic molecules, allowing for a single vibrational temperature to characterize the vibrational energy of all di-atomic molecules. However, in hypersonic flows, multi-species vibrational non-equilibrium can significantly impact thermodynamic properties and reaction rates. HANSA addresses this issue by independently solving vibrational energy equations for each species and modelling vibrational-vibrational energy exchange between them. Detailed modelling of multi-species vibrational temperature is presented below.

Using a Landau-Teller model, the energy relaxation between vibrational energies of other molecules is modelled as:

$$S_{vib-vib,s} = \sum_{r\neq s}^{\text{All molecules}}\left(\rho_s \frac{e_{vib,s}(T'_{vib,s}) - e_{vib,s}(T_{vib,s})}{\tau_{vib-vib,s-r}}\right) \tag{8}$$

where $\tau_{vib-vib,s-r}$ is the vibrational-vibrational energy relaxation time and $T'_{vib,s}$ is the vibrational temperature of two collision molecules after the collision. HANSA has modelled $T'_{vib,s}$ as:

$$\varepsilon_{vib,s}(T'_{vib}) + \varepsilon_{vib,r}(T'_{vib}) = \varepsilon_{vib,s}(T_{vib,s}) + \varepsilon_{vib,r}(T_{vib,r}) \tag{9}$$

where ε_{vib} is a vibrational energy of a single molecule. HANSA has modelled theoretically the vibrational-vibrational relaxation time, $\tau_{vib-vib,s-r}$, using an empirical expression as:

$$\tau_{vib-vib,s-r} = \frac{101324}{p_s}(AT^B + C) \tag{10}$$

The used coefficient, A, B, and C, for several molecules are given in **Error! Reference source not found.**.

Table 3. The coefficient of the vibrational-vibrational energy relaxation time

Collision	A	B	C

N_2 – NO	5.988×10^5	-1.82	5.91×10^{-13}
N_2 – O_2	4.979×10^5	-2.37	1.50×10^{-10}
O_2 – NO	6.191×10^5	-1.82	8.31×10^{-13}

HANSA has only included the vibrational-electron energy coupling of diatomic nitrogen as the coupling of other molecules such as O_2 and NO is two orders of magnitude weaker [23]. Lee's model has been used for the relaxation time of nitrogen molecule as:

$$\tau_{es} = \frac{kT_e}{p_e \cdot \left[\left(1 - e^{-\frac{\theta_{vib}}{T_e}}\right)^2 \cdot \frac{1}{2} \int k_{0,j}^{e-vib} j^2 dj \right]} \tag{11}$$

where $k_{0,j}^{e-vib}$ is a vibrational excitation rate coefficient from vibrational state 0 to j. The vibrational excitation rate coefficient is modelled as:

$$k_{0,j}^{e-vib}(T_e) = 10^{-15} \cdot aT_e^{1.5} \cdot e^{\left(\frac{b}{T_e} + c\right)} \tag{12}$$

where T_e is in eV. The coefficients for N_2 are given as [24]:

Table 4. The coefficients of the vibrational excitation rate coefficient model [24].

j	a	b	c
1	8.034	-2.227	2.005
2	7.924	-2.235	1.479
3	7.876	-2.257	1.054
4	7.626	-2.334	0.6499
5	7.326	-2.454	0.2049
6	4.900	-2.556	0.007448
7	2.457	-2.702	0.002952
8	1.119	-2.865	0.001133
9	0.4681	-3.042	0.004312
10	0.1837	-3.223	0.0002219

B. Electron energy non-equilibrium

Low-fidelity hypersonic codes consider a single temperature to characterize vibrational and free electron energy modes. LeMANS and HANSA treat electron non-equilibrium separately. An electron translational energy is modelled as [24]:

$$\frac{\partial E_e}{\partial t} + \frac{\partial}{\partial x_i}(E_e u_i) - \frac{\partial}{\partial x_i}\left(-q_{e,i} + \tau_{e,ij} u_j - \frac{J_{e,i} E_e}{\rho_e}\right) = S_e \tag{13}$$

where the source term, S_e, is modelled as:

$$S_e = S_{trans-e} + S_{inelastic,e} + S_{chemical,e} + S_{pressure,e} \tag{14}$$

where $S_{trans-e}$ represents the energy transfer between the translational and electron translational energy modes, $S_{inelastic-e}$ describes the energy transfer between electrons and the vibrational-electronic energy mode and the rotational energy mode of molecules, $S_{chemical-e}$ is the energy gained or lost by electrons during chemical reactions, $S_{pressure-e}$ is an approximation to the energy gained by electrons as they travel through the electric field set up by the presence of both the ions and the electrons in the flow field. Using the ambipolar diffusion approximation, it is modelled as [25]:

$$S_{pressure,e} = -p_e \nabla \cdot \vec{u} \tag{15}$$

C. Rotational energy non-equilibrium

Rotational relaxation typically occurs much faster than vibrational or free electron relaxation. However, in certain conditions such as rapid nozzle expansions, rotational and translational temperatures can diverge due to non-equilibrium effects. Hence, HANSA explicitly accounts for rotational non-equilibrium, as detailed below. The rotational energy relaxation with other energy modes has been modelled as:

$$S_{rot,relax} = S_{rot-tra} + S_{rot-e} \tag{16}$$

The rotational-translation energy relaxation, $S_{rot-tra}$, is modelled using a Landau-Teller model as:

$$S_{rot-tra} = \sum_s^{\text{All Molecules}} \left(\rho_s \frac{e_{rot,s}(T_{tra}) - e_{rot,s}(T_{rot})}{\tau_{rot-tra,s}} \right) \tag{17}$$

where $\tau_{rot-tra,s}$ is a rotational relaxation time evaluated from the mean collision time, $\tau_{c,s}$, and the rotational collision number, $Z_{rot,s}$ as [26]:

$$\tau_{rot-tra,s} = \tau_{c,s} Z_{rot,s} \tag{18}$$

$$Z_{rot,s} = \frac{Z_{rot,s}^{\infty}}{1 + \frac{\pi^{1.5}}{2}\left(\frac{T_s^*}{T}\right)^{0.5} + \left(\frac{\pi^2}{4} + \pi\right)\left(\frac{T_s^*}{T}\right)} \tag{19}$$

where $Z_{rot,s}^{\infty}$ and T_s^* are constant for each species. HANSA has included the energy relaxation between the rotational and electron energies due to the electron interactions with the molecular multipoles. The rotational-electron energy relaxation term is simplified using an energy transfer rate factor, $g_{rot,s}$, which is the ratio of the rotational-electron energy relaxation time to the translational-electron energy relaxation time for the molecular species. Therefore, the source term for rotational-electron energy exchange is given as:

$$S_{rot-ele} = 2\rho_e \frac{3}{2} k (T_{rot} - T_e) \sqrt{\frac{8kT_e}{\pi m_e}} \sum_{s \neq e}^{\text{All molecules}} \left(g_{rot,s} \frac{\rho_s}{m_s^2} \sigma_{es} \right) \tag{20}$$

The rotational-electron energy transfer rates for neutral molecules used in HANSA are given in Table 5. For molecular ions, HANSA assumes they have the same rate factor as their neutral molecules.

Table 5. The energy transfer rate factors of rotational-electron energy relaxation.

Species	g_{rot}
N_2	10
O_2	10
NO	100

2.1.3.2 Chemical Non-equilibrium

A finite rate chemical kinetics model is generally used to describe chemical non-equilibrium. The reactions are categorized as dissociative, exchange, recombination ionization, charge exchange, and impact ionization. All reactions are described generically as:

$$\sum \alpha_s[S] \rightleftharpoons \sum \beta_s[S] \quad (21)$$

where $[S]$ is chemical species and α and β are the stoichiometric coefficients of chemical reactions. The chemical source term of species *s* in reaction *k* is modelled as:

$$\dot{\omega}_{sk} = (\beta_{sk} - \alpha_{sk})\left[10^3 k_{fk} \prod_j \left(10^{-3}\frac{\rho_j}{M_j}\right)^{\alpha_{kj}} - 10^3 k_{bk} \prod_j \left(10^{-3}\frac{\rho_j}{M_j}\right)^{\beta_{kj}}\right] \quad (22)$$

The source terms in the species conservation equations are given by

$$S_{chem} = M_s \sum_k \dot{\omega}_{sk} \quad (23)$$

where M_s is molecular weight of species 's'. The forward and backward reaction rates are affected by the level of non-equilibrium in the flow. The forward reaction rates, k_{fk}, calculated using Arrhenius curve fits on the controlling temperature, T_c as:

$$k_{fk} = A T_c^{\eta} e^{-\frac{E_a}{T_c}} \quad (24)$$

where, T_c is the controlling temperature, A, η and E_a are constants for each reaction, can be found in Ref. [18]. A vibrationally excited molecule requires less collisional energy to dissociation than a molecule in a low vibrational state. To account for that, Park introduced an empirical two-temperature model [18] for dissociation reactions. In this model, the dissociation reactions are controlled by a combination of the translational-rotational and the vibrational-electron-electronic temperature.

$$T_c = T^a T_v^b \quad (25)$$

where two different set of values are typically used for a and b: $a = b = 0.5$ or $a = 0.7$ & $b = 0.3$.

Most of the CFD solvers use Park's two temperature model to model dissociation reactions. DPLR uses translational temperature to control all other reactions. **Error! Reference source not found.** presents the baseline finite rate chemistry model in the DPLR code. The backward rates are computed using the forward rates, and equilibrium constants are evaluated using the Van ’t Hoff equation in the DPLR.

Table 6. Baseline forward reaction rate coefficients, $\left(\frac{m^3}{molecules \cdot s}\right)$

Reaction	Rate coefficient
$N_2 + M \rightleftarrows N + N + M$	$1.162 \times 10^{-8}\, T^{-1.6} \exp\left(\frac{-113,200}{T}\right)$
$N_2 + A \rightleftarrows N + N + A$	$4.980 \times 10^{-8}\, T^{-1.6} \exp\left(\frac{-113,200}{T}\right)$
$N_2 + e^- \rightleftarrows N + N + e^-$	$4.980 \times 10^{-8}\, T^{-1.6} \exp\left(\frac{-113,200}{T}\right)$
$O_2 + M \rightleftarrows O + O + M$	$3.321 \times 10^{-9}\, T^{-1.5} \exp\left(\frac{-59,400}{T}\right)$
$O_2 + A \rightleftarrows O + O + A$	$1.660 \times 10^{-8}\, T^{-1.5} \exp\left(\frac{-59,400}{T}\right)$
$NO + M \rightleftarrows N + O + M$	$8.302 \times 10^{-15} \exp\left(\frac{-75,500}{T}\right)$
$NO + A \rightleftarrows N + O + A$	$1.826 \times 10^{-13} \exp\left(\frac{-75,500}{T}\right)$
$O + NO \rightleftarrows N + O_2$	$1.389 \times 10^{-17} \exp\left(\frac{-19,700}{T}\right)$
$O + N_2 \rightleftarrows N + NO$	$1.069 \times 10^{-12} T^{-1} \exp\left(\frac{-37,500}{T}\right)$
$N + N \rightleftarrows N_2^+ + e^-$	$3.387 \times 10^{-17} \exp\left(\frac{-67,700}{T}\right)$
$O + O \rightleftarrows O_2^+ + e^-$	$1.859 \times 10^{-17} \exp\left(\frac{-81,200}{T}\right)$
$N + O \rightleftarrows NO^+ + e^-$	$8.766 \times 10^{-18} \exp\left(\frac{-32,000}{T}\right)$
$N + e^- \rightleftarrows N^+ + 2e^-$	$8.434 \times 10^{-14} \exp\left(\frac{-121,000}{T}\right)$
$O + e^- \rightleftarrows O^+ + 2e^-$	$1.054 \times 10^{-14} \exp\left(\frac{-106,200}{T}\right)$
$N_2 + O^+ \rightleftarrows O + N_2^+$	$1.511 \times 10^{-18}\, T^{0.360} \exp\left(\frac{-22,800}{T}\right)$
$NO + O^+ \rightleftarrows O_2 + N^+$	$2.324 \times 10^{-25}\, T^{1.900} \exp\left(\frac{-15,300}{T}\right)$
$O_2 + NO^+ \rightleftarrows NO + O_2^+$	$3.985 \times 10^{-17}\, T^{0.410} \exp\left(\frac{-32,600}{T}\right)$

$N + NO^+ \rightleftarrows O + N_2^+$	$1.195 \times 10^{-16} \exp\left(\frac{-35{,}500}{T}\right)$
$O + NO^+ \rightleftarrows O_2 + N^+$	$1.660 \times 10^{-18}\, T^{0.500} \exp\left(\frac{-77{,}200}{T}\right)$
$N + O_2^+ \rightleftarrows O_2 + N^+$	$1.444 \times 10^{-16}\, T^{0.140} \exp\left(\frac{-28{,}600}{T}\right)$
$N_2 + O_2^+ \rightleftarrows O_2 + N_2^+$	$1.644 \times 10^{-17} \exp\left(\frac{-40{,}700}{T}\right)$
$N + NO^+ \rightleftarrows N_2 + O^+$	$5.645 \times 10^{-17}\, T^{-1.080} \exp\left(\frac{-12{,}800}{T}\right)$
$O + NO^+ \rightleftarrows N + O_2^+$	$1.195 \times 10^{-17}\, T^{0.290} \exp\left(\frac{-48{,}600}{T}\right)$

LeMANS considers the inclusion of electron temperature non-equilibrium while modelling ionization reactions. The controlling temperature [27] is modified as:

$$T_c = T_{tr}^a T_{ve}^b T_e^c \tag{26}$$

The values of the parameters a, b and c used in the electron nonequilibrium simulations are given in **Error! Reference source not found.** for both the forward and backward rates of each type of reaction mechanism [27].

Table 7. The parameters of controlling temperature for various reaction types.

Reaction	Forward			Backward		
	a	b	c	a	b	c
Dissociation	0.67	0.33	0.0	1.0	0.0	0.0
Neutral exchange	1.0	0.0	0.0	1.0	0.0	0.0
Associative ionisation	1.0	0.0	0.0	0.0	0.5	0.5
Charge exchange	1.0	0.0	0.0	1.0	0.0	0.0
Electron impact dissociation	0.0	0.5	0.5	0.5	0.0	0.5
Electron impact ionisation	0.0	0.0	1.0	0.0	0.0	1.0

The backward reaction rate is modelled using the equilibrium constants as:

$$k_{bk} = \frac{k_{fk}(T_c)}{K_{eq}(T_c)} \tag{27}$$

The equilibrium constants on LeMANS are modelled using Gibb's free energy as:

$$K_{eq} = \left(\frac{p_0}{RT_c}\right)^{\nu} e^{-\sum_s(\beta_s-\alpha_s)\left(\frac{\hat{h}_s}{RT_c}-\frac{\hat{s}_s}{R}\right)} \tag{28}$$

$$\nu = \sum_s (\beta_s - \alpha_s) \tag{29}$$

where the normalized enthalpy, $\frac{\hat{h}_s}{RT_c}$, and entropy, $\frac{\hat{s}_s}{R}$, are modelled using the NASA Lewis CEA database.

Chemical reaction coefficients are related to the different temperature modes based on the type of reactions. Since HANSA incorporates rotational, multi-species vibrational and electron non-equilibrium models, the controlling temperature, T_c, in HANSA is modified in the following way:

$$T_c = T_{trans}^{a} T_{rot}^{b} T_{vib,1}^{c_1} \cdots T_{vib,s}^{c_s} T_e^{d} \tag{30}$$

where the values of a, b, c_s and d used in the HANSA are listed in **Error! Reference source not found.** in term of reaction types.

Table 8. Coefficients of the controlling temperature for various reaction types.

Reaction	Forward				Backward			
	a_f	b_f	c_f	d_f	a_b	b_b	c_b	d_b
Dissociation	0.34	0.33	$\frac{0.33}{N_{reactant\ molecules}}$	0.0	1.0	0.0	0.0	0.0
Neutral exchange	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
Associative ionisation	1.0	0.0	0.0	0.0	0.0	0.0	$\frac{0.5}{N_{product\ molecules}}$	0.5
Charge exchange	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
Electron impact dissociation	0.0	0.0	$\frac{0.5}{N_{reactant\ molecules}}$	0.5	0.5	0.0	0.0	0.5
Electron impact ionisation	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0

2.1.4 Challenges in Flow Modelling

The fidelity of hypersonic CFD simulations depends upon the accurate representations of non-equilibrium processes, including relaxation and reaction rates. Traditional approaches often rely on data extrapolated from lower-temperature shock tube experiments. For hypersonic applications, high-temperature values are usually extrapolated from such data, which may not fully capture the complexities associated with the non-equilibrium flow conditions. Recent advancements in quantum chemistry calculations have shown promise in improving these calculations. Potential Energy Surfaces (PES), derived from quantum chemistry, are used to calculate nonequilibrium reaction rates through Quasi-Classical Trajectory (QCT) methods [28] [29]. Some studies have determined reaction rates based on available quantum mechanically derived PES for several reactions with the help of massive parallel supercomputers [30] [31] [32]. While QCT methods offer valuable insights and improved results than the existing methods, their application is limited by the computational expense of constructing PES for all relevant atmospheric species and the inherent uncertainties in both PES generation and QCT calculations.

The state-to-state (StS) method is the most detailed approach for calculating rate coefficients, as it can describe arbitrary vibrational energy distributions [33] [34]. The primary assumption of this method is that the timescale associated with vibrational relaxation is much greater than that of translational and rotational relaxation, but comparable to the chemical reaction timescale, which is valid in hypersonic simulations. The StS approach provides accurate predictions for strongly non-equilibrium flows, exhibiting excellent agreement with experimental data [35],[36],[37]. However, it is computationally prohibitive. For instance, molecular vibrational energy levels calculated using anharmonic oscillator models include 47 states for N_2, 36 for O_2, and 39 for NO, significantly increasing the number of conservation equations to be solved. This makes it impractical to couple StS with CFD for the entire flow domain. To overcome these limitations, recent research has explored the use of data-driven models, such as machine learning, to predict relaxation terms and reaction rates [38]. Therefore, future directions should focus on integrating CFD with StS using machine learning methods, thereby avoiding expensive direct coupling between CFD and StS.

2.2 Material Response Models

Re-entry flows are often treated as conjugate heat transfer problem, where the governing equations are solved at solid and fluid domains simultaneously. The exchange of information happens between the domains through boundary conditions such as heat flux and surface temperature. The fluid models were discussed in the previous section; therefore, this section presents a review of the material response models. As existing material response studies are performed for thermal protection system (TPS), the same is presented here.

When the peak heat flux due to shock increases the vehicle surface temperature, the virgin material undergoes transformation through the pyrolysis process, during which the material decomposes, producing pyrolysis gases. These gases are transported out of the material by diffusion and convection through the pore network and their chemical composition evolves, as their temperature increases. Following pyrolysis, the char material undergoes a process called ablation, which involves the char composed of residual carbonized matrix and any remaining non-pyrolyzing gases. Depending on the local conditions, ablation can also occur due to heterogeneous chemical reactions such as oxidation and nitridation, phase changes like sublimation and structural erosion, known as spallation. The accuracy of any material response code depends on accurately predicting the ablation rate and peak surface temperature.

Most of today's material response codes trace their origins back to models developed in the 1960s, particularly the Aerotherm report from 1968 and CMA model [39]. Although this model is one of the earliest comprehensive material response codes, this is based on a set of assumptions and several physical phenomena were neglected. Over the years, many of the assumptions have been removed in many solvers by adapting high-fidelity models, while some have persisted in others. One common assumption is the omission of the time derivative, thereby treating the problem as a steady state. This assumption is valid as long as the time associated with temperature or pressure variations is large compared to the characteristic time of pyrolysis gas flow. The characteristic time is usually defined as the ratio of the char layer thickness to the velocity of the gas. In typical re-entry flows, this value is roughly around 0.01 seconds, which is higher than the time step of temperature variation ($O \sim 1\ s$), making this assumption valid. However, this assumption may not hold when the char layer is thick. The second important assumption is that the gas flow is perpendicular to the surface and directed towards it. In higher-dimensional problems, this may not be valid, necessitating the determination of flow direction by solving the momentum conservation equation [40].

As mentioned earlier, the base code of most material-response solvers is almost the same, but they differ in terms of dimensionality and the level of fidelity, such as the consideration of different phenomena. Material response solvers can be categorized as into three types, as defined in Ref. [41].

- **Type - I:** Simplified approaches fall in this type, that implements 1960s CMA or an equivalent model. Heat transfer in the material and the decomposition due to pyrolysis are modelled, but a simplified approach is used to model the transport of the pyrolysis gas. Moreover, many physical phenomena are not considered and involves three major assumptions: the residence time of the gas inside the control volume is short, the direction of the pyrolysis gas is perpendicular and direct towards the surface, and thermal equilibrium between the solid and the gas phase.
- **Type-II:** This type is more accurate than type – I. The second assumption in type-I is removed by implementing the average momentum equation (Darcy's law) for the transport of pyrolysis gas. They do not track species production, instead, the average mass production is computed from the Arrhenius laws same as type - I.
- **Type-III:** Higher-fidelity response solvers fall in this type. These codes detail several physical phenomena and include finite-rate chemistry, multi-component diffusion, radiative heating, in-depth coking, ablation, spallation, etc. The species conservation equation accurately tracks species transport and chemical reactions within the pores of the material.

Several macroscopic and microscopic phenomena occur during re-entry ablation. Figure 4 illustrates these phenomena as an ablative material degrades under high enthalpy flow conditions. The figure also highlights which phenomena are captured by different levels of material response code fidelity. Some of the well-known solvers are listed in Table 9.

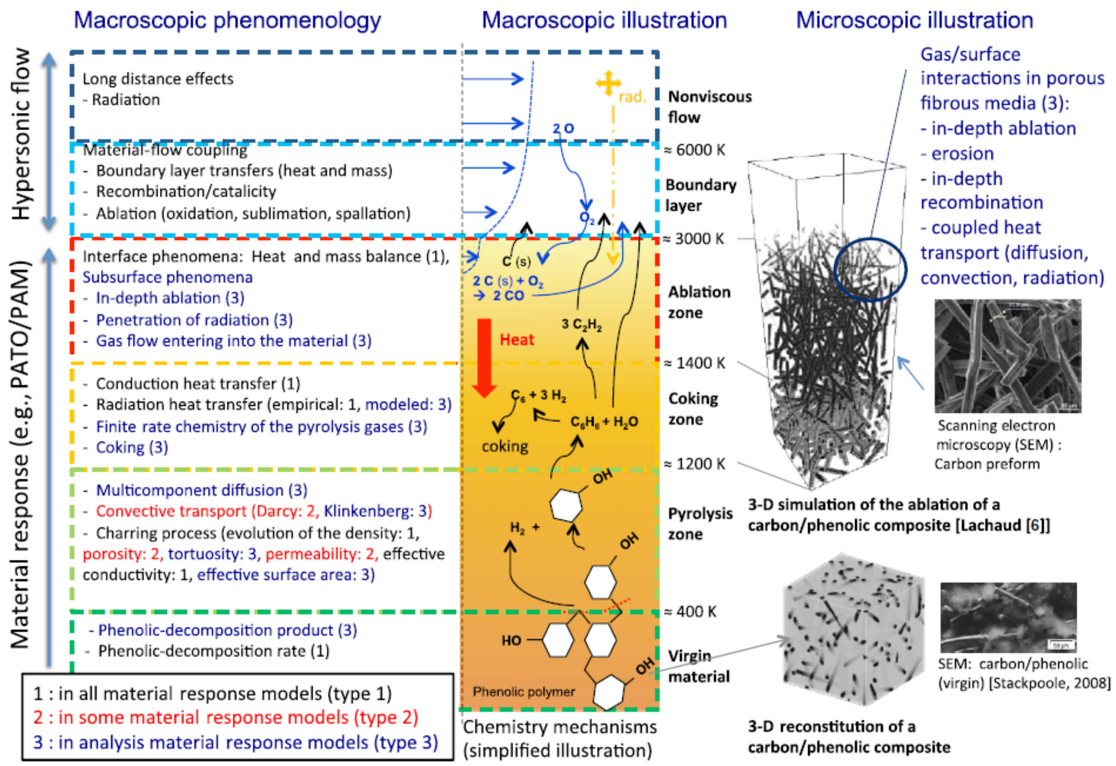


Figure 4. Illustration of macroscopic and microscopic phenomena occurring during re-entry ablation [41].

Table 9. Notable Material Response Solvers along with their features.

Name	Dimension	Institution	Country	Features
FIAT [42], [43]	1D	NASA	USA	Implicit time integration with tri-diagonal matrix Non-equilibrium pyrolysis gas
TITAN[44], [45]	2D	NASA	USA	Time integration by Gauss-Seidel line relaxation Specific grid topologies Orthotropic thermal conductivity
3dFIAT [46]	1D / 2D / 3D	NASA	USA	Multi-block grid Implicit time integration with both structured and unstructured solvers. Darcy flow with orthotropic permeability
Icarus [48]	1D / 2D / 3D	NASA	USA	Parallel computing, Structured solver Under-development
PATO [49]	1D / 2D / 3D	NASA	USA	Unstructured finite volume solver

				Finite-rate capability and advanced material models (fracture) Built on Open FOAM and integrated to DPLR Mutation++, and DAKOTA.
CHAR [50]	1D / 2D / 3D	NASA	USA	Comprehensive set of boundary conditions, featuring surface-to-surface radiation exchange and contact interfaces. Adaptive mesh refinement and coupled thermos-electric solver. Licensed across the industry, limited only to US government contractors
CMA SODDIT CHALEUR [51]	1D	Sandia National Laboratories	USA	Equilibrium chemistry ablation models In-depth decomposition No surface recession rate
COYOTE II [51]	2D / 3D	Sandia National Laboratories	USA	Finite element code with ablating boundary conditions. Moving mesh capabilities for modelling surface recession. Variable material properties as a function of temperature.
KCMA [52]	1D	ISA/ESA	France	Estimates surface recession rate through carbon oxidation and sublimation. Wall at chemical equilibrium condition.
KATS [53]	3D	University of Kentucky	USA	Solid decomposition model Chemical equilibrium pyrolysis model Anisotropic material properties and spallation models.
CHyPS [54]	1D / 2D	University of Illinois at Urbana-Champaign	USA	Arbitrary Lagrangian Eulerian (ALE) formulation solved using discontinuous Galerkin method.
MRS [55]	1D	University of Southampton	UK	Under-development

NASA Ames Research Center (ARC) has developed several thermal response codes, namely FIAT, TITAN, 3dFIAT, and Icarus, for addressing one-dimensional to three-dimensional problems. The Fully Implicit Ablation and Thermal response (FIAT) code [42] is widely used by NASA for one-dimensional analysis in the design of spacecraft thermal protection systems (TPS). In FIAT, it is assumed that the pyrolysis gas remains in thermal equilibrium with the solid material and that the internal flow behaves in a quasi-steady manner. These assumptions are typically suitable for cases where a one-dimensional analysis is appropriate. Later, FIAT was extended by adding a detailed nonequilibrium chemistry [43]. The two-dimensional implicit thermal response and ablation (TITAN) code [44], [45] was developed to analyse two-dimensional and axisymmetric geometries. However, in some cases, even two-dimensional analyses proved insufficient, leading to the development of three-dimensional ablation code, 3dFIAT, for high-fidelity simulations [46]. The 3dFIAT solver can evaluate the thermal response of a spacecraft's heat shield during atmospheric entry at any angle of attack. Additionally, integrating 3dFIAT with MARC [47], a multi-physics simulation system, enables the analysis of structural heat transfer, in-depth pyrolysis and decomposition, and surface recession due to thermal ablation for three-dimensional objects under hypersonic non-equilibrium conditions. In both TITAN and 3dFIAT, it was assumed that the pyrolysis gas flows along predetermined lines perpendicular to the TPS surface. This assumption was essential to define the internal quasi-steady flow and is valid when the char depth is small compared to the model size. However, this assumption becomes invalid if the char depth is large. The next-generation ablation solver, Icarus [48], is currently under development at NASA-ARC. Icarus employs an unstructured finite volume method, enhancing flexibility in simulating complex surface geometries. The Porous material Analysis Toolbox based on OpenFOAM (PATO) [49] is a high-fidelity, unstructured finite volume solver developed by NASA, used as a library within OpenFOAM. PATO comprises two modules: the global analysis module, can be used to run a full ablative material response with an applied/macroscopic scale point of view, and the elementary analysis module, aimed at studying specific fundamental aspects with detailed/microscopic scale point of view. The Charring Ablator Response (CHAR) code [50] is an unstructured continuous Galerkin finite-element heat conduction and ablation solver with both direct and inverse modes. CHAR addresses several phenomena, including in-depth chemical non-equilibrium, and condensation and decomposition modelling. However, the license is limited only to U.S. government and industry contractors. Other notable material response solvers are: CMA, SODDIT, CHALEUR and COYOTE II from Sandia National Laboratories, KCMA from ISA/ESA, KATS from the University of Kentucky, USA, CHyPS from the University of University of Illinois at Urbana-Champaign, USA and MRS from the University of Southampton, UK, which is under-development.

2.2.1 Challenges in Material Response Modelling

Existing material response solvers are primarily designed for the TPS of re-entry vehicles, with limited integration of structural response solvers. However, when considering satellite ablation, it is essential to account for structural damages. Moreover, these solvers have been designed and validated for typical TPS materials, but satellite components differ significantly, usually made from metals such as aluminium, nickel, magnesium, and stainless-steel alloys. Thus, existing models must be validated or extended to accommodate these materials.

A critical gap lies in the incomplete consideration of ablation by-products. While spallation and its effect on flow characteristics are incorporated in some models, the crucial aspect of oxidation and its by-products, which significantly impact the atmosphere, is often neglected. Therefore, to accurately address satellite ablation, material response models must account for the unique characteristics of satellite materials, incorporate coupled structural and material responses, and comprehensively model ablation processes, including oxidation and its by-products.

2.3 Ground Test Facilities and Techniques

Reproducing the conditions of atmospheric entry on Earth is highly challenging, yet crucial for re-entry missions. There are two primary approaches to do experimental studies in this field. The first involves equipping space vehicles with various instruments to collect in-flight data. Some experiments are FIRE II, Atmospheric Re-entry Demonstrator (ARD), Intermediate eXperimental Vehicle (IXV), Galileo, Mars Path Finder and Mars Science Laboratory (MSL) space probes [56]. While effective, this method is expensive due to the high costs associated with rocket launches. The alternative approach is to simulate atmospheric entry conditions using specialized ground facilities, such as hypersonic wind tunnels and plasma tunnels. These facilities, available globally, can replicate some realistic flight conditions, although not all extreme aspects of atmospheric entry can be perfectly mimicked. These facilities can be broadly categorized into short-duration and long duration test environments, shown in Figure 5Fig. 5. Short-duration facilities, such as shock tunnels and shock tubes, are designed to simulate high-speed aerodynamic conditions over a very short periods and are typically used for studying flow characterization. On the other hand, long-duration facilities, including arc jets and Inductively Coupled Plasma Tunnels (ICPT), are crucial for testing materials and systems under sustained thermal loads, mimicking the extreme thermal loads experienced during spacecraft re-entry. Arc jets can be further divided into segmented and Huels types, each offering distinct advantages for specific testing requirements.

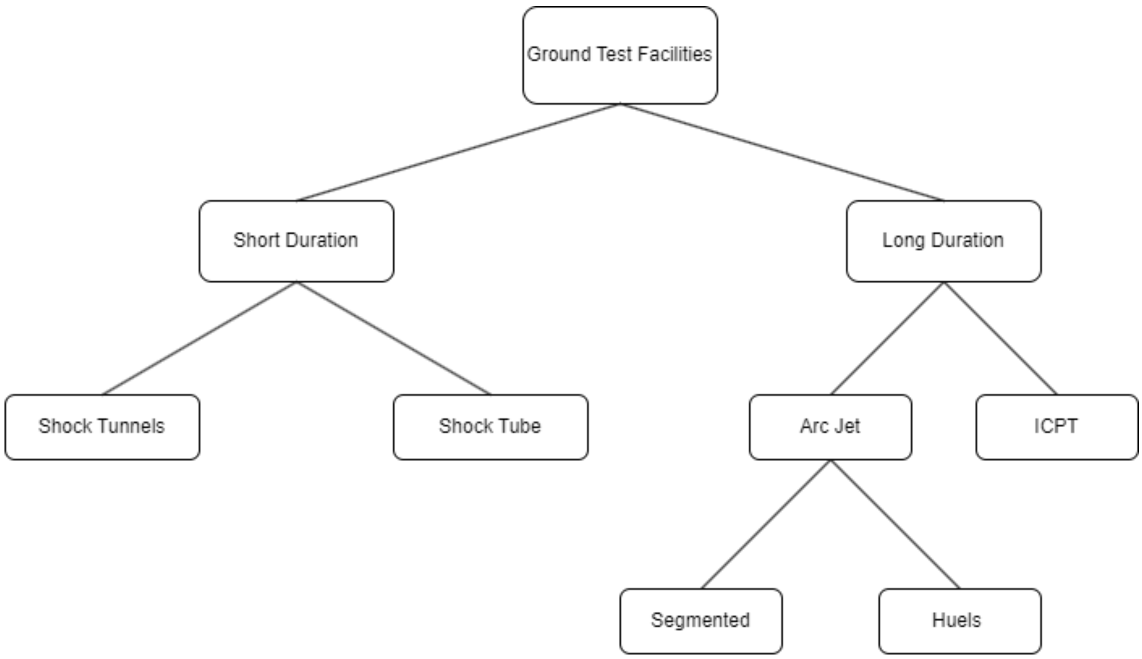


Figure 5. Classification of Ground Test Facilities.

Figure 6 provides a comprehensive overview of various ground test facilities used for evaluating thermal protection systems (TPS), highlighting their operational capabilities in terms of stagnation temperature, equivalent velocity, total enthalpy, and flow duration. The x-axis represents the flow duration, ranging from microseconds to hours, while the y-axis on left indicates the stagnation temperature and the right indicates equivalent velocity and total enthalpy. Shock tubes and shock tunnels are typically used for short-duration tests, lasting microseconds to milliseconds, and can achieve high stagnation temperatures and velocities, making them ideal for studying transient aerodynamic phenomena. Blowdown tunnels operate in a slightly longer duration regime, but at lower temperatures compared to shock tunnels. For longer-duration tests, ranging from seconds to minutes, arc-heated tunnels and ICPT are used. Arc-heated tunnels can produce extremely high enthalpy flows, while ICPTs provide a stable plasma environment for comprehensive testing.

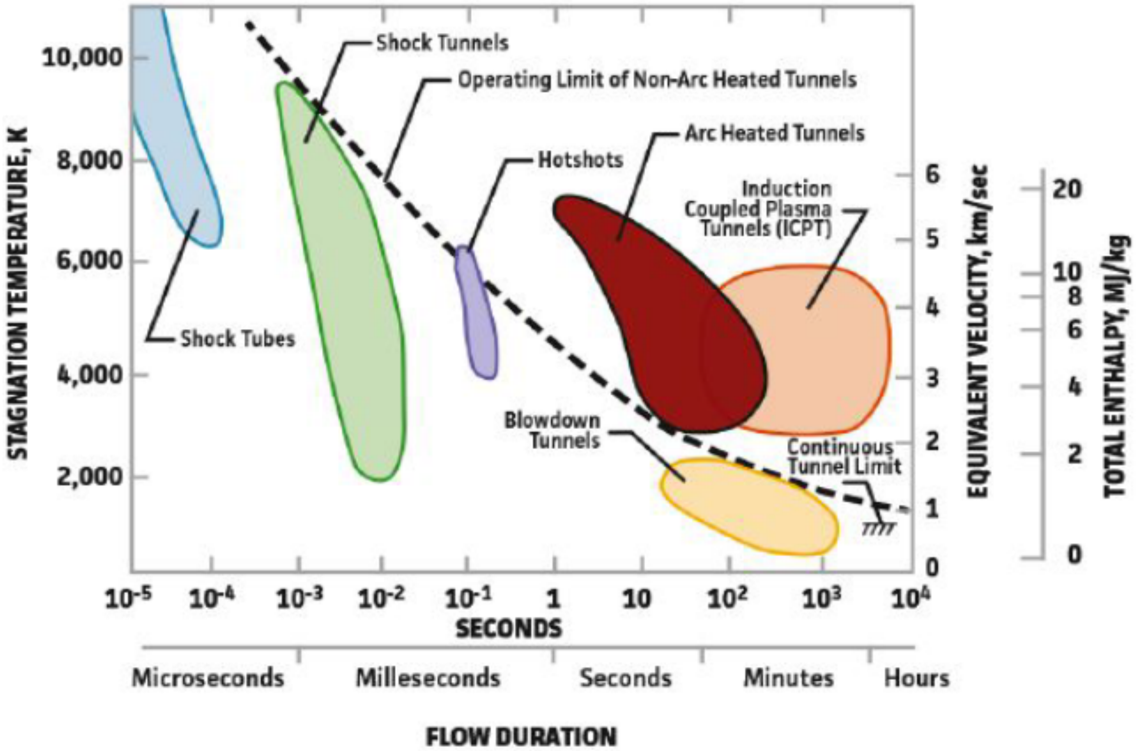


Figure 6. Operational ranges of ground test facilities [57],[58]

2.3.1 Blow-down hypersonic wind tunnels

Blow-down hypersonic wind tunnels are specialized facilities designed to simulate the extreme aerodynamic conditions encountered by vehicles operating at hypersonic speeds such as space launch vehicles, missiles, projectiles, and spacecraft re-entry. Fundamentally, hypersonic wind tunnels operate on principles similar to supersonic tunnels, however, achieving hypersonic speeds necessitates the wind tunnels must employ nozzles with very high contraction ratios. Additionally, establishing the flow requires an immense pressure difference between the upstream and downstream sections of the tunnel (often exceeding 3300:1 for Mach 10 flows) [59], which poses substantial engineering challenges. The significant energy demands of hypersonic wind tunnels typically dictate a blow-down configuration. In this setup, compressed air or other gases are stored at high pressure and then rapidly released into the test section. While this method allows for the generation of intense flow conditions, it also limits test duration. Blow-down hypersonic wind tunnels can sustain flow for several seconds or even minutes, whereas hot tunnels, designed to replicate higher temperatures, are often restricted to test durations of a few hundred milliseconds.

Blow-down hypersonic tunnels can achieve Mach numbers up to 10, providing a valuable environment for investigating high-speed aerodynamic phenomena such as shock wave patterns, boundary layer development, flow separation and shock wave boundary layer interactions. However, the relatively low temperatures within these facilities limit their capability to study the effects of real gases, which become significant at the extreme temperatures encountered in actual hypersonic flight such as thermal non-equilibrium and chemical reactions. This necessitates hypersonic hot or hyper-enthalpic wind tunnels. The R1Ch, R2Ch and R3Ch wind tunnels at ONERA Meudon centre, France are of this type.

2.3.2 Hot shot tunnels

Hot shot wind tunnels are a type of hypersonic facility that uses an electric arc to rapidly heat a test gas to extremely high temperatures and pressures. This method allows for the generation of short-duration, high-enthalpy flows, simulating the conditions experienced by vehicles during atmospheric re-entry.

A typical hot shot tunnel consists of an arc chamber, a nozzle, and a test section. The test gas, such as air or nitrogen, is stored in the arc chamber and heated by a powerful electric arc. Once the desired gas conditions are attained, a diaphragm separating the chamber from the nozzle ruptures, propelling the high-pressure gas through the nozzle to generate hypersonic flow. The test durations are typically a few hundred milliseconds. However, these facilities can achieve extremely high temperatures and pressures, making them suitable for studying real gas effects. The F4 high enthalpy wind tunnel at ONERA, Fauga-Mauzac is an example of this type (see Figure 7). Typical tests performed in F4 include force measurements on space glider models and re-entry capsules at high angle of incidence, as well as measurements of thermal flux and wall pressure distributions.

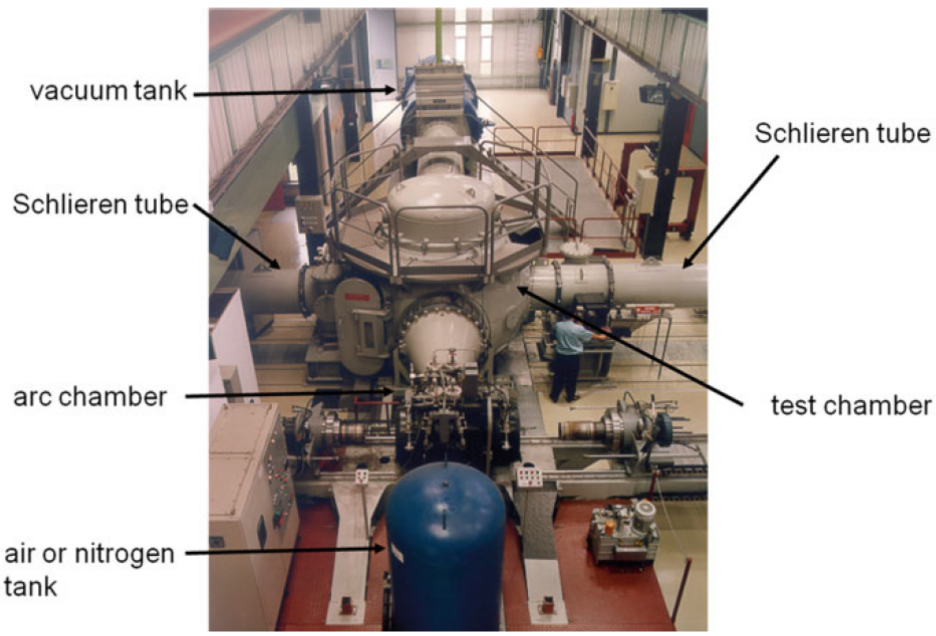


Figure 7. ONERA F4 high-enthalpy wind tunnel [59].

2.3.3 Shock Tunnels

Shock tunnels are specialized facilities designed to simulate high-speed flight conditions by utilizing the energy released from a shock wave. This method offers a cost-effective alternative to traditional wind tunnels, particularly for achieving the high temperatures and pressures required for hypersonic research. A shock tunnel consists of a long tube divided into two sections: a high-pressure driver section and a low-pressure driven section separated by a diaphragm. When the diaphragm ruptures, a shock wave propagates through the driven section, compressing and heating the test gas. This high-energy gas is then expanded through a nozzle to create a hypersonic flow.

While shock tunnels excel at producing high-enthalpy flows, their test times are extremely short, typically in the microsecond to millisecond range. This limitation restricts their application to specific types of experiments, such as studying shock wave phenomena and rapid chemical reactions. The High Enthalpy Shock Tunnel Göttingen (HEG), German Aerospace Centre (DLR), shown in Fig. 8, is an example of a shock tunnel that uses a piston to compress the driver gas before diaphragm rupture, increasing the shock wave intensity. The facility comprises a secondary reservoir, a compression tube, separated from the actual shock tube by a primary diaphragm, followed by a test nozzle and a recovery tank.

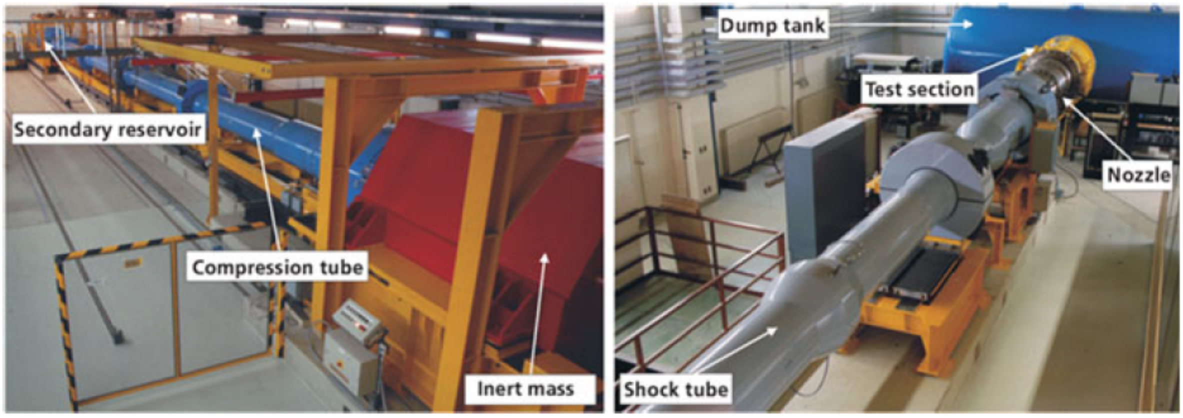


Figure 8. High Enthalpy Shock Tunnel Göttingen at DLR [59]

2.3.4 Arc-heated Plasma Tunnels

Plasma tunnels and arc jet facilities are designed to replicate the high enthalpy environment experienced during atmospheric re-entry. They are used to analyse the response of thermal protection system of re-entry capsules by exposing samples to high enthalpy flows, such as plasma. Data is then collected using various instruments, including thermocouples. This section details some worldwide ground testing facilities used for material testing.

2.3.4.1 2.3.4.1 SCIROCCO Plasma Wind Tunnel (CIRA, Italy)

The SCIROCCO Plasma Wind Tunnel (PWT) located at the Centro Italiano Ricerche Aerospaziali (CIRA) in Capua, Italy, is the world's largest and more powerful hypersonic, high enthalpy, low pressure arc-jet facility in operation. It was established by the European Space Agency (ESA) through the Hermes program, it has been operational since 2002. The layout of this tunnel is shown in Fig. 9. The facility is designed to replicate the high heat flux and pressure conditions experienced by space vehicles during re-entry into Earth's atmosphere, utilizing arc-jet technology. The main goal of the facility is to qualify large-scale test articles up to 600 mm in diameter, including TPS, hot structures and payloads of space re-entry vehicles.

The core of the SCIROCCO facility is a 70 MW arc heater, which can generate a plasma jet of up to 2 meters in diameter, at Mach 12, for a test duration of up to 30 minutes. The heater, known as a plasmatron, has a segmented design with a bore diameter of 0.11 meters and a length of 5.5 meters. It heats the test gas, a mixture of air and Argon with a maximum mass flow rate of 3.5 kg/s, to plasma temperatures ranging from 2000 K to 10,000 K. Hypersonic speeds are achieved by accelerating the plasma flow through a converging-diverging conical nozzle. There are five different nozzle configurations available ranging from 0.187 to 1.95 metres to achieve the desired flow condition. The experimental models or test articles are placed in the plasma jet inside a cylindrical test chamber with an overall height of 9 meters and an inner diameter of 5 meters. The hypersonic jet then transitions to subsonic speeds in a 50-meter-long diffuser, where it is cooled by a heat exchanger. A vacuum pump maintains low-pressure conditions in the upstream test leg. Before releasing the gas into the atmosphere, the facility uses a DeNOx system to remove nitrogen oxides produced during the hypersonic-subsonic transition.

SCIROCCO's operational capabilities are showcased in terms of total enthalpy and pressure, as well as simulated altitude and velocity comparable to typical space shuttle re-entry trajectories. The facility is equipped with extensive instrumentation to fully characterize the hypersonic jet flow and its impact on experimental models. This includes hot wall thermocouples, IR pyrometry, IR thermography, pressure sensors, cold wall heat flux calorimetric sensors, and optical flow diagnostics through emission spectroscopy (OES) and laser-induced fluorescence (LIF).

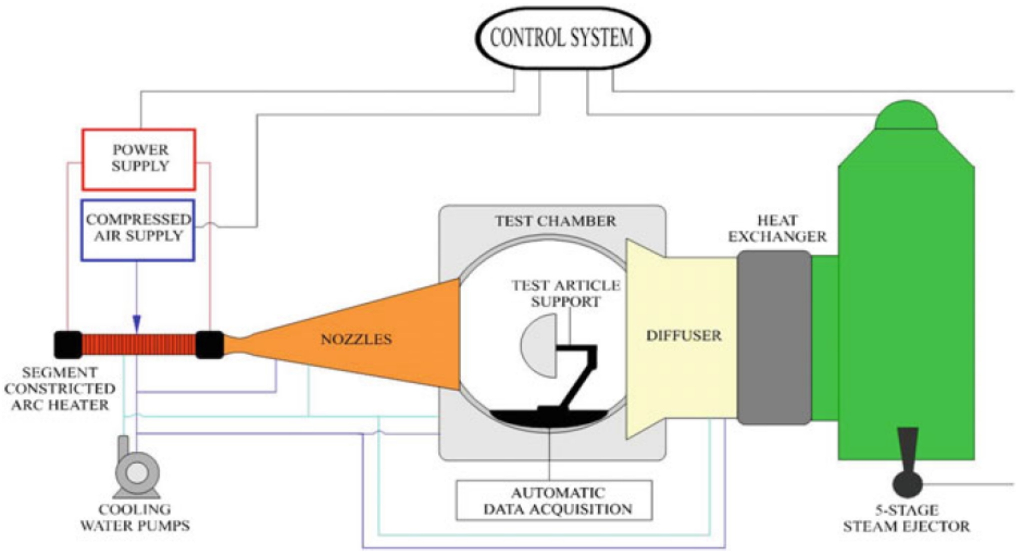


Figure 9. Layout of SCIROCCO plasma tunnel [59]

2.3.4.2 GHIBLI Tunnel (CIRA, Italy)

The GHIBLI Plasma Wind Tunnel, shown in Figure 10, is another hypersonic, high-enthalpy, low-pressure arc-jet facility, operated by CIRA for testing materials up to 80 mm in diameter. Its applications encompass material characterization, aerodynamic phenomenon investigation, CFD model validation, and advanced measurement technique development.

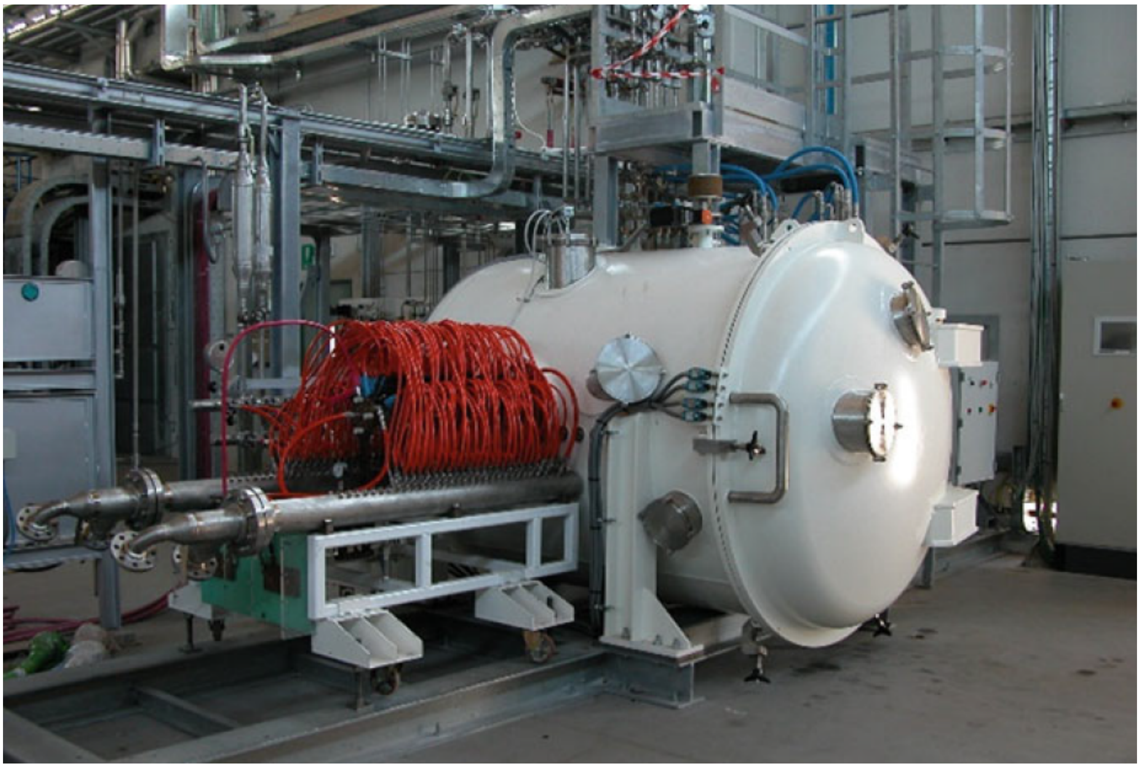


Figure 10. Arc heater and test chamber of GHIBLI tunnel at CIRA [59].

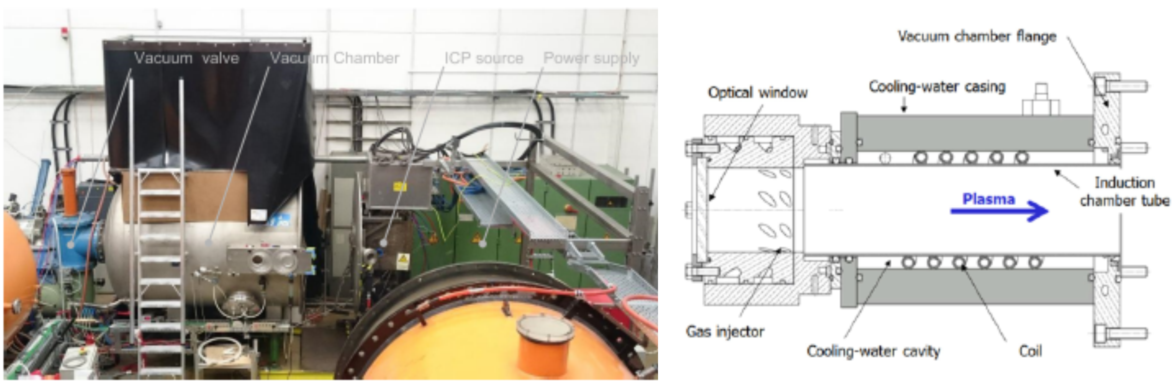
The tunnel is powered by a 2 MW arc heater capable of generating a high-temperature plasma flow of nitrogen, air, and argon. This plasma is accelerated to hypersonic speeds, approximately Mach 10, through a converging-diverging conical nozzle with a 152 mm exit diameter. The resulting high-enthalpy flow is directed into a cylindrical test chamber with an inner diameter of 1800 mm and a length of 2000 mm. The test model is introduced into the plasma jet using a model motion system within a horizontal cylindrical test chamber. After interacting with the test model, the plasma jet conveyed to the diffuser, where it undergoes a hypersonic-to-subsonic transition and is subsequently cooled by a heat exchanger. A vacuum system, consisting of root pumps, maintains the necessary suction during operation before the flow is ejected into the atmosphere.

2.3.4.3 PWK (University of Stuttgart, Germany)

The University of Stuttgart Institute of Space Systems (IRS) operates four Plasma Wind Tunnel test facilities, each distinguished by its plasma generator type. PWK1 and PWK2 utilize SF-MPG (Stationary Field Magneto-plasmadynamic Generator) systems, which produce high-enthalpy gas flows under low-pressure conditions, making them ideal for simulating early re-entry phases and extreme heat fluxes associated with high-altitude trajectories. The RD5 and RD7 facilities also use SF-MPG systems but feature coaxial electrodes with an outer copper nozzle as the anode and a thoriated tungsten cathode. An electric arc ignited by Paschen breakdown creates a diffuse, diverging arc that dissociates and ionizes the primary test gas, typically nitrogen. This gas is then accelerated through the nozzle by thermal expansion and electromagnetic forces from the arc's self-induced magnetic field, functioning as a magnetic nozzle. To protect the cathode and anode from oxidation/corrosion, oxygen is introduced only after the gas has passed the nozzle throat, and a circumferential argon flow around the anode prevents damage by reducing arc attachment.

The vacuum vessels of PWK1 and PWK2 are 6 meters long and 2 meters in diameter, featuring double-walled water-cooling systems. These tanks end in hemispherical domes and are connected to a powerful vacuum system, protected by water-cooled copper shields and baffles. On the far side, the vacuum chamber can be opened by moving the lid on a guide rail. The plasma source is not located in the vessel itself but flanged onto an inward-pointing conical element at the lid's centre. Each facility includes a 4-axis positioning system for mounting various plasma probes, allowing limited simulation of re-entry trajectory conditions, though real-time control of stagnation pressure and enthalpy is challenging due to limited response times.

The PWK3 tunnel operates as an inductively coupled plasma (ICP) source. This system functions by generating plasma within a tube that is encircled by a coil connected to a resonant circuit. The plasma discharge is generated inside the tube through particle collisions with highly accelerated free electrons. Depending on input power, gas mass flow, tube dimensions, and operational frequency, high-enthalpy flow exits the tube. There are designs with and without a nozzle at the tube end and various designs are aiming at keeping the tube temperature below thermal failure.



(a) (b)

Figure 11. Plasma wind tunnel facility at the IRS (University of Stuttgart); (a) PWK3 facility. (b) Cross section of IPG4 inductive heater [60].

A dedicated in-house power supply features six identical current-regulated thyristor rectifiers, each providing up to 1MW of power for the operation of the plasma generators, in total 6 MW. These rectifiers can be configured in series or parallel to achieve the necessary output. This system can operate at a maximum current of 48 kA at 125 V or a maximum voltage of 6000 V at 1000 A, with a rectifier ripple below 0.5%. The vacuum pumping system connected to the PWK tunnels has been upgraded to support the demanding requirements of modern plasma wind tunnel operations. It can achieve stagnation point pressures corresponding to re-entry trajectories up to 100 km altitude. The four-stage pump system includes roots-type blowers, a multiple-slide valve-type pump, and a rotary-vane-type pump. It has a combined suction power of 6000 m³/h at standard pressure and exceeds 250,000 m³/h at 10 Pa, with adjustable pressures up to approximately 500 hPa by modifying the pump stages or mixing air into the system**.** PWK3 is capable of generating heat flux levels that are critical for simulating the extreme thermal environments encountered during atmospheric re-entry. The maximum heat flux attainable in the PWK3 is on the order of several megawatts per square meter, which is essential for testing materials and systems designed to withstand re-entry velocities.

2.3.4.4 Plasmatron (VKI, Belgium)

The Von Karman Institute (VKI) Plasmatron [61] is a high-enthalpy facility, designed to generate plasma jets in a test chamber maintained at sub-atmospheric pressures ranging from 5 to 350 mbar. Plasma is produced by heating gases such as argon, nitrogen, carbon dioxide, air, or various gas mixtures to temperatures approaching 10,000 K through electrical current loops induced in a plasma discharge. Unlike traditional arc jets, the Plasmatron utilizes electrodeless inductively coupled plasma generators, which offer superior plasma purity by avoiding contamination from vaporized electrode materials.

This facility operates with a high-frequency, high-power solid-state generator (400 kHz, 1.2 MW, 2 kV) that supplies an 80 mm or 160 mm diameter plasma torch via a single-turn inductor. The plasma torch is mounted on a water-cooled test chamber that is 1.4 m in diameter and 2.5 m long, featuring nine 500 mm diameter portholes for unrestricted optical access to the horizontally oriented plasma jet. The hot gas from the chamber exits through a 700 kW heat exchanger and processed by a set of three rotary-vane vacuum pumps and a roots pump, which collectively achieve a suction capacity of 9,000 m³/h and a terminal vacuum of 0.005 mbar.

Cooling is provided by a 1.05 MW system that uses a closed-loop deionized water circuit (2090 litres/min) and fan-driven air coolers to maintain operational temperatures. The facility is managed via a computer control system with 719 I/O lines PLC and two PCs for operation and monitoring. Additionally, a 96-channel data acquisition system with a 12-bit A/D converter operating at 100 kHz supports data collection. The Plasmatron is utilized for testing materials under space re-entry conditions with heat fluxes up to 15 MW/m², including catalycity determination and general plasma flow analysis. Instrumentation includes intrusive cooled pressure and heat flux probes, a one-meter emission spectrometer with a CCD camera, and a two-colour pyrometer. The layout of the Plasmatron is shown in Figure 12.

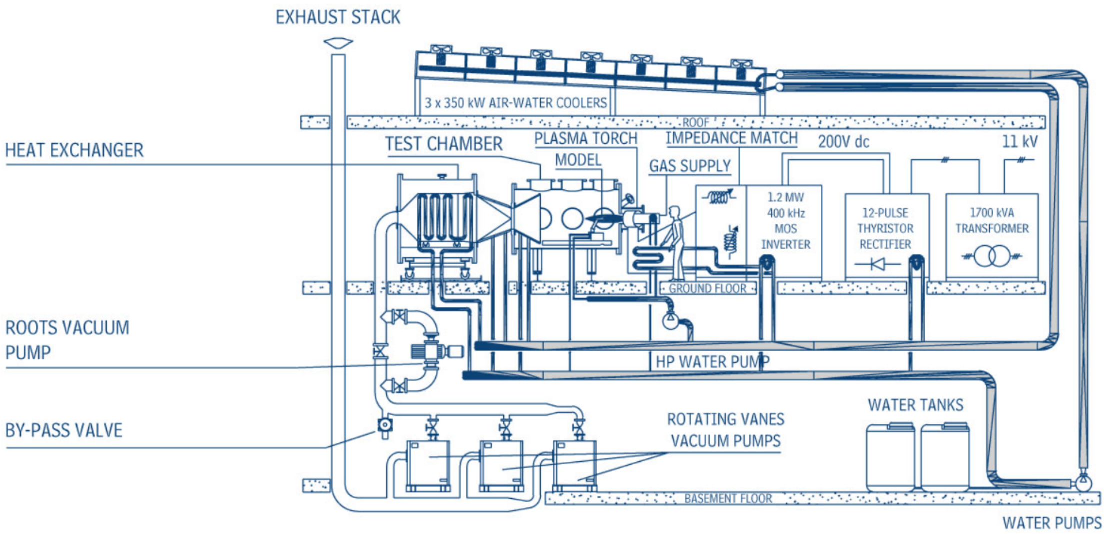


Figure 12. Layout of VKI Plasmatron [62].

2.3.4.5 LBK (DLR, Germany)

The L2K facility incorporates a Huels-type arc heater capable of operating across a gas mass flow range of 5 to 75 g/s. A schematic view of the configuration is shown in Fig. 13. The facility accommodates blunt models up to 100 mm in diameter and flat plates of sizes up to 150 mm x 250 mm x 50 mm.At a gas mass flow rate of 50 g/s, the L2K facility achieves moderate specific enthalpies of up to 10 MJ/kg, corresponding to a reservoir pressure of approximately 1500 hPa. The maximum electrical power of L2K is 1.4 MW that allows cold-wall heat flux up to 2 MW/m^2 at stagnation pressures up to 15 k Pa. The flow is still hypersonic even after passing through test models, with deceleration and pressure recovery occurring within a diffuser equipped with a centre body. Subsequently, the hot gas is cooled in the heat exchanger before entering mechanical vacuum pumps.

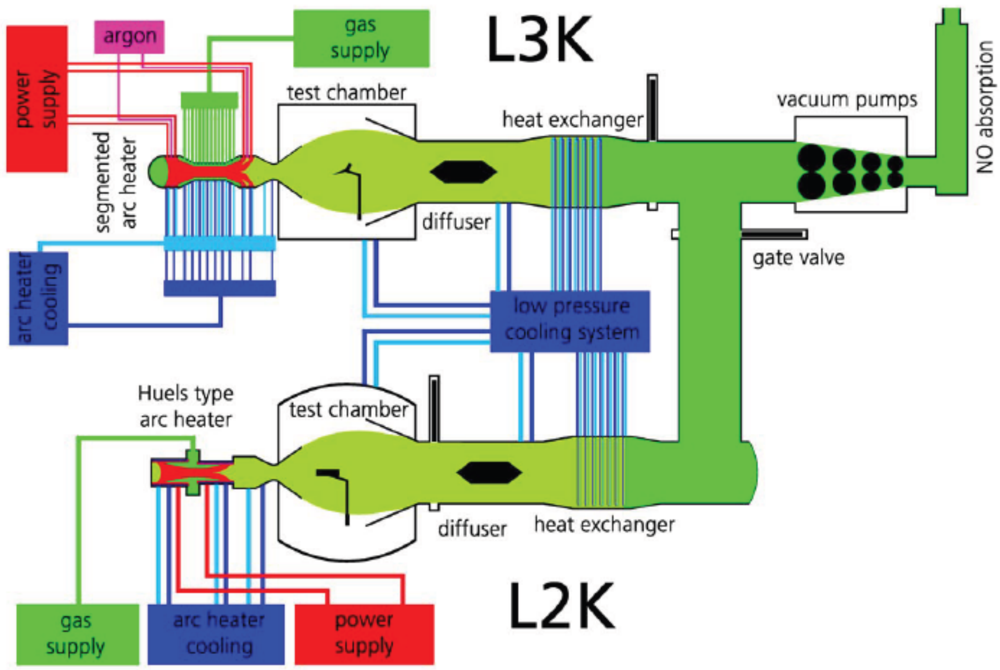


Figure 13. Schematic configuration of the LBK plasma wind tunnel facility in DLR [63]

The L3K wind tunnel, part of the DLR's LBK facility, is specifically designed for research into hypersonic and high-enthalpy flows. It is equipped with a segmented arc heater that heats the working gas to achieve high enthalpy flows. This heated gas is then accelerated to hypersonic speeds, reaching velocities up to Mach 10.22 using a convergent-divergent nozzle. The nozzle features a conical expansion part with a half-angle of 12 degrees, and it offers various throat diameters ranging from 14 mm to 29 mm, paired with exit diameters of 100 mm, 200 mm, or 300 mm. The facility can maintain hypersonic flow for up to 30 minutes, providing sufficient time for testing ablators and conducting thermal load experiments. The facility operates with a maximum electrical power of 7.0 MW, supporting Mach numbers between 5 and 10 at Reynolds numbers up to 105. A Coherent Anti-Stokes Raman Spectroscopy (CARS) system is employed for precise temperature measurements within the flow. This system measures translational, rotational, and vibrational temperatures with high temporal resolution.

2.3.4.6 Plasma Tunnels (JAXA, Japan)

The 750kW Arc-heated wind tunnel and the 110kW ICP wind tunnel [64] [65] are the test facilities of JAXA with a high enthalpy flow over 20 MJ/kg. These facilities are capable of testing materials such as Carbon/Carbon composites at surface temperatures of up to 1973 K. In the arc-heated wind tunnel, the test gas is heated by Joule heating due to high-frequency currents, reaching temperatures of up to 8300 K and achieving a heat flux of 2.7MW/m². Similarly, in the ICP wind tunnel, the gas is heated by Joule heating through a high-frequency induction electric field, producing a heat flux of 1.8MW/m². Both wind tunnels ensure that the flow remains uncontaminated and clean, making them ideal for catalytic effect research without the risk of contamination from metal electrodes or arc heaters. The gas supply system for these wind tunnels delivers the working gas to both the arc heater and the plasma torch via a pressure regulation system. This system includes two groups of 20 gas cylinders, each with a volume of 7 m³, ensuring a steady and regulated supply of gas. These wind tunnels can create high-enthalpy conditions for re-entry vehicles and are used for the heating testing of TPS for re-entry vehicle. Specifications of arc-heated and ICP are shown below.

Table 10. JAXA's plasma wind tunnel facilities for ablation tests

	750kW Arc-heated Wind Tunnel	110kW ICP-heated Wind Tunnel
Type	Segmented arc-heater	Inductively coupled plasma heater
Enthalpy	Up to around 30MJ/kg	Up to around 20MJ/kg
Max heat flux	2.7 MW/m²	1.8 MW/m²
Speed	Uptp Mach 4.8	Subsonic

Power conditions for the arc heater are supplied by an arc-heater facility operating at AC 3300V, 3-phase, 3-wire type, and 50 Hz, with a capacity of up to 2,000 kW and a maximum current of 1,000 A. The cylindrical test chamber, with dimensions of 1.6 m in diameter and 1.4 m in length, features an arm-type sample injection system, a 3D traverse-type pitot tube, and a heat flux sensor. These are used for various experimental works, along with an optical window for infrared image observation and model surface temperature measurement. High-temperature gas generated in the test chamber is continuously exhausted by the vacuum pump system. This system includes three mechanical booster pumps at the upstream position and four rotary pumps downstream, with a total capacity of approximately 100,000 m³/h, operating within a pressure range of 1.3 Pa to 13 kPa. To maintain optimal conditions, the facility is cooled by circulating cooling water.

2.3.4.7 PlasmaSonic (TEKNA, Canada)

Tekna [66] has three primary high enthalpy ground testing facilities for high enthalpy material testing: Induction Plasma Heater, Huels Plasma Heater, and Segmented Plasma Heater.

The PlasmaSonic - ICPT provides a high-purity plasma discharge, for studying the surface catalytic effects of TPS. The ICPT system ensures high plasma stability and uniform flow, making it suitable for simulating high-altitude conditions at hypersonic speeds. Additionally, erosion testing is facilitated by introducing powder into the centre of the plasma jet. Tekna's ICPT operates within a power range of 15 kW to 2 MW, using an RF generator (2-5 MHz), and supports various gases such as Ar, O_2, N_2, Air, H2, and CO_2. The torch operates at pressures of 5 bar or higher, with torch enthalpies between 3 and 35 MJ/kg, and an operation time of few hours. The chamber pressure can be adjusted from 5 to 1000 mbar. Specific capabilities include a minimum torch enthalpy of 3 MJ/kg and maximum torch enthalpies of 12 MJ/kg at 5 bar, 16 MJ/kg at 1 bar, and 35 MJ/kg at 0.3 bar. The system accommodates test samples ranging from 8 to 50 mm in diameter, with a heat flux capability of up to 20 MW/m² and stagnation pressures ranging from 50 mbar to 3.5 bar.

The PlasmaSonic - Segmented Arc Plasma Technology (SPT) is another plasma tunnel developed by Tekna for hypersonic material testing. It uses a fixed electrical arc length with arc rotation at both electrodes ensured by an electromagnetic field, this system employs cold copper electrodes, available in either dual or single configurations. The SPT guarantees high plasma stability and uniform flow, critical for simulating hypersonic conditions at low altitudes. Operating at a maximum power of 10 MW with a DC generator, it supports various gases including air, O_2, N_2, and CO_2. The torch pressure is up to 30 bar or higher and enthalpy ranging from 5 to 25 MJ/kg, with capabilities reaching 12 MJ/kg at 20 bar and 25 MJ/kg at 4 bar. The system's chamber pressure can be adjusted between 10 and 1000 mbar, accommodating test sample sizes from 10 to 55 mm in diameter. Additionally, it can measure a heat flux of up to 50 MW/m² and stagnation pressures of up to 8.5 bar, to replicate extreme aerodynamic conditions.

The PlasmaSonic - Huels Plasma Technology (HPT) is designed to simulate intermediate altitude conditions at hypersonic speeds. This system generates an electrical arc between a cathode and anode, with arc rotation ensured by an electromagnetic field and gas vortex. It uses cold copper electrodes; the HPT delivers high stagnation pressure and medium enthalpy. HPT operates across a power range from 200 kW to 10 MW with a DC generator, supporting gases such as Air, O_2, N_2, and CO_2. The torch operates at pressures of 30 bar or higher, with torch enthalpies ranging from 5 to 20 MJ/kg, and can function for durations from minutes to hours.

2.3.4.8 High-enthalpy Plasma Wind Tunnel, (Chonbuk National University, S. Korea)

High-enthalpy plasma wind tunnels with power levels of 0.4 MW and 2.4M W have been developed at Chonbuk National University to study TPS materials under high-temperature environments [67]. Despite their power differences, both facilities share a common design architecture.

The core components include a segmented arc plasma torch, a test chamber equipped for sample manipulation, a diffuser, a removable section, a heat exchanger, and vacuum equipment (see Figure 14). The diffuser channels the supersonic plasma flow directly into the exhaust, preventing recirculation within the test chamber. This design, incorporating a middle cone section, homogenizes the gas flow and ensures a uniform temperature profile for optimal heat exchanger performance. The linear arrangement of the reactors, diffuser, and heat exchanger delivers optimized efficiency, long operational time and a supersonic plasma flow with enthalpy exceeding 10 MJ/kg (0.4 MW system) and 20 MJ/kg (2.4 MW system). This setup produces heat fluxes surpassing 10 MW/m², providing a crucial environment for evaluating thermal protection materials.

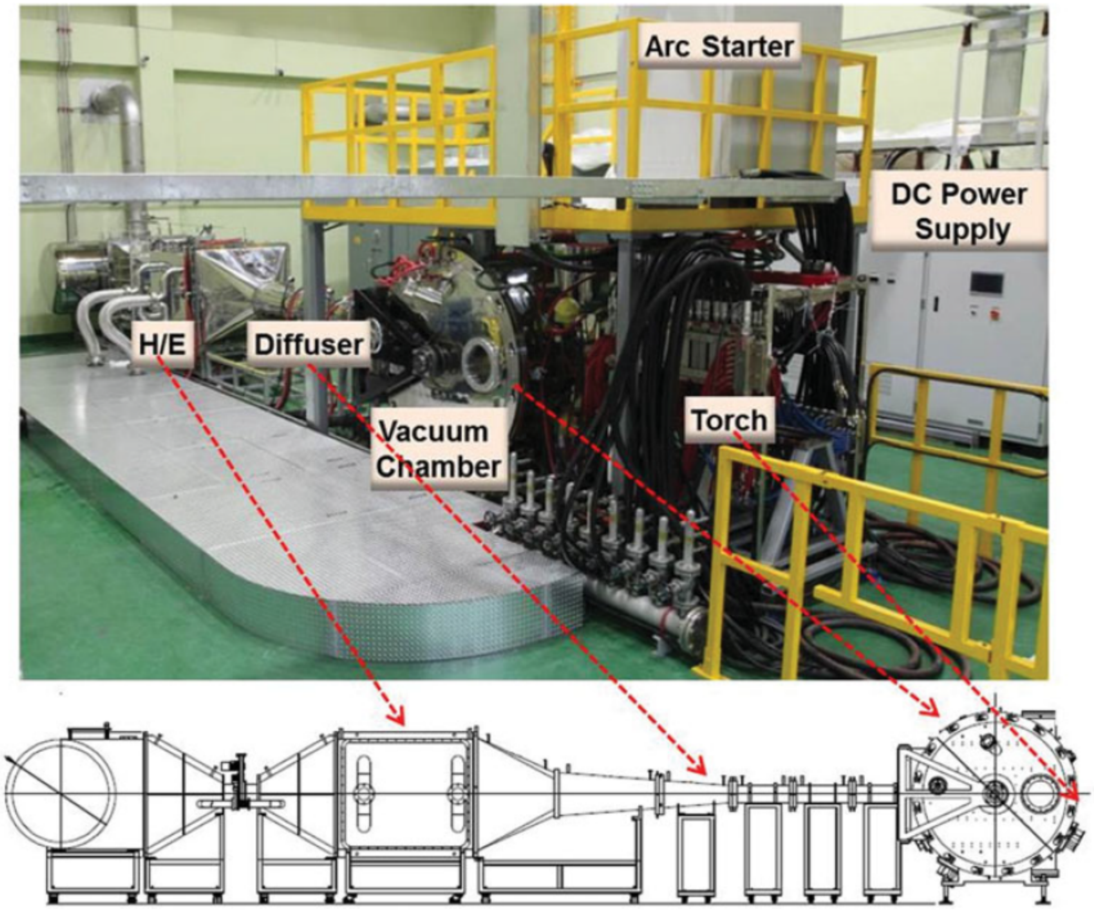


Figure 14. Layout of the 2.4 MW plasma tunnel [67].

The core of the plasma wind tunnels is the segmented arc plasma torch, which comprises a dual anode, convergent and divergent sections, constrictor disks, and a dual cathode. The electric arc is generated between ring-type electrodes made of oxygen-free copper. Metallic tubular disks, electrically isolated and independently cooled, maintain optimal arc column spacing. The number of constrictor packs can be adjusted to regulate enthalpy levels. High-velocity gas injection between torch segments creates a swirling pattern, stabilizing the arc. Integrated permanent magnets produce an axial magnetic field, mitigating electrode erosion and inducing arc rotation.

The stainless-steel test chamber, featuring a water-cooled double wall, is configured for diverse material testing and plasma diagnostics. Dimensions vary between the two systems: 1.6 m by 2.6 m for the 0.4 MW tunnel and 1.8 m by 2.2 m for the 2.4 MW. A versatile substrate manipulation system enables precise sample positioning within the chamber. Four water-cooled arms, designed to install heat flux probes, enthalpy probes, and test materials. Diagnostic capabilities include both intrusive methods (enthalpy and heat flux probes) and non-intrusive techniques (pyrometry, high-speed imaging, optical emission spectroscopy, and laser Thomson scattering).

2.3.4.9 IPG-x (IPM, Russia)

Two plasmatrons, IPG-3 and IPG-4, are in operation in the Laboratory for Plasma/Surface Interaction (IPM), Russia [68] [69], for material testing under extreme conditions.

The IPG-3 plasmatron of 1 MW class is the most powerful facility in the IPG series. It was specifically developed for testing full-scale TPS and simulating hypersonic vehicles. The facility uses high-enthalpy air flows to test large-scale thermal protection materials and elements (150-500 mm), including ceramic tiles, manhole covers with windows, and carbon-carbon structures with antioxidative coatings. This facility can be used to test materials to up to 1523 K and numerous cycles to evaluate their durability and performance under realistic re-entry conditions.

The IPG-3's design features a discharge channel with a diameter of 1200 mm, divided into two chambers of low and atmospheric pressure by a thick flange. The facility can generate gas temperatures between 7000 and 11000 K, and its high-enthalpy air jets can reach velocities between 500 and 1100 m/s. The total enthalpy of the jet ranges from 10 to 40 MJ/kg, with pressures varying from 0.01 to 0.3 atm. The heat flux to the test models can range from 10 to 1000 W/cm², with a Reynolds number of 50-150.

The IPG-4 plasmatron represents a significant technological advancement over its predecessors, designed to meet modern requirements for experimental high-temperature gas dynamics. Unlike previous models, the IPG-4 can generate stable high-enthalpy jets within a pressure range of 0.01-1.0 atm while maintaining constant gas enthalpy. This capability allows for the simulation of hypersonic vehicle trajectory parameters more accurately, enabling studies of non-equilibrium heat transfer and surface catalysis in various dissociated gases.

The IPG-4's discharge channel has a diameter of 800 mm and features a small inductor chamber to maintain atmospheric pressure around the inductor. The facility can produce gas temperatures from 4500 to 10500 K, with velocities ranging from 20 to 950 m/s. The total enthalpy of the jets is consistent with the IPG-3, at 10 to 40 MJ/kg, but the IPG-4 operates at a higher efficiency range of 40 ~ 64%. The heat flux can reach 15 to 600 W/cm², and the Reynolds number ranges from 50 to 200. The working gas for IPG-4 plasmatrons include Air, N_2, O_2, CO_2, and Ar, with an anode power range of 12 ~ 76 kW and a flow rate of 2 ~ 6 g/s. The facility's ability to regulate pressure and enthalpy smoothly makes it useful for extensive re-entry material testing, including the study of catalytic properties and thermochemical stability of TPS materials.

2.3.4.10 Plasma Wind Tunnel (CARDC, China)

A 1 MW high-frequency plasma wind tunnel is developed at the Aerodynamics Research and Development Center (CARDC) in China. The wind tunnel comprises a high-frequency power supply, plasma generation system, nozzle, test chamber, diffuser, cooling system, vacuum system, and associated water, power, air supply, and monitoring systems. It features a large silica tube encased in a copper induction coil, where dry air at several kPa is transformed into plasma. The generated plasma is accelerated by a nozzle and used to ablate samples, with the assistance of an evacuation pump. A schematic view is presented in Figure 15. This high-enthalpy wind tunnel operates at sub-atmospheric pressure and can produce flow speeds ranging from 0.5 Mach to 2 Mach by adjusting the nozzle. It allows continuous operation for up to an hour. The stagnation pressure is measured with a Pitot tube, with an accuracy within ±2%, while the cold-wall heat flux is recorded using a sample-size slug calorimeter. The atmospheric composition can be adjusted by controlling the gas pressure ratios, and the flow enthalpy is calculated from the stagnation pressure and heat flux measurements.

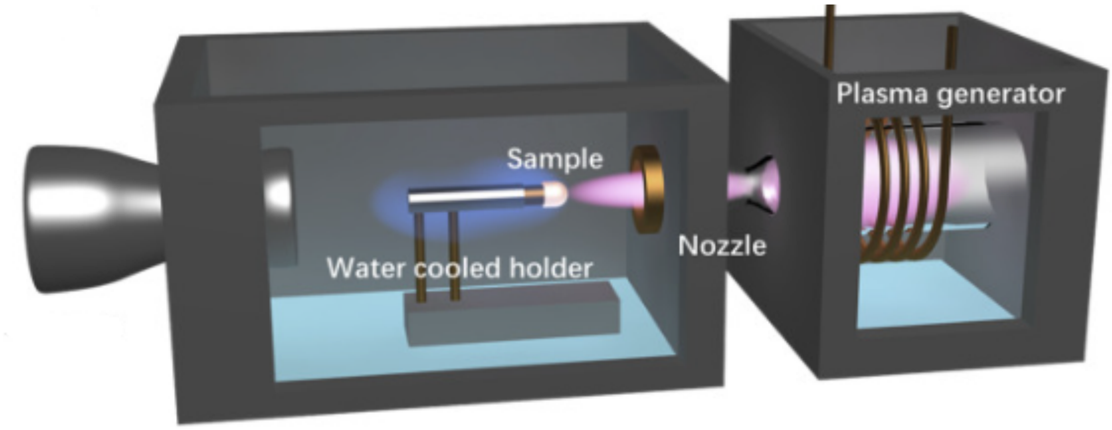


Figure 15. Schematic view of the plasma tunnel in CARDC, China [70]

2.3.4.11 IHF (NASA Ames, USA)

The Interaction Heating Facility (IHF) at NASA Ames (shown in Figure 16) uses a segmented type arc heater with multiple ring electrodes on either end of the heater. The heater operates off the 60-MW power supply; however, the typical maximum operating power is approximately 45 MW. The facility uses argon shield gas over the electrodes to help with arc attachment on the electrodes. The facility uses air or nitrogen as test gas and can sustain test durations of up to 60 minutes. The IHF features various nozzle exits, including conical shapes with diameters ranging from 152 mm to 1041 mm, and a semi-elliptical shape measuring 203 mm by 813 mm. It supports different test article types such as stagnation point articles up to 380 mm in diameter and wedge or flat plates up to 610 mm x 610 mm. The IHF can achieve bulk enthalpy levels between 2 to 28 MJ/kg and surface pressures ranging from 1 kPa to 155 kPa. It supports flow rates from 0.03 kg/s to 1.7 kg/s and heating rates between 250 kW/m² and 20,000 kW/m². Instrumentation includes thermocouples, IR pyrometry, and radiometry for hot wall temperature measurements; Pitot and static pressure sensors; calorimetric probes for cold wall heat flux; and optical diagnostics such as optical emission spectroscopy, laser-induced fluorescence, and photogrammetric ablation rate measurements. The facility has been instrumental in testing and validating TPS materials and designs for various NASA missions, providing a critical environment to replicate the extreme conditions of hypersonic flight.

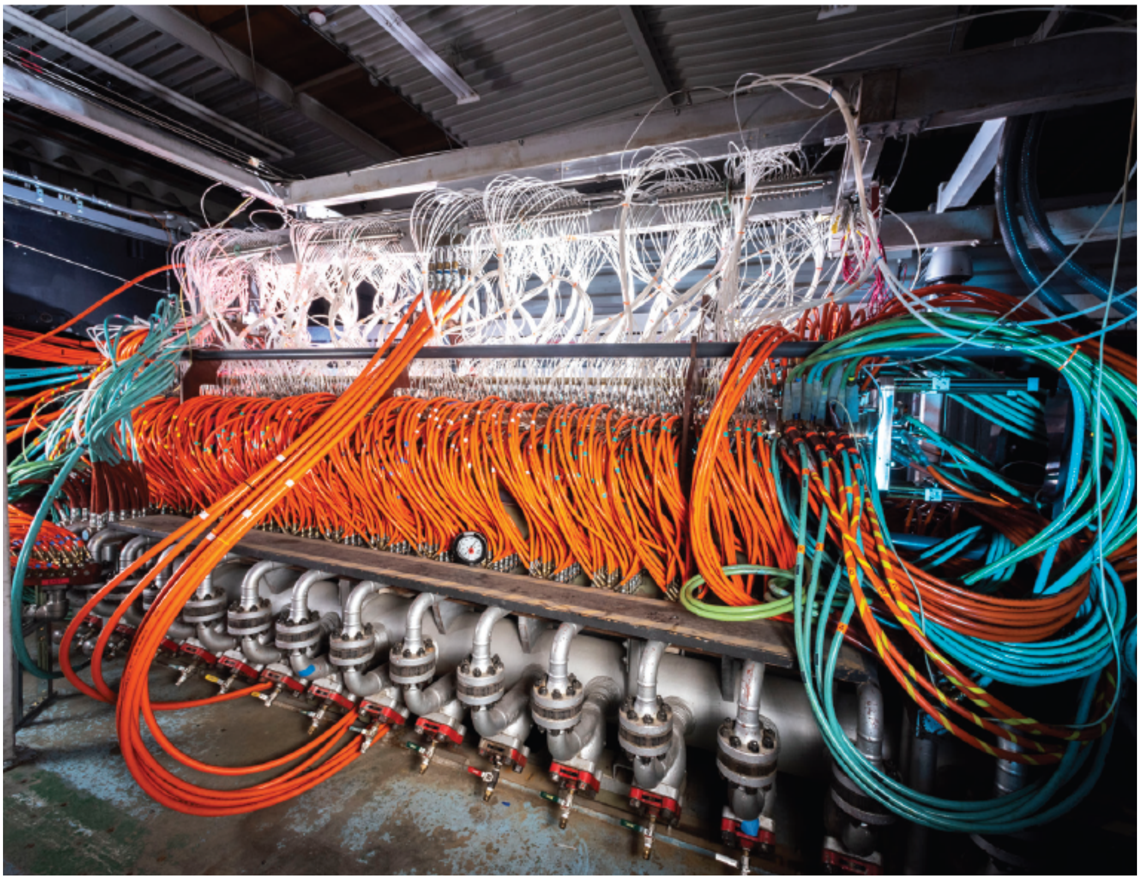


Figure 16. Segmented arch heater in the IHF [71].

2.3.4.12 AHF (NASA Ames, USA)

The Aerodynamic Heating Facility (AHF) at NASA Ames, shown in Figure 17, is a versatile arc jet testing environment equipped with either two 20 MW arc heaters paired with various conical nozzles or a 10 MW arc heater with its own set of conical nozzles. The segmented arc heaters operate at reservoir pressures between 0.1 MPa and 1 MPa and achieve enthalpy levels in air ranging from 5 to 28 MJ/kg. The Huels arc heater, on the other hand, functions at pressures from 0.1 MPa to 1.7 MPa and provides enthalpy levels between 3.5 MJ/kg and 9.3 MJ/kg. Due to high enthalpy levels, consistent performance, and minimal contamination, the segmented arc heaters are primarily used for testing.

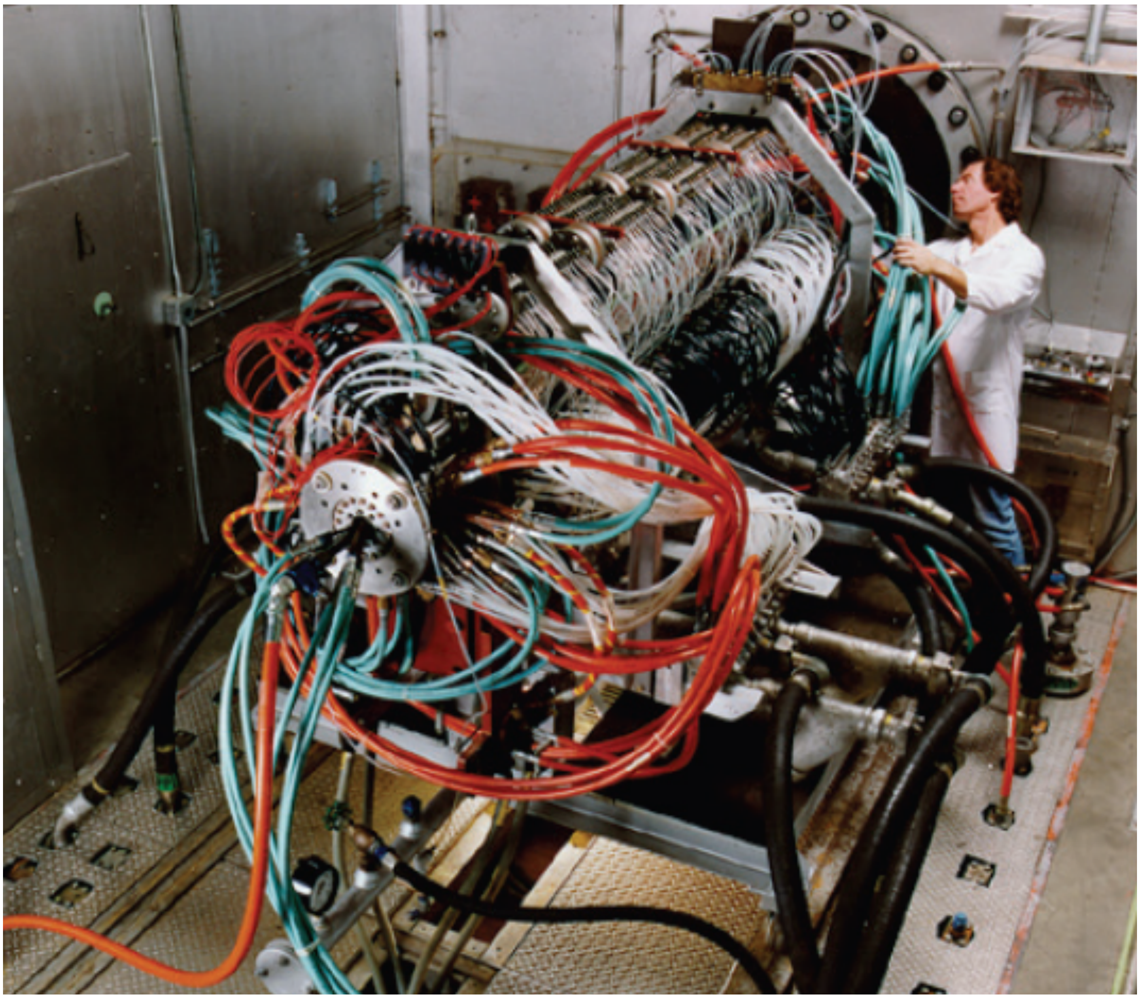


Figure 17. 20 MW AHF segmented arc heater [71].

The 20 MW arc heaters can use air, nitrogen, or argon as test gases and can be fitted with a family of 8-degree half-angle conical nozzles with exit diameters ranging from 18 cm to 91 cm. Each nozzle has interchangeable throats with diameters of 2.5 cm or 3.8 cm, and the Huels heater includes an additional 5.1 cm diameter throat. The high-temperature gas flows are directed into a 2 × 2 × 3-meter test chamber, where the flow is captured by a 150 cm diameter diffuser before passing through a heat exchanger into the steam-ejector vacuum system. The static pressure in the cabin can be adjusted between 10 Pa to 1000 Pa, depending on mass flow and pumping rates. Test specimens are subjected to high-temperature plasma within the test chamber in an open jet between the nozzle exit and the diffuser entrance. The chamber contains two model support mechanisms: a five-arm, floor-mounted carriage and an overhead swing-arm sting, accommodating either stagnation point or wedge-shaped configurations. Water cooling is provided for temperature management, and diagnostic equipment is readily accessible via internal patch panels. Optical ports on the sides and ceiling allow imaging of the test articles and plasma stream. The AHF allows run durations of up to 30 minutes, with a 45-minute cool-down period between runs.

2.3.4.13 TP-x (NASA JSC, USA)

The Johnson Space Center (JSC) operates two primary test bays (shown in Figure 18), both equipped with vacuum systems and shared support infrastructure including power, cooling, gas supply, and vacuum generation systems. These bays share a common infrastructure that includes a 10 MW power supply, but, both facilities generally operate at power levels between 5 and 6 MW. Both test bays house segmented arc heaters, employing a tungsten cathode and copper anode configuration. A mixture of nitrogen and oxygen, with variable proportions, serves as the test gas. Argon is not used as an electrode shield.

Figure 18. Picture of TP-1 (left) and TP-2 (right) [72].

The TP-1 facility is uniquely designed as a channel-flow facility, featuring a 51 mm wide channel and three test locations along a 10-degree half-angle nozzle. The test locations can handle sample sizes of 203 mm by 254 mm, 305 mm by 305 mm, and 610 mm by 610 mm, with each sample integrated into the nozzle side wall. To enhance testing capabilities, a new 102 × 102mm, 10-degree duct has been developed to produce higher heat fluxes, pressures, and shear stresses compared to the existing 203 × 254 mm test section. The opposing side wall of the test channel can be equipped with pressure and heat flux gauges or heated for radiant heating, but there is no optical access to the test sample.

The TP-2 facility employs a series of 15-degree half-angle conical nozzles with exit diameters ranging from 127 mm to 1016 mm. The spacious 3.66 m test chamber enables video and optical temperature measurements. Equipped with two hydraulically controlled sting arms, the facility can support models weighing up to 227 kg. It can test both stagnation point and shear-type models such as wedge-shaped models. The model size is dependent on the nozzle exit diameter, with standard wedge configurations available in sizes of 114 mm by 127 mm, 152 mm by 152 mm, 305 mm by 305 mm, and 610 mm by 610 mm.

2.3.4.14 HEAT-x (Arnold Engineering Development Center, USA)

The HEAT-H1 test unit is an advanced facility designed to replicate the extreme conditions experienced by hypersonic vehicles. The schematic view is shown in Figure 19. It generates high-pressure, high-enthalpy environments to evaluate the performance of TPS materials, nose tips, and structural components under intense heating and aerodynamic forces. A segmented arc heater, operating at approximately 20,000 V and 1,200 A, produces high-temperature air at pressures up to 120 atm. This air is expanded into a supersonic-free jet within the test chamber. The centreline enthalpy is determined through measurements of stagnation point heat flux on calibration probes and Pitot pressures, can be adjusted between 1000 and 2326 to 19,737 kJ/kg. To enhance test flexibility, a mixing chamber with cold air can be introduced to modify flow properties, such as enthalpy and Reynolds number.

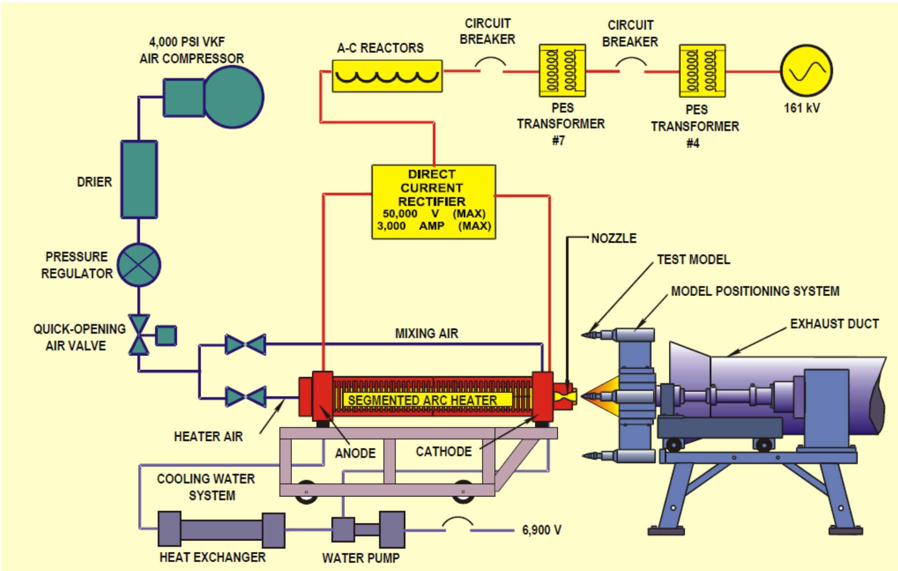


Figure 19. Schematics of H1 acr-heater [73].

The test unit features a sophisticated model injection system capable of accurately positioning test articles within the high-enthalpy flow. This system allows for precise control of model exposure time, position, and orientation. A variety of interchangeable nozzles provide flexibility in tailoring test conditions to specific requirements. Diagnostic tools, including transient calibration probes, are used to characterize the flow field and monitor test parameters. The HEAT-H1 facility shares essential utilities, such as a 70-megawatt power supply, cooling water, and high-pressure air, with other test units within the complex.

The HEAT-H2 facility, shown in Figure 20, is a specialized wind tunnel designed to generate high-temperature, high-pressure airflows capable of simulating the aerodynamic environment encountered by vehicles at pressure altitudes between 21 and 49 km. At its core is an N-4 Huels-type arc heater, which produces a superheated gas that is subsequently expanded through a hypersonic nozzle into a sub-atmospheric test chamber. This configuration, coupled with advanced exhaust systems, enables the generation of high enthalpy flows at Mach numbers ranging from 5 to 9.4. To tailor the flow characteristics to specific test requirements, the distribution of injected air can be carefully controlled to optimize enthalpy across the test section. The facility is capable of sustained operation for periods exceeding 30 minutes under specific conditions. A four-strut model positioning system allows for the precise placement of test articles and diagnostic instrumentation within the high-speed airflow.

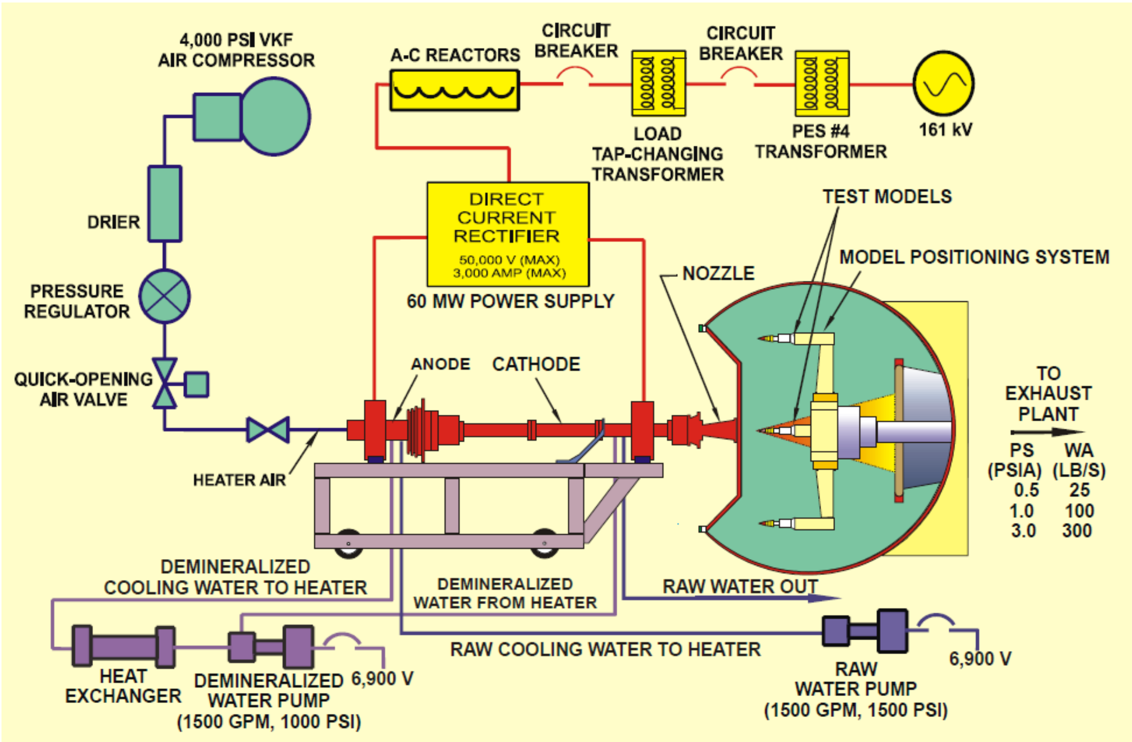


Figure 20. Schematics of H2 arc-heated tunnel [73].

The HEAT-H3 tunnel is an arc heater tunnel, which is a fifty per cent geometric enlargement of the existing H1 segmented arc heater and operate at 2.25 times the power of the H1. The heater plenum is designed as a 76 mm bore and a 114 mm electrode diameter, pressure vessels for up to 200 atm, though operational limits are set at 150 atm. Since its inception in 1995, H3 has undergone rigorous testing to validate its design and capabilities. The arc jet facility was successful in running up to the power level 70 MW. A table summarizing the key parameters of the H1, H2, and H3 arc heater facilities is presented in Table 11.

Table 11. AEDC arc facilities specifications [73]

Facility Name	Facility Type	Max. Run Time (min)	Nozzle Mach No.	Nozzle Exit Diameter (cm)	Stagnation Pressure (atm)	Stagnation Enthalpy (kJ/kg)	Mass Flow Rate (kg/sec)
HEAT-H1	Atmospheric Exhaust, Freejet	Up to 2	1.8 to 3.5	2.0 to 7.5	Up to 90	1400 to 20,000	0.2 to 3.6
HEAT-H2	Sub-Atmospheric Freejet	Up to 30	3.4 to 8.3	13.0 to 107	Up to 10	2750 to 15,000	1.0 to 4.5
HEAT-H3	Atmospheric Exhaust, Freejet	Up to 2	1.8 to 3.5	3.0 to 12.7	Up to 90	1400 to 20,000	1.4 to 8.0

2.3.4.15 CHESS (UIUC, USA)

The Center for Hypersonics and Entry Systems Studies (CHESS) Plasmatron is a high-power induction plasma wind tunnel, was designed and constructed by Tekna Plasma Systems Inc. to meet the requirements of the CHESS roadmap [74]. The roadmap outlines a critical need for advanced materials testing under extreme thermal conditions in high-purity, well-characterized plasma flow, surpassing the capabilities of existing infrastructure, scalable and affordable operation capabilities and a comprehensive set of methods, tools, diagnostics, and uncertainty quantification.

The system constitutes a 350-kW high-power radio frequency power supply operating at a nominal frequency of 2.1 MHz. This power is channelled through a tank circuit to the PN-100 induction plasma torch, featuring a 100 mm internal diameter. The torch's modular design enhances flexibility. A central core houses the induction coil, surrounded by a water-cooled ceramic tube for plasma containment. Gas and coolant distribution systems are integrated into the torch's rear, while the torch exit is adaptable to accommodate various exit-side torch nozzles. The test section is equipped with a versatile carousel-style sample manipulator, enabling precise positioning of test specimens or instrumentation within the plasma stream. Operating parameters for the plasmatron include a maximum input power of 350 kW, a plasma gas flow rate ranging from 15 to 60 g/s, and the capability to utilize a variety of gases including argon, nitrogen, oxygen, and carbon dioxide. The system can achieve internal pressures between 30 and 400 kPa, generating plasma with specific enthalpies exceeding 2.8 MJ/kg, with a maximum of 12 to 31 MJ/kg depending on operating pressure.

2.3.4.16 ICP (University of Vermont, USA)

The University of Vermont (UVM) ICP torch facility is capable of generating chemically pure plasmas of air, N_2, O_2, CO_2, and Ar, as well as their mixtures [75]. The plasma jet, constrained by a 36 mm inner diameter quartz tube, operates at a normal pressure of 21 kPa. In the induction zone, the plasma reaches temperatures exceeding 10,000 K, before exiting the tube as a free jet that gradually cools towards a local thermodynamic equilibrium state. Upon reaching the test section, the plasma temperature stabilizes between 5,000 and 6,000 K.

A schematic view of this tunnel is presented in Figure 21. The facility comprises a 30 kW radio frequency (RF) power supply, a gas injection system, a quartz tube, a test chamber, a cooling system, and a vacuum pump. These systems function concurrently to produce a stable and controlled plasma jet. Initially, test gas at room temperature is routed through the injector block, directed through an annulus into the inner diameter quartz tube. The annulus generates a recirculating flow within the tube, promoting coupling and cooling the tube to prevent melting. A water-cooled copper induction coil, encircling the quartz tube, carries the alternating RF current from the power supply. This alternating current creates an alternating magnetic field, heating and ionizing the test gas to form the plasma ball inside the tube. The plasma then flows up the tube and into the pressure-controlled stainless steel test chamber. Finally, the gas passes through a heat exchanger before being routed through the main vacuum pump and expelled from the lab. Key operating parameters include a maximum power of 30 kW, operating pressures between 13 to 26 kPa, stagnation heat flux ranging from 10 to 150 W/cm², and a Mach range of 0.3 to 1.4. The operating frequency spans from 2 to 3 MHz.

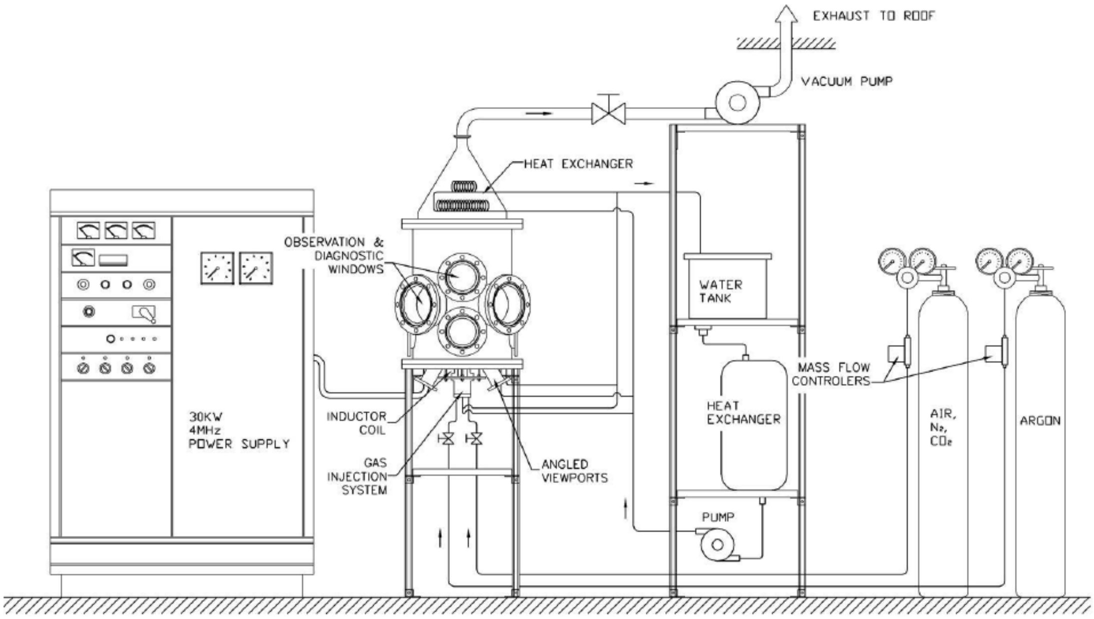


Figure 21. Schematics of the UVM-ICP Torch [75].

2.3.4.17 LCAT (Boeing, USA)

The Boeing Large Core Arc Tunnel (LCAT) facility, situated in St. Louis, Missouri, employs a Huels arc heater and a pumped test chamber to replicate the hypersonic aerothermal environment. The facility is equipped with optical viewing ports for capturing video, still images, and thermal data through pyrometry and infrared cameras.

The Boeing arc jet complex comprises two test facilities: one is a free jet to the atmosphere, and the other features vacuum exhaust capability. The LCAT facility features a vacuum-capable test bay and is powered by a 12 MW power supply. Equipped with a Huels arc heater, the LCAT incorporates a rotary model injection system capable of accommodating up to four models per test, although typically limited to three. A versatile nozzle system includes three conical options with exit diameters of 10.2 cm, 15.2 cm and 30.4 cm. Additionally, the LCAT facility includes a square nozzle and a semi-elliptic nozzle.

2.3.4.18 TAG (Ariane group, France)

Ariane group Space Transportation operates five Thermal Arc Generation (TAG) ground testing facilities [76], each offering distinct capabilities to accommodate a wide range of operating conditions. The specifications for four of these facilities; COMETEE, SIMOUN, GSHE, and JP-200 [74].

COMETEE can provide a wide range of stagnation heat fluxes with appropriate torch nozzles. SIMOUN is suitable for air, nitrogen, and carbon dioxide plasmas, offering flexibility in adjusting stagnation pressures and enthalpies. The facility incorporates diverse nozzle configurations to suit various testing needs. GSHE is designed for new project demonstrations with high mass flow rates and arc currents. JP-200 is built for ballistic missile testing with high internal pressures and short run times. Some important specifications of these facilities are presented in Table 12.

Table 12. Details of Ground Test Facilities at Ariane group, France

Facility	Type	Power (MW)	Gas	Pressure Range (kPa)	Enthalpy (MJ/kg)	Stagnation Heat Flux (MW/m²)	Test Duration (s)
COMETEE	Low-pressure, open discharge, inductively coupled	0.11	Air	3-50	8	0.1-3 Possibility of increasing up to 7-8	1800
SIMOUN (Stagnation point)	Huels-type, Mach 4.5	6	Air, N_2, CO_2	5-20 can be extended to 20 - 50	4-14	0.7 – 2.5	< 60
SIMOUN (flat plate and wedge)	Huels-type, Mach 5	6	Air, N_2, CO_2	0.3 - 18	4 – 14	0.02 – 1.6	< 60
GSHE	Segmented TAG	18	Air	1000-17000	5-20	N/A	< 60
JP-200	Huels-type	20	Air	7000	6-12	N/A	< 60

2.3.5 Challenges in Ground Tesging Facilities

Hypersonic blow-down tunnels offer to study flow characteristics, but their short test duration limits material testing. Plasma tunnels address this limitation by achieving specific enthalpy, stagnation pressure, and temperature that re-entry vehicles experience over an extended period. This section reviewed the existing plasma facilities, highlighting two main types of plasma wind tunnels developed globally: DC-powered thermal arc tunnels and inductively coupled plasma (ICP) tunnels. Unfortunately, the electrodes in arc-type tunnels can erode and vaporize, contaminating the plasma flow with metal vapours. Even small amounts of these metal vapours can significantly affect the thermal conductivity of plasma, leading to a higher heat flux on the test sample than would occur under non-contaminated conditions during actual re-entry. While ICP tunnels generate non-contaminated plasma, most are limited to subsonic speeds.

Plasma tunnels and actual re-entry environments differ significantly in their plasma generation processes. In re-entry, high-speed vehicles create shockwaves that ionize the surrounding air, forming a plasma, whereas plasma tunnels generate plasma through electrical energy before accelerating the gas. While the re-entry conditions are achieved on plasma tunnels, they cannot fully replicate the shock-induced ionization of re-entry or the real gas effects. Moreover, building a plasma facility demands a substantial initial investment and maintaining and operating a plasma tunnel can be expensive due to high energy consumption and specialized equipment requirements.

2.4 Measurement and Diagnostics

Accurate characterization of flow fields is very crucial in hypersonic flows and the measurement techniques can be broadly categorized into two primary groups: intrusive and non-intrusive [77]. Intrusive methods involve the insertion of physical probes or sensors into the flow to obtain data. Examples of intrusive probes include pitot tubes, total temperature probes, static pressure tubes, etc. While these techniques have been refined over several decades and can provide valuable insights, they inherently disturb the flow field, potentially affecting measurement accuracy. On the other hand, non-intrusive techniques rely on remote sensing to gather information without physically interacting with the flow.

However, it is important to note that while non-intrusive techniques offer advantages in terms of flow disturbance, present challenges such as high costs, complex data analysis, limited resolution, sensitivity to environmental factors, and dependence on specific flow conditions. This section discusses different flow measurements of flow measurement techniques used in flow measurements, with a particular focus on non-intrusive methods.

2.4.1 Intrusive Techniques

Even today, flow characteristics in some wind tunnels are measured using traditional probes like Pitot tubes and thermocouples. These instruments have proven invaluable in capturing mean flow properties and providing insights into coherent structures. Despite their advancements in reliability and low cost to justify their use, their intrusive nature raises concerns due to flow disturbance, measuring shear layers in separated flows or operating in transonic conditions. Additionally, the necessary supports for probe stability can introduce significant blockage, distorting the intended pressure distribution. Some of the intrusive techniques are explained here.

2.4.1.1 Pitot probe

A Pitot probe is a simple yet effective instrument for measuring stagnation pressure. It consists of a tube with an orifice facing the oncoming flow. As the fluid is brought to rest at the probe's tip, its kinetic energy is converted into pressure. The resulting pressure is recorded using a transducer connected to the probe and is used to determine various flow characteristics such as velocity and Mach number. At high Mach numbers, the Pitot probe encounters a bow shock. The measurement of stagnation pressure downstream of this strong shock can be used to determine the local Mach number using normal shock relations. However, the accuracy of Pitot probe measurements in hypersonic conditions is affected by shock wave interference, probe geometry, local heat transfer and boundary layer effects.

2.4.1.2 Total Temperature Probes

There are two types of total temperature probes: Shielded and Unshielded. Unshielded total temperature probes are the simplest form of these instruments. They typically consist of a small thermocouple mounted within a supporting tube. When placed within a flowing fluid, the fluid is brought to rest (stagnated) at the thermocouple junction due to the probe's shape. This stagnation point results in the conversion of fluid kinetic energy to thermal energy, increasing its temperature to the total temperature. However, there are significant challenges in accurately measuring the total temperature using an unshielded probe. The thermocouple can lose heat to the surrounding environment through conduction along the probe's support tube and through radiation. To compensate for these losses, a calibration process is typically performed in a known freestream condition before the actual measurement. This calibration allows to determine the correction factors to be applied to the measured temperature to obtain the true total temperature. Shielded probes incorporate a protective shield around the thermocouple. The primary purpose of the shield is to minimize radiation heat losses. As the shield is exposed to the flow, it quickly reaches a temperature close to the total temperature, reducing radiation losses. However, shielded probes introduce new challenges. The boundary layer that develops within the shield can affect the temperature measurement. This effect needs to be carefully considered and corrected in the data analysis.

2.4.1.3 Enthalpy Probe

An enthalpy probe is a double-walled tube designed to extract gas from a high-temperature environment in the central tube to determine enthalpy and a cooling fluid circulates through the outer shell to prevent overheating. The gas extracted through the central probe tube is subjected to vacuum pumping before being introduced to a mass flow controller. A portion of this gas stream is further sampled and directed to a quadrupole mass spectrometer for compositional analysis. This technique works on a two-step energy balance. The first step is a measurement of the heat load to the probe in the absence of gas sampling conditions (tare measurement). In the second step, the heat load is measured during gas extraction. The energy difference between these two states is associated with the extracted gas sample. By correlating this energy with the gas mass flow, as measured by a mass flow controller, the specific enthalpy of the gas can be calculated.

2.4.2 Non-Intrusive Techniques

Non-intrusive measurement techniques are based on optical methods and offer significant advantages over intrusive measurements but also come with limitations. The primary challenges include the need for clear visual access to the experimental area and the ability to effectively guide light or lasers for sufficient illumination. This often requires redesigning the experimental setup with large, high-quality optical windows. For applications using invisible light, such as infrared light, special materials such as quartz or zinc selenide are necessary for window design. Additionally, factors like focal length, mechanical vibrations, and optical aberrations can restrict the use of these techniques, especially in high-speed testing environments. One of the main advantages is that non-intrusive techniques do not create flow disturbances, enabling precise measurements in a hypersonic environment. Additionally, they often provide high-speed data acquisition capabilities. Even though they are expensive, many modern-day tunnels are equipped with non-intrusive techniques such as optical emission spectroscopy, Raman scattering, laser-induced fluorescence, etc [78].

2.4.2.1 Optical Emission Spectroscopy (OES)

OES is a technique that capitalizes on the naturally emitted light from a hypersonic flow. It does not require an external light source, which simplifies the experimental setup. OES presents an often-simple experimental method to access the thermochemical state of emitting gases. By dispersing the emitted light, this non-intrusive technique offers quantitative data on properties such as temperature, pressure, and species information. Moreover, if properly calibrated, OES can also provide quantitative information on electronic, vibrational, or rotational excited states. However, its application is limited to environments where the flow is sufficiently luminous. Furthermore, OES tends to average the emitted light along the optical path, which makes it difficult to determine the spatial information of properties and reduce the resolution of the measurements.

2.4.2.2 Absorption Spectroscopy

Absorption spectroscopy analyses the amount of light absorbed by a sample as light passes through it. By comparing the intensity of light transmitted through the sample to a reference, the technique quantifies the sample's absorption along the optical path, thus providing detailed quantitative data about species concentration and temperature. The non-intrusive nature of this technique makes it suitable for studying hypersonic flows without disturbing the flow field. However, like OES, absorption spectroscopy averages the data over the light path, which may result in the loss of localized information. Additionally, the technique requires precise alignment between the light source and detector, which can be challenging, especially in the harsh environments typical of hypersonic facilities.

2.4.2.3 Rayleigh Scattering

Rayleigh Scattering involves detecting the light that is elastically scattered by gas molecules. Unlike OES and absorption spectroscopy, Rayleigh scattering offers spatially localized measurements, which helps to avoid the pitfalls of path-averaged data. This technique is versatile and can be applied in various flow conditions, making it a valuable tool for hypersonic flow diagnostics. However, the signal from Rayleigh scattering is often weak, necessitating highly sensitive detection equipment. Moreover, Rayleigh scattering from different molecules cannot be distinguished spectrally, so it is not usually used to detect individual species.

2.4.2.4 Raman Scattering

Raman Scattering is based on the inelastic scattering of light, where the scattered photons experience an energy shift that provides information about the molecular vibrational and rotational states. This technique can yield detailed spectral information about the species concentration in the flow and their respective temperatures. However, the signal produced by Raman scattering is even weaker than that of Rayleigh scattering, typically three orders of magnitude smaller than Rayleigh scattering for most gases, requiring advanced detection methods. Additionally, the inelastic nature of the scattering complicates data analysis, making the interpretation of results more challenging.

2.4.2.5 Laser-Induced Fluorescence (LIF)

LIF is a highly sensitive technique that involves a two-step process: molecules first absorb photons, transitioning from a lower energy state to a higher excited state, subsequently, they return to the ground state through either the emission of a photon (fluorescence) or energy dissipation via collisions (quenching). The emitted light is detected and analysed to infer various properties of the flow. LIF is particularly advantageous due to its high sensitivity, allowing for the detection of low concentrations of species. It also offers excellent spatial and temporal resolution, making it suitable for capturing detailed flow dynamics. However, the technique requires precise tuning of the laser wavelength to match specific molecular transitions, which can complicate the setup. Additionally, LIF may suffer from interference from other fluorescent species in the flow, potentially affecting the accuracy of the measurements.

2.4.2.6 Coherent Anti-Stokes Raman Spectroscopy (CARS)

CARS is a nonlinear spectroscopic technique that utilizes multiple laser beams to interact with the flow, generating a coherent signal beam that retains its intensity over long distances. This technique offers a high signal-to-noise ratio, making it particularly useful in luminous environments where other techniques might struggle with background light interference. CARS is also relatively insensitive to flow luminosity, further enhancing its applicability in challenging conditions. However, the technique requires complex alignment of multiple laser beams, which can be difficult to achieve. The nonlinear interactions involved in CARS also make the analysis and interpretation of data more complex.

2.4.2.7 Tunable Diode Laser Absorption Spectroscopy (TDLAS)

TDLAS uses tunable diode lasers to measure absorption at specific wavelengths, enabling high-resolution detection of species concentrations and temperatures. This technique stands out for its high time resolution, making it well-suited for studying fast, transient phenomena in hypersonic flows. The diode lasers used in TDLAS are compact, robust, and capable of operating in harsh environments. However, the tunable range of these lasers is limited, restricting the range of species that can be measured. Additionally, the relatively low power output of diode lasers might limit their effectiveness in certain applications where higher power is needed.

2.4.2.8 Interferometry

Interferometry is a technique that relies on the interference of light waves to measure changes in the refractive index of a medium, which corresponds to variations in density, temperature, or composition within a flow. In hypersonic flow diagnostics, interferometry can provide precise, real-time measurements of these parameters over large areas. The main advantage of interferometry is its high sensitivity to small changes in the flow field, allowing for the detection of subtle phenomena. However, interferometry requires a highly stable setup and is sensitive to vibrations and other environmental disturbances, which can complicate its use in the dynamic environments typical of hypersonic facilities. Additionally, the technique usually provides line-integrated data, which means that information is averaged along the optical path, potentially obscuring local variations.

2.4.2.9 Background-Oriented Schlieren (BOS)

BOS is an optical technique that visualizes density gradients in a flow by observing distortions in a patterned background. Unlike traditional Schlieren photography, which requires complex optics and precise alignment, BOS uses a simple camera setup and a high-contrast background pattern. By comparing images taken with and without the flow, pixel shifts caused by refractive index gradients can be determined. While BOS offers advantages like low cost and large field of view, it requires image processing to obtain quantitative density information. For 2D flows, direct density gradient calculations are possible, but for axisymmetric or non-axisymmetric flows, more complex reconstruction techniques like tomography are needed. Although BOS provides valuable qualitative and quantitative data, its spatial resolution is limited compared to laser-sheet based methods, especially in unsteady flows. Additionally, BOS does not provide real-time visualization, as image processing is necessary to extract the desired information.

2.4.2.10 Electron-Beam Fluorescence

Electron-Beam Fluorescence involves directing a beam of high-energy electrons into a flow, where the electrons excite the molecules, causing them to emit fluorescence. This emitted light is then detected and analysed to provide information about temperature and density. Electron-Beam Fluorescence is particularly advantageous for measuring properties in very high-speed flows, including those with significant ionization. The technique can provide spatially resolved measurements. At higher pressures, several challenges arise that complicate the use of electron-beam fluorescence. Firstly, quenching becomes significant, which complicates the interpretation of concentration data and reduces the fluorescence lifetimes needed for flow tagging velocity measurements. Secondly, the electron beam tends to disperse in higher-density environments, making it difficult to obtain measurements along a line or plane. Additionally, excitation from scattered electrons increases at higher pressures, further complicating the interpretation of the resulting images. Despite these issues, electron-beam fluorescence has proven to be effective in a wide range of low-pressure hypersonic flows and even holds potential for in-flight measurements.

2.4.2.11 Degenerate Four-Wave Mixing (DFWM)

DFWM is a nonlinear optical technique that involves the interaction of three laser beams within a medium to generate a fourth beam, which carries information about the flow properties. Since DFWM is an absorption-based technique, it is insensitive to collisional quenching and can provide accurate information on species concentrations. DFWM is highly suitable for luminous flows as background radiation can be spatially filtered with an aperture. However, the technique is complex and requires precise alignment of multiple laser beams, low spatial resolution, sensitive to absorption of the laser beams, sensitive to saturation of the molecular transitions and it requires high beam quality to obtain images.

2.4.2.12 Laser-Induced Thermal Acoustics (LITA)

LITA is a four-wave mixing technique that generates acoustic waves through the interaction of two pump laser beams. A probe laser scatters off these waves, producing a detectable signal. Unlike other four-wave mixing methods, LITA primarily analyses signal intensity over time to determine flow properties. By examining the damped oscillations in the signal, the flow properties can be determined. This method offers high precision in measuring velocity and temperature, reaching accuracies on the order of 1 m/s and 1 K, respectively. However, LITA is limited to single-point measurements and requires relatively large probe volumes, which might not be ideal for all flow conditions, particularly turbulent flows.

2.4.3 Challenges in Diagnostics

This section has presented an overview of measurement techniques, with a particular focus on non-intrusive options applicable to hypersonic nonequilibrium flows. It is evident that no single technique is universally optimal; selecting a suitable method requires careful consideration of multiple factors. Experimental requirements, including desired parameters, spatial and temporal resolution, and data quantity, must be meticulously defined. These requirements should then be aligned with the capabilities and limitations of available techniques, considering equipment availability, expertise, and cost. Current measurement techniques are primarily designed for re-entry models. To accurately model the satellite ablation, it's crucial to incorporate techniques that can capture the dynamic behaviour of the ablation process and effectively measure the by-products of ablation.

3 Space Policy and Legal Framework

3.1 Review of Space Policy

Today's space domain is characterized by an increasingly diverse set of space activities, actors, and uses. This includes a dramatic increase in the number of satellites in orbit, an increasing number of countries operating satellites, and a shift in the predominant type of operator (by number of satellite) from government to commercial.

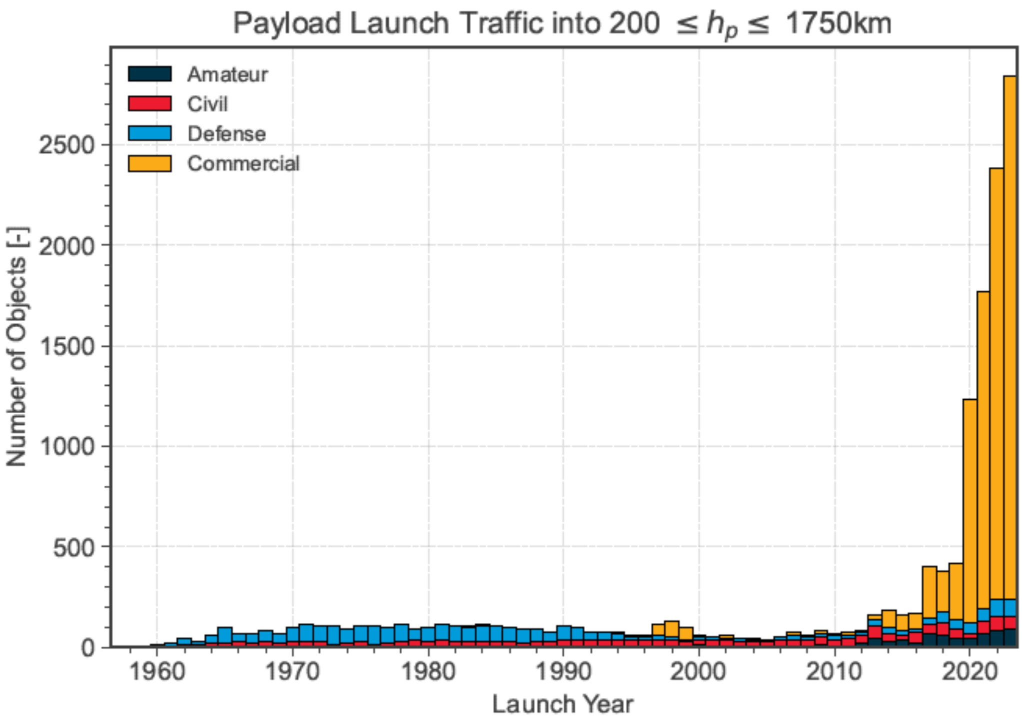


Figure 22. A Changing Space Domain: Objects Launched Into LEO (Souece: ESA, 2024)

However, most of the key governance principles that inform space regulation were defined in an era where space was dominated by government operators. The main concern of the treaty process was preventing conflict in a cold war context; academic, private and other non-government use was anticipated but not detailed. As private sector space activity becomes more prevalent - the pace of activity and the introduction of new services/applications, such as large constellations in low Earth orbit, private space stations, and satellite servicing and maintenance, challenge the efficacy and efficiency of existing regulation and policy focused on space governance and sustainability.

These novel space activities – and the potential impacts they have on both the space and terrestrial environment require updated approaches to governance. Approaches must both be appropriate to the challenges but also fit for purpose to the activities being governed and allow for continued technical, business, and policy innovation. Achieving this will require coordination of multiple different stakeholder groups and enhanced mechanisms for improving understanding between the private sector and adapting space governance to this new context [79].

Potential impacts on terrestrial environments from atmospheric ablation of re-entering space objects falls squarely into this coordination need. Space policy can be a tool to support this coordination, if properly referenced into existing practices and structures.

3.1.1 Space Policy: Purposes and Overview

Public policy, as a governmental function, can be broadly described as the why, how, and to what effect, governments pursue particular courses of action or inaction. Public policy generally involves making trade-off decisions concerning competing options, through evaluating potential positive and negative impacts of policies, regulations, and/or funding choices. In the case of space actives, as an example, policymakers may need to weigh the connectivity or security benefits of support for satellite broadband constellations versus the potential negative environmental impacts of those same constellations. Public policy is generally implemented through a public administration process, which entails the government structure, programs and institutions which provide for the day-to-day running of services and activities [80].

In the space sector policy takes on many forms and functions. Some countries may put into place an overall national space which described the broad goals which that state is seeking to achieve through investment and development of space activities. A national space policy may be accompanied by narrower policies covering specific space sectors such as launch, communications, or remote sensing; or by narrower policies covering specific sectors such as national security or commercial space. Other states may instead develop space policy through organizational specific strategies (such as within a national space agency or science ministry) or through legislative action establishing priorities and projects.[1]

Common topics, often interrelated and cross-cutting, addressed through space policy include:

- National security: *goals and strategies for the role of space systems and capabilities in national security, defence, and competition with adversaries*
- Economic and commercial development: *goals and strategies for the role space plays in economic growth, innovation, and competitiveness and how governments seek to leverage or develop this*
- Societal benefit: *goals and strategies for ensuring societal benefit from the development and application of space technology*
- Science and exploration: *goals, strategies and plans for basic science, exploration and research and development activities in the space sector*
- International cooperation: *goals, strategies and plans for working with allied and partner countries in conducting space activities, including the role of space in foreign policy and diplomacy*

Other topics such as space sustainability, planetary defence, human capital development, and public engagement may also be addressed through space policy. Regulation is used in support of space policy goals, but also to fulfil international obligations.

[1] *Ibid*

3.1.2 The Polycentric Space Governance Regime

The space governance system can be described as polycentric: there are many different levels and centers of governance, which are coordinated at times, but more often operate independently of each. Furthermore, there is a wide range of actors and interests represented in these centers of governance. The specific definition of polycentric governance varies slightly between authors, but it can be generally described as “a system of governance in which multiple authorities oversee the same area, albeit with different but overlapping interests and scopes of responsibility.” Polycentricity is a common or inherent aspect of shared or commons domains, where resources, access, and consequences cross or extend beyond national jurisdictions.[2]

As described by Oltrogge and Christensen, global development of space debris mitigation policies, guidelines, and requirements shows this overlapping nature of governance systems in the space domain. Figure 23 shows the organizational interaction of institutions, stakeholders, and regulatory and policy institutions of global space debris mitigation activities. This is but an illustrative example of the complex nature of space governance.[3]

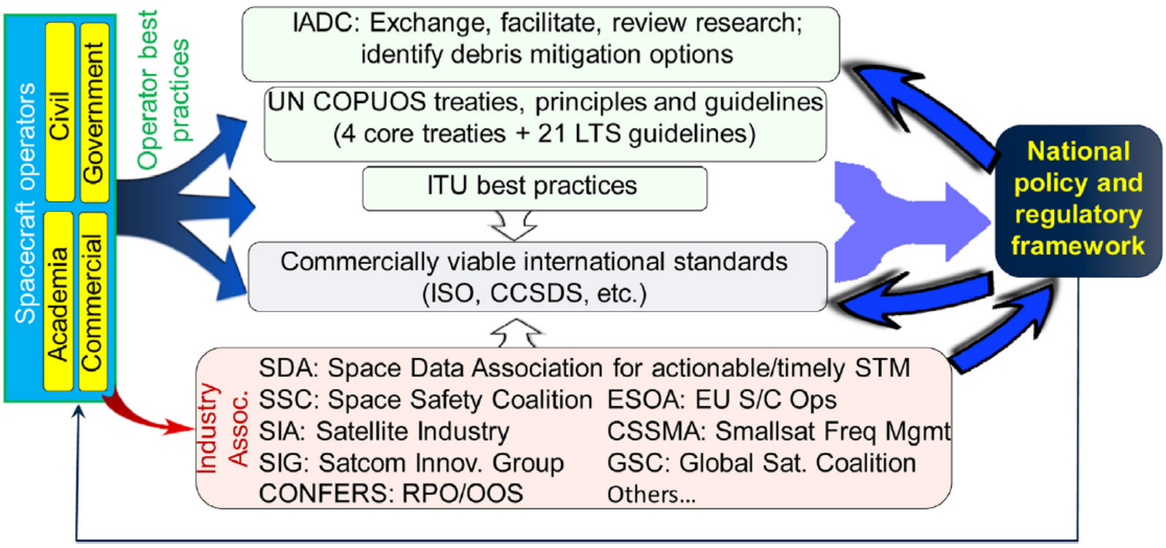


Figure 23. An Example of Polycentric Space Governance: Space Debris Mitigation Policy (Source: Oltrogge and Christensen, 2020)

At the international level, the United Nations (UN) has acted as the main co-ordinating and standard-setting institution in the space field. Much of this work has been carried out under the auspices of the UN Committee on the Peaceful Uses of Outer Space (COPUOS). The Committee, established in 1959, has a remit that includes supporting research on space, the dissemination and exchange of information on space, and studying the legal issues that can arise in the field.[4] COPUOS has two sub-committees, the Legal and Scientific Sub-Committees, which report back to the main Committee. Alongside COPUOS, the UN Office

[2] C. Otto, “Polycentricity and Space Governance,” *Secure World Foundation Space Sustainability Briefs,* 2022. Accessed Aug 2, 2024. [Online]. https://swfound.org/media/207513/swf_brief_polycentricity__space_governance_pp2302_final.pdf
[3] Oltrogge and Christensen, 2020
[4] Michael Friedl, The COPUOS Briefing Book (Secure World Foundation, 2024).

for Outer Space Affairs (UNOOSA) supports countries in the implementation of international space law and in developing their space sectors. The 2021 UN General Assembly Resolution 76/3 reaffirmed the broad mandates of both COPUOS and UNOOSA and emphasised their respective roles in supporting sustainable space development, in line with the UN 'Space 2030 Agenda'.[5] This incorporates the objective to '[f]acilitate and promote the integration of the space sector with other sectors, including energy, public health, the environment, climate change, the management of resources and information and communication technology, as well as the development of multi-stakeholder partnerships leading to innovative space-based solutions for social and economic development that can be integrated into mechanisms for implementing the Sustainable Development Goals'.[6]

In addition, the UN encompasses a wide range of agencies, such as the International Telecommunication Union (ITU), the United Nations Educational Social and Cultural Organisation (UNESCO), the World Meteorological Organisation (WMO) and the International Civil Aviation Authority (ICAO), as well as other organisations that are more or less directly interested in space. 'UN Space' serves to facilitate co-ordination and the exchange of information among 37 such organisations, which meet annually.[7]

COPUOS successfully negotiated the drafting of the five international space treaties during the period of the Cold War and more recently adopted the 2019 Guidelines for the Long-term Sustainability of Outer Space Activities.[8] Brokering agreement at the international level is, however, challenging, made more difficult by current political tensions. The effectiveness of the UN framework, and, in particular, COPUOS with its 102 members, in resolving legal questions and developing standards for the space sector, has increasingly come into question.[9] COPUOS is not an agency of the UN and its mandate is determined by the General Assembly; it does not have regulatory competence and decisions are made on the basis of consensus, effectively giving each State a veto.[10] From a fragmentation perspective, there is no formal procedure for communication between the legal and scientific sub-committees and there is no formal mechanism for engagement with private entities, which are not entitled to observer status. On the other hand, non-governmental organisations have been granted observer status, including the Committee on Space Research (COSPAR), thus creating a link with the space scientific community. It is questionable whether many of the 37 UN organisations with remits that touch on space have the resources to engage meaningfully with this technical area, although links with the UN Environment Programme, as well as with non-governmental organisations working in the environmental field, are potentially important.

Difficulty in reaching international agreement, even on non-binding guidelines, can encourage groups of states to resolve problems at bilateral or regional levels. The U.S led Artemis

[5] UN General Assembly Resolution, The "Space2030" Agenda: space as a driver of sustainable development, at A/RES/76/3, 25 October 2021.
[6] Ibid, par.19 (1.2).
[7] UN Space explained at: https://www.unoosa.org/oosa/en/ourwork/un-space/index.html
[8] UNCOPUOS, Guidelines for the Long-term sustainability of Outer Space Activities, ST/SPACE/79 at: https://www.unoosa.org/res/oosadoc/data/documents/2021/stspace/stspace79_0_html/st_space79E, for discussion: Martinez, 'The UN COPUOS Guidelines for the Long-term Sustainability of Outer Space Activities', 2021 8 *Journal of Space Safety Engineering*, p.103.
[9] David Kendall and Gerard Brachet, 'COPUOS: Current and Future Challenges' (2023) 48 *Air and Space Law*, Special Issue, pp.7-18.
[10] Ibid.

Accords are sometimes mentioned in this context.[11] Although strategic collaboration of this nature can feed into the development of international solutions, it can also result in variable standards, market isolation, and political tensions. There is also a risk that developing countries, or those yet to establish a significant space presence, which are represented and supported within the UN system, become more marginalized. At the European level, the intergovernmental European Space Agency and the EU co-ordinate activities among their respective 22 and 27 member states.[12] These organization are large enough to have a significant space presence and can contribute to the development of policy both upwards and downwards, at international and national levels.[13]

As indicated in Figure 23, and discussed in more detail below, the international governance 'vacuum' is being partially filled by industry, through the development of space-related standards. Individual firms, alongside academia, also have an incentive to develop innovative solutions to common problems, within the framework of intellectual property protection. But industry also has an interest in light-touch regulation and may resist international or national moves to establish requirements that impose present costs in order to pre-empt environmental damage at some point in the future.

A similar complexity is present at the national level, where different state departments can be responsible for specific aspects of space activities, even where a dedicated space agency takes the lead. Regulatory authority can similarly be fragmented, with, for example, oversight of the radio spectrum and responsibility for satellite fillings resting with the Office of Communications (OFCOM) in the UK, while licensing of space ports, launch and operational activities rests with the Civil Aviation Authority (CAA). The UK situation is further complicated by the fact that space and the agreement of international treaties are matters reserved for the UK Parliament, whereas the environment is a devolved matter.[14]

Though the locus of the decision-making varies depending on the state, ultimately a decision will have to be made as to the priority to be afforded specific policy objectives, such as environmental protection, safety, or industrial development. In the context of a global market, this can lead to forum shopping and deregulatory pressures, as industry locates to states with the lightest regulatory burden, which in turn encourages states to seek the development of common standards at regional or international levels.

This polycentric system nevertheless offers certain benefits in addressing the complex policy and governance challenges evident in the space domain. In polycentric systems, multiple authorities oversee or govern the same area. While this does produce fragmentation, it allows both for the system to be more adaptive or responsive to change and allows for governance

[11] NASA, in co-ordination with the US Department of State, The Artemis Accords. Principles for Cooperation in the Civil Exploration of the Moon, Mars, Comets and Asteroids, 2020, at: https://www.nasa.gov/wp-content/uploads/2022/11/Artemis-Accords-signed-13Oct2020.pdf?emrc=653a00

[12] EU competence rests on Article 189 of the Treaty on the Functioning of the European Union, *OJ* C 202, 7.6.2016, p.1–388.

[13] Consider, for instance, the ESA's facilitation of the 'Zero Debris' Charter at: https://esoc.esa.int/sites/default/files/Zero_Debris_Charter_EN.pdf

[14] Scotland has actively supported the development of a sustainable Scottish space sector and a space sustainability roadmap, see: Scottish Enterprise, 'Scotland's Space Sector Set to become the Greenest on Earth', 6 September 2022, at: https://www.scottish-enterprise-mediacentre.com/news/scotlands-space-sector-set-to-become-greenest-on-earth.

approaches to develop at the level closest to the actors involved; while not precluding action at a more central level. As researcher Eytan Tepper writes:

"Embracing polycentric space governance means facilitating and encouraging stakeholders-led governance of separate sub-issue-areas, by forming separate, issue-area-specific governance centers, which will together encompass the vast majority of the entire issue-area of space activities, and which may be interconnected by a joint coordinating forum."

In other words, it offers the ability to engage coalitions of actors to develop specific governance approaches through whichever means or forms are appropriate. Examples of this can be found in the historical generation of planetary protection provisions, the current evolution of space debris governance, and the emerging approaches to the mitigation of the impacts of satellite constellations on dark and quiet skies.

A closely related concept emerging from management of common pool resources and environmental asset management known as adaptive governance has been applied in the governance of climate change and sustainable environmental practices.[15] Reviews of adaptive governance approaches in these areas have shown that it "enabled actors to collaborate across diverse interests, sectors, and institutional arrangements and detect opportunities and problems as they developed while nurturing adaptive capacity to deal with them."[16] This may be instructive for new challenges in space governance.

A polycentric system can appear to be muddled and uncoordinated. But by embracing it and leveraging the multiple levels, issues such as atmospheric ablation impacts, might be addressed at the appropriate level.

3.1.3 Space Sustainability as a Policy Objective

A key aspect of space activities is the reality the actions of one actor in the space domain can affect the ability of others to safely operate, even when those actors are regulated under different national frameworks or jurisdictions. Given this fact, and the increasing scale of space activities, in recent years – the last decade or so – space sustainability has increased in salience as a policy objective.[17] Space sustainability can be broadly defined as the ability of all humanity to continue to use outer space for peaceful purposes and socioeconomic benefit over the long term. Policy and governance to support or enable space sustainability considers the impact of national space actors – government or non-governmental – on the safety and security of the space environment.

Space sustainability is a broad umbrella topic that covers a number of issues underneath it, covering technical, operational, governance, diplomatic, security, and finance aspects of space activities. These range from transparency and confidence building measures in national security space activities; to identifying and following responsible space operations practices,

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[15] Oltrogge and Christensen, 2020.

[16] Schultz, Lisen, et al. "Adaptive Governance, Ecosystem Management, and Natural Capital." *Proceedings of the National Academy of Sciences of the United States of America*, vol. 112, no. 24, June 2015, pp. 7369–74. *PubMed Central*, https://doi.org/10.1073/pnas.1406493112.

[17] Martinez, Peter. 2023. "The Development and Implementation of International UN Guidelines for the Long-Term Sustainability of Outer Space Activities." *Advances in Space Research* 72 (7): 2597–2606. https://doi.org/10.1016/j.asr.2022.06.046.

to policy and legal approaches to expanding access to space technology and services. Table 13, below, lists an example set of actions that collectively define space sustainability.[18]

Table 13. Example set of actions that collectively define space sustainability (Source: Martinez, 2023, Room Journal)

Ten Steps to Enhance Space Sustainability
1. Promote the universal adoption and implementation of existing space treaties and guidelines for space sustainability.
2. Act in a manner consistent with the recognition that near-Earth orbits and the electromagnetic spectrum are limited natural resources that have to be used equitably, efficiently and rationally.
3. Assess the environmental impact of space systems over their entire life cycle.
4. Move away from a disposable culture in space towards a circular space economy.
5. Design space systems for resiliency against natural and anthropogenic hazards.
6. Use market access rules to shape behavior.
7. Determine how to quantify orbital carrying capacity and allocate it rationally and equitably.
8. Strengthen and harmonise space governance.
9. Promote responsible investment in space activities.
10. Refrain from deliberate actions that degrade the space environment for all.

Historically global concerns about space sustainability began with worries about the generation of space debris and the risk posed to future space operations by its increase. Accordingly, a large portion of policy and governance efforts around space sustainability have focused on space debris mitigation and remediation, as well as on space situational awareness and space traffic management capabilities, with the objective of reducing collision risk in the orbital environment. Historically, space sustainability objectives have focused on the space environment, and risks to space operations; as well as on risk to third parties on Earth from space activities. It is only recently that consideration of impacts on the terrestrial environment have emerged in space sustainability discussion.

3.1.3.1 Policy Initiatives Related to Space Sustainability

In 2010, the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) established the Working Group on the Long-Term Sustainability (LTS) of Outer Space Activities. The Working Group was tasked with producing a set of voluntary guidelines for all space actors to help ensure the long-term sustainable use of outer space. The Working Group's mandate ended in June 2018. During its work on LTS, COPUOS member States agreed on 21 guidelines and a context-setting preambular text. In June 2019, the Guidelines for the Long-term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space were adopted by COPOUS. COPUOS has also continued discussions

[18] Martinez, Peter. 2023. "A Multifaceted Approach to Space Sustainability - Room: The Space Journal." *Room the Space Journal of Asgardia*. May 2023. https://room.eu.com/article/a-multifaceted-approach-to-space-sustainability.

of space sustainability guidelines under a dedicated agenda Working Group of the Scientific and Technical Subcommittee of COPUOS.[19]

The majority of the 21 Guidelines focus on the space environment, and, in the words of the Chair of Working Group which produced them, the Guidelines are to be considered "minimum standards for the responsible conduct of space activities."[20] The Guidelines are voluntary, and are to be implemented at the national level through policies, standards, guidelines, regulations, and operational practices. Atmospheric ablation of re-entering space objects is not addressed directly by the Guidelines and although they do make reference to addressing "risks to the environment associated with the launch, in-orbit operation and re-entry of space objects;" and call for operators to "assess all risks to the long-term sustainability of outer space activities associated with the space activities conducted by the entity, in all phases of the mission life cycle, and take steps to mitigate such risks to the extent feasible," it is unlikely atmospheric ablation was considered when the Guidelines were drafted.[21]

While developed within the context of a diplomatic forum, COPUOS, the LTS Guidelines were drafted through a process that considered initial input from a set of Expert Groups. These Expert Groups were composed of experts nominated by their national governments, but serving in an individual capacity and not necessarily representing State positions. The LTS Working Group also formally consulted a number of outside expert bodies, including the Committee on Space Research (COSPAR), the Inter-Agency Space Debris Coordination Committee (IADC), the International Space Environment Service (ISES), and the International Organization for Standardization (ISO), among others. This process allowed for the inclusion of scientific and technical information in the development of the Guidelines.[22]

The LTS Guidelines are a demonstration of international consensus of the importance of space sustainability. As evidence of their political importance, annual communiques resulting from the annual G7 Leaders Summit (representing the Governments of Canada, France, Germany, Italy, Japan, the USA, the UK and the EU) have referenced support for the LTS Guidelines since the 2021 Summit hosted by the UK.[23] The 2023 communique stated:

> "We reiterate our commitment to promoting the safe and sustainable use of outer space, given our ever-greater reliance on space systems. Restating the importance of addressing the issues of space debris, we strongly support the implementation of international guidelines adopted at the UN Committee on the Peaceful Uses of Outer Space as urgent and necessary. We welcome national efforts to develop further solutions for space debris mitigation and remediation as

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[19] P. Martinez. "Implementing the Long-Term Sustainability Guidelines: What's Next?" *Air and Space Law*, vol. 48, no. Special, Mar. 2023. *kluwerlawonline.com*, https://kluwerlawonline.com/journalarticle/Air+and+Space+Law/48.Special%20Issue/AILA2023030 pp. 41-58; P. Martinez. "The Development and Implementation of International UN Guidelines for the Long-Term Sustainability of Outer Space Activities." *Advances in Space Research*, vol. 72, no. 7, Oct. 2023, pp. 2597–606, https://doi.org/10.1016/j.asr.2022.06.046.

[20] *Ibid*

[21] The Guidelines for the Long-term Sustainability of Outer Space Activities (LTS Guidelines) were adopted by the Committee on the Peaceful Uses of Outer Space (COPUOS) in 2019, available at: https://spacesustainability.unoosa.org/content/the_guidelines

[22] See P. Martinez (2023) at *supra 12*

[23] See:https://www.gov.uk/government/news/g7-nations-commit-to-the-safe-and-sustainable-use-of-space#

well as further research and development of orbital debris mitigation and remediation technologies."[24]

Statements of this type represent a political validation of the importance of the issue; but meaningful progress on implementation must be made through national initiatives.

3.1.3.2 National Space Sustainability Policies: the examples of the U.K. and the U.S.

The United Kingdom (UK) is focused on becoming a competitive player in the international space sector. Following its National Space Strategy (NSS), the government aims to situate the UK as 'one of the world's most innovative and attractive economies'.[25] This is done by directing the UK Space Agency (UKSA) to focus on three key areas: supporting investment towards non-government contracts and private capital; promoting space missions in science, technology and applications; and expanding the value of space activities in other areas such as climate emergency, health and more. The NSS highlighted eight key priorities for UK support, the three most relevant to the ablation project being sustainability, innovation, and discovery.[26]

Sustainability requires improved space object tracking capabilities and space debris mitigation, with accompanying regulation, and standard setting. Although the governance of space debris ablation is not specifically discussed, there is scope here for the UK to lead in recognising atmospheric ablation as a serious consideration in the development of space sustainability policies, at the domestic as well as international and regional levels. Services such as the ESA's Space Surveillance and Tracking service, for example, offer scope for enhanced monitoring of debris and its movements, and collaboration with organisations such as the ESA could thus feed into further research on the chemical composition of the atmosphere after re-entry of space objects.

The second priority, innovation, highlights the importance of supporting commercial markets through investment and responsive regulation, oriented to the future of space. The UK has worked towards supporting development and research in the field of Active Debris Removal (ADR), an innovative solution to orbital congestion. Its recent feasibility studies, projected to conclude this year (2024), involving collaboration with four companies: Astroscale, ClearSpace, Orbit Fab and Thales Alenia Space, demonstrate a clear commitment to space debris mitigation[27]. The promotion of ADR, however, also has implications for the scale and rate of atmospheric ablation, underlining the importance of a holistic approach to sustainability when supporting innovative space technology.

Although the last priority, discovery, seems geared towards space-based national and international missions, there is no necessary reason why its remit could not be expanded to

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[24] See:https://www.whitehouse.gov/briefing-room/statements-releases/2023/05/20/g7-hiroshima-leaders-communique/

[25] UK Space Agency (2022). Corporate Plan 2022-2025. Retrieved from https://assets.publishing.service.gov.uk/media/62d66a5ed3bf7f285e787745/6192_UKSA_Corporate_Plan_CB_v9a_Bb.pdf p. 6

[26] Ibid

[27] UK Space Agency (2024). "UK Space Agency Annual Report 2023-2024". Retrieved from https://www.gov.uk/government/publications/uk-space-agency-annual-report-and-accounts-2023-2024/uk-space-agency-annual-report-2023-2024

cover the effects of atmospheric ablation. The UK is not the only country to investigate the issue of space object atmospheric ablation, as illustrated by the recent (2024) high-level workshop on the impact of spacecraft re-entry hosted by the European Space Agency,[28] and the Lunar and Planetary Institutes second International Orbital Debris Conference in 2023[29], but the UKSA is in a prime position to lead further dialogue on the issue and become a vocal advocate for further co-ordinated research on this space activity.

In the United States, space sustainability is an element of space policy and strategy across multiple agencies and regulatory authorities. At the national level, the December 2021 "United States Space Priorities Framework" sets out the key goals and elements of U.S. strategy and policy. It states that "The United States will prioritize space sustainability and planetary protection." Discussion under this item focuses on space debris mitigation, tracking and remediation and spaceflight safety, in addition to planetary protection. The Framework also emphasizes strengthening global governance of space activities, including contributing to the long-term sustainability of space activities. Beyond specific mention of space sustainability, the Framework also discusses the role of space in invocation, economic growth, international cooperation, U.S. leadership and national security, and in climate change action (among other topics). [30]

Major sustainability related policy issues within the Biden administration have focused on space situational awareness and space traffic coordination as well as on efforts to address regulatory authorities for novel commercial space activities not clearly covered in existing authorities at the FCC, FAA and/or NOAA.

In December 2023 the White House released its proposed *United States Novel Space Activities Authorization and Supervision Framework*, which defines the key principles and roles the administration seeks to implement to modernize the current oversight regime for novel commercial space activities in the U.S. This document refers to the importance of space sustainability several times, including that "consideration of the long-term sustainability of space activities across the life cycle of space systems is critical to ensure that the outer space environment remains suitable for exploration and use by current and future generations." However, this Framework requires further action, including by Congress, to be implemented fully and detailed implementation guidance is not available. [31]

In the areas of space situational awareness and space traffic coordination U.S policy has been focused on implementing Space Policy Directive 3, dating from the Trump Administration, which aims to set up a civil space situational awareness system at the Department of Commerce, and transfer responsibility for basis spaceflight safety notification functions from

[28] European Space Agency (2024). Program of the workshop on "Understanding the Atmospheric Effects of Spacecraft Re-entry". Retrieved from https://indico.esa.int/event/493/timetable/?view=standard_inline_minutes
[29] Lunar Planetary Institute (2023). Program of the conference on Orbital Debris. Retrieved from https://www.hou.usra.edu/meetings/orbitaldebris2023/technical_program/?session_no=207
[30] The White House. "United States Space Priorities Framework" December 1, 2021. https://www.whitehouse.gov/wp-content/uploads/2021/12/United-States-Space-Priorities-Framework-_-December-1-2021.pdf
[31] The White House. "United States Novel Space Activities Authorization and Supervision Framework" December 20, 2023. https://www.whitehouse.gov/wp-content/uploads/2021/12/United-States-Space-Priorities-Framework-_-December-1-2021.pdf

the Department of Defense to the Department of Commerce. This system, the Traffic Coordination System for Space (TraCSS) at the Office of Space Commerce (OSC), is scheduled to begin initial limited operations by the end of September 2024.[32] While related to space safety and sustainability, this policy goal does not directly pertain to atmospheric ablation.

NASA released its first Space Sustainability Strategy in March 2024. In this document NASA defines "space sustainability as the ability to maintain the conduct of space activities indefinitely into the future in a manner that is safe, peaceful, and responsible to meet the needs of the present generations while preserving the outer space environment for future activities and limiting harm to terrestrial life."[33] The first volume of this strategy focuses on the sustainability of NASA's operations in low Earth orbit including space situational awareness, space traffic coordination, space weather awareness, orbital debris management, and spacecraft servicing. NASA intends to develop subsequent volumes which will focus on other aspects of the agency's operations, including in deep space, in cislunar space, and on the Earth. In discussion of the latter, NASA specifically notes that the potential impact of ablation of re-entering spacecraft and satellites on the atmosphere is an area of concern.[34] The NASA Space Sustainability Strategy pertains only to NASA's activities, and is not a regulatory document.

3.1.3.3 Private Sector Best Practice Initiatives

In recent years, significant efforts have been made by a number of industry, non-government, and civil-society groups to develop and promulgate voluntary guidelines, principles, and practices for space sustainability and/or space operations. Many of these efforts focus on space debris mitigation and or space traffic coordination. These initiatives are motivated by a number of factors including maintaining space safety and continuity of operations; informing regulation, and establishing marketing position as a responsible space actor.

Table 14. Illustrative Listing of Voluntary Best Practices Initiatives

1. AIAA: Satellite Orbital Safety Best Practices
2. CONFERS: Guiding Principles for Commercial Rendezvous and Proximity Operations (RPO) and On-Orbit Servicing (OOS)
3. Earth and Space Sustainability Initiative: Memorandum of Principles for Space Sustainability
4. European Space Agency: Zero Debris Charter
5. Global Expert Group on Sustainable Lunar Activities: Recommended Framework and Key Elements for Peaceful and Sustainable Lunar Activities
6. GSOA Code of Conduct on Space Sustainability

[32] C, Joseph, "Overview Presentation on the Traffic Coordination System for Space (TraCSS)," 2024 *Small Satellite Conference*, Logan, Utah. August 7, 2024. https://www.space.commerce.gov/wp-content/uploads/SmallSat-2024-TraCSS-Introduction.pdf

[33] NASA, "NASA's Space Sustainability Strategy Volume 1: Earth Orbit," March 23, 2024, https://www.nasa.gov/wp-content/uploads/2024/04/nasa-space-sustainability-strategy-march-20-2024-tagged3.pdf?emrc=9a7020

[34] Ibid

7. Hague Institute for Global Justice: Washington Compact
8. Paris Peace Forum: Net Zero Space Initiative
9. Satellite Industry Association: Space Safety Principles
10. Space Safety Coalition: Best Practices for the Sustainability of Space Operations
11. Sustainable Markets Initiative: Astra Carta
12. World Economic Forum: Space Debris Mitigation Recommendations

Heterogenous in intent, format, and level of detail, these initiatives, while voluntary and non-binding, form another layer in the polycentric space governance system. Elements of these principles might be codified through standards and regulations.

3.1.4 Examples Where Technical and Scientific Information Has Informed Policy in the Field of Space Sustainability

3.1.4.1 Space Debris Mitigation Requirements

Perhaps the most well-known example of the integration of scientific and technical recommendations into policy and regulation in the field of space sustainability is the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines. The purpose of the IADC is to help coordinate and share research on space debris among participating space agencies. The first IADC Space Debris Mitigation Guidelines were published in 2002 and last updated in 2021. These guidelines define specific protected regions of Earth orbit and the recommended operational practices satellite operators should take to minimize the creation of long-lived space debris in the protected regions; including the well-known "25-year rule," which states that space objects should be removed from orbit or placed into a graveyard orbit within 25 years of end of mission. [35]

The IADC is composed of space environment and space operations experts from the world's leading space agencies. It describes its purpose as to "exchange information on space debris research activities between member space agencies, to facilitate opportunities for cooperation in space debris research, to review the progress of ongoing cooperative activities, and to identify debris mitigation options."[36] A simplified subset of the IADC guidelines, the COPUOS space debris mitigation guidelines (which are more political in nature) were endorsed by the United Nations in 2009.[37] Although the IADC guidelines remained voluntary, several countries have implemented the debris mitigation guidelines through national regulations and policy.

While the IADC Guidelines do not address atmospheric ablation; they do provide an example of process by which technical recommendations can be developed and codified in regulation, standards, and policies. A review of the process and application of the IADC Guidelines is

[35] "IADC Space Debris Mitigation Guidelines – IADC-02-01 Rev. 3, June 2021 https://iadc-home.org/documents_public/file_down/id/5249
[36] See https://iadc-home.org/what_iadc
[37] UN Office for Outer Space Affairs, "Space Debris Mitigation Guidelines of the Committee on Peaceful Uses of Outer Space", 2010 https://www.unoosa.org/pdf/publications/st_space_49E.pdf

instructive for consideration of policy approaches to the potential impacts of atmospheric ablation.

IADC Space Debris Mitigation Guidelines have served or been the baseline for numerous non-binding policy documents, binding national legislation, and act as a starting point for the derivation of technical standards (some of which are used in procurement requirements by space agencies). Governments around the world developed specific national standards and guidelines building on the work of the IADC. The IADC Guidelines have also been adapted and codified through voluntary industry standards, including through the International Standards Organisation.

The Example of the Debris Mitigation Guidelines

- Oct 1987: NASA/ESA coordination meeting
- 1988-1993: Coordination meetings ESA/Japan/NASA/Russia
- Oct 1993: IADC formally estab.
- 1993-onward: IADC membership expands
- 1997: IADC begins regular technical briefings to COPOUS
- 2002: IADC publishes first international Space Debris Mitigation Guidelines
- 2009: COPUOS space debris mitigation guidelines adopted
- 2021: Most recent update to IADC guidelines

- 2002: International Organization for Standardization (ISO) working group established based on IADC guidlines
- 2010: ISO standard on *Space debris mitigation requirements* - ISO 24113:2023 published
- 2016/2017: Industry "best practices" initiatives for space sustainability/safety begin to emerge
- ~ 2020-2023: industry initiatives reflect near consensus around voluntary 5-year PMD
- 2022: US FCC adopts 5-year PMD requirement (enacted 2024)

However, in recent years, the IADC Space Debris Mitigation Guidelines have been surpassed by more detailed or advanced guidelines. Voluntary industry-led "best practices" initiatives for space sustainability and safety have reflected near consensus around voluntary post mission disposal (PMD within) of 5 years for LEO spacecraft (instead of the 25-year IADC guidelines). In the United States the Federal Communications Commission has adopted a 5-year PMD requirement for licensees operating in non-geostationary orbits, which will go into force in late 2024, including for non-US domiciled entities seeking market access to the United States.[38] In late 2023 the European Space Agency update its space debris mitigation standards so that the "maximum time spent in protected low-Earth orbits at end of life for new ESA missions has been reduced from 25 years to just five."[39] The new standards also require mitigation efforts related to potential impacts on dark and quiet skies. Both requirements go beyond what is required by the IADC Guidelines, the COPOUS Space Debris Guidelines, or the ISO Space Debris Mitigation Standard. ESA's standards apply both to missions operated by the Agency and to missions procured by the Agency.

At one level these developments – surpassing the IADC and COPOUS guidelines – suggest a challenge in keeping consensus-based technical guidance up to date with technical progress and scientific knowledge. On the other hand, they may be an example of polycentrism at work. Lower-level entities like ESA and the FCC are able to move faster, and issue more specific guidance than centralized authorities such as the IADC or COPUOUS. Individual

[38] See https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites-0
[39] See https://www.esa.int/Space_Safety/Space_Debris/Mitigating_space_debris_generation

IADC members have indicated that if the global satellite operator community uniformly adopts stricter practices than the current IADC guidelines, or space-faring nations widely adopt stricter national regulations than the IADC guidelines, then the IADC would likely also strengthen their guidelines in response.[40]

These developments come even as compliance with the existing IADC 25-year guideline lags. In the 2024 edition of its annual Space Environment Report, ESA reports that between 20 and 65% of payloads operating in orbits in the LEO IADC protected region that do not decay naturally within 25 years and reaching end of life in the last decade, have been non-compliant with the IADC guidelines. Constellation operators are more likely to be compliant. Rocket bodies in the same orbits have been between 50 and 95% compliant, with a trend towards increasing compliance. ESA notes that "whereas adoption of, and compliance to, space debris mitigation practices at a global level is noted as slowly increasing, it is of importance to note that the successful implementation is still at a too low level to ensure a sustainable environment in the long-run."[41] This demonstrates a challenge, namely that even well-articulated technical guidance, standards, and regulation may not achieve desired outcomes if not aligned with both incentives and enforcement. In this regard, it is notable the FCC issued the first-ever fine to a satellite operator for not complying with orbit debris mitigation requirements in late 2023.[42]

The ESA is also facilitating an industry-led process to develop improved space debris mitigation compliance. The Zero Debris Charter, and associated Zero Debris Approach, announced in November 2023, aim to stop the generation of new space debris by space missions by 2030. The Charter includes a principle that the adverse effects of space debris on the Earth's environment when re-entering the atmosphere "be anticipated and mitigated to the greatest extent possible." The ESA is working with industry to develop aspirational practices for implementing the Charter's principles.

The development and widespread adoption of the IADC Guidelines took decades, and compliance still lags. While the model offers a good example of the integration of technical guidance and policy and regulatory practice; we must ask whether the timeline will be acceptable for the issue of atmospheric ablation, given the pace of development in today's space sector.

3.1.4.2 Planetary Protection Policy

Planetary protection (PP) has been a concern of the international space exploration community since the inception of the space age. In general PP is a "principle in the design of interplanetary missions that aims to prevent biological cross contamination between the target body and Earth. Planetary protection policies and procedures have worked to mitigate forward contamination (from Earth) and back contamination (to Earth)"[43] Planetary protection policies

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[40] Oltrogge and Christensen, 2020.
[41] ESA Space Environment Report 2024. https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf
[42] See https://www.space.com/space-debris-fcc-first-fine-dish-deorbit-satellite#:~:text=The%20United%20States%20government%20has,deorbiting%20its%20EchoStar%2D7%20satellite.
[43] J. McKaig, and T. Caro et. Al., "Chapter 10: Planetary Protection—History, Science, and the Future," *Astrobiology* 2024 24:S1, S-202-S-215, https://doi.org/10.1089/ast.2021.0112

are developed at international level through a consensus process lead by the COSPAR Panel on Planetary Protection (PPP) and implemented at national level by policies and procedures both in national space agencies and in regulatory practices. [44] While a detailed review of the scope and intent of the PP guidelines are beyond the scope of this research, the process through the PP guidelines are developed and implemented may be instructive for developing policy and technical frameworks for mitigating atmospheric ablation.

In the early part of the space age, NASA, COPUOS and national scientific authorities began to establish initial national level practices for preventing biological contamination in space missions. The Committee on Space Research (COSPAR) had been established in 1958 to coordinate worldwide space research, and in 1961 its parent organization, the International Council for Science, called on agencies conducting space research to share with COSPAR information needed to evaluate the potential for contamination. To conduct this evaluation COSPAR established a Consultative Group on Potentially Harmful Effects of Space Experiments. In 1964 COSPAR published an "interim quantitative framework for developing planetary protection standards" that was largely based on NASA's planetary protection policies. This framework replaced in 1969 by a more detailed framework. In the early 1980s NASA conducted a review of its planetary protection guidelines, which resulted in a change from a quantitative based assessment to a qualitative approach. COSPAR largely followed suite with an updated set of guidelines in 1984. Since 1984 COSPAR planetary protection policies have been often updated, on an as needed basis, resulting from technical and scientific input.[45] COSPAR's Policy on Planetary Protection is currently developed through the deliberations of the COSPAR Panel on Planetary Protection, which was restructured in 2019. The most recent update of the Policy was published in March 2024.[46]

The COSPAR Policy on Planetary Protection is the primary international policy on planetary protection. COSPAR reports that the Policy is "the primary scientifically authoritative international reference standard guiding compliance with Article IX of the Outer Space Treaty."[47] The PPP meets regularity to consider new scientific findings with policy implications or discuss new activities or concerns that could affect compliance with the Policy.[48] The Panel also holds workshops or other meetings with other bodies or forums, such as UNCOPOUS, national scientific academies, or other academic and industry groups.[49] In this way the PPP conducts regular evaluation of the current "peer-reviewed scientific knowledge that is provided by external groups or by a subcommittee of the COSPAR PPP."[50] Updates to the Policy are developed by the PPP and referred to the COSPAR Bureau for confirmation and publication.

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[44] See McKaig and Caro, 2024, *Ibid*; National Academies of Sciences, Engineering, and Medicine (NASEM), 2018. *Review and Assessment of Planetary Protection Policy Development Processes*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25172.
[45] See NASEM, 2018, *Ibid*
[46] COSPAR, "COSPAR Policy on Planetary Protection" 20 March 2024.
https://cosparhq.cnes.fr/assets/uploads/2024/07/PP-Policy_SRT_220-July-2024.pdf
[47] A. Coustenis, N. Hedman, et. Al., "Planetary protection: Updates and challenges for a sustainable space exploration," *Acta Astronautica*, Volume 210, 2023, Pages 446-452,
https://doi.org/10.1016/j.actaastro.2023.02.035.
[48] See NASEM, 2018, *Supra 36*
[49] See A. Coustenis, N. Hedman, et. Al., 2023 at *Supra 39*
[50] COSPAR, "COSPAR Policy on Planetary Protection" 20 March 2024.
https://cosparhq.cnes.fr/assets/uploads/2024/07/PP-Policy_SRT_220-July-2024.pdf

The COSPAR Policy on Planetary Protection Policy, and associated requirements and guidelines are not legally binding under international law. Implementation takes place at the national level through standards, procurement requirements and regulation. NASA and ESA have both published Planetary Protection Standards, which implement and refine COSPAR guidance. In the United States the Federal Aviation Administration assess commercial missions' compliance with planetary protection requirements as part of the payload review process conducted during a launch license application.

The PPP is structured to ensure interdisciplinary engagement in its deliberations. Panel members are drawn from national space agency and other relevant expert bodies[51] and generally include expertise "in various fields attached to planetary protection such as (astro)biology, planetary sciences, geology and geophysics, microbiology, sample treatment, aerospace engineering and operations, space law and space policy, among others."[52] The Chair of the Panel is typically chosen based on scientific expertise, while the two Vice Chairs are chosen to represent knowledge in planetary protection issues and connection to the implementation of the Outer Space Treaty, respectively.[53]

In this way the COSPAR Policy on Planetary Protection is an iterative document that is updated in consultation with technical and policy authorities.[54] However despite this structure, the PPP is challenged by many of the same dynamics affecting other areas of space governance including the rapid pace of private sector activities, jurisdictional or regulatory authority gaps, and methodologies for including private sector perspectives in discussions.[55]

3.1.4.3 Dark and Quiet Skies

In recent years the increasing deployment of satellite constellations has led to increasing optical and radio interference with Earth and space-based astronomical observations.[56] In response, the international astronomical scientific and observation community has become involved both in advocating for policy and regulatory responses and in working with the satellite operator community to develop mitigation strategies, led by organizations such the International Astronomical Union (IAU), the American Astronomical Society (AAS), and the Royal Astronomical Society (RAS) as well as large observatories such as the NSF NOIRLab (U.S. National Science Foundation National Optical-Infrared Astronomy Research Laboratory) and the Square Kilometre Array Organization (SKAO). While still an emerging area, the experience of the community in responding to this issue does offer some insights into

[51] See A. Coustenis, N. Hedman, et. Al., 2023 at *Supra 39*
[52] See "COSPAR Policy on Planetary Protection" at *Supra 42*
[53] See https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-planetary-protection-ppp/
[54] See A. Coustenis, N. Hedman, et. Al., 2023 at *Supra 39* and NASEM, 2018 at *Supra 36*
[55] See McKaig and Caro, 2024, *Supra 35;* COSPAR, "The COSPAR Panel on Planetary Protection Role, Structure and Activities," 2019. https://cosparhq.cnes.fr/assets/uploads/2019/07/PPP_SRT-Article_Role-Structure_Aug-2019.pdf
[56] G. Long, "The Impacts of Large Constellations of Satellites," November 2020. *JASON. The Mitre Corporation*. Report for the National Science Foundation. https://www.nsf.gov/news/special_reports/jasonreportconstellations/JSR-20-2H_The_Impacts_of_Large_Constellations_of_Satellites_508.pdf ; United States Government Accountability Office (GAO), "Technology Assessment. Large Constellations of Satellites: Mitigating Environmental and Other Effects," Sept 2022. Accessed Aug 1, 2024. [Online]. https://www.gao.gov/assets/gao-22-105166.pdf

approaches that might be pursued in the context of a polycentric governance system, when seeking to realise mitigation steps for potential impacts of atmospheric ablations.

In 2022, the International Astronomical Union established a Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS), which is co-hosted by NSF's NOIRLab and the SKAO.[57] According to the IAU the "mission of the CPS is to coordinate efforts and unify voices across the global astronomical community with regard to the protection of the dark and quiet sky from satellite constellation interference."[58] The CPS has organized itself into four "hubs", each seeking to facilitate collaboration around a difference aspect of the challenge of satellite constellation interaction with astronomy:[59]

- the Satellite hub,
- the Policy Hub,
- Industry and Technology Hub and;
- the Community Engagement Hub.

In March 2024, the CPS released its first recommendations paper entitled *Call to Protect the Dark and Quiet Sky from Harmful Interference by Satellite Constellations.* This paper, led by the Policy Hub, states the recommendations from the CPS for the mitigation of satellite constellations' impact on astronomy. It proposes, a "range of measures and mitigation strategies for different stakeholders, including the astronomy community itself, but also industry and regulators." These include voluntary mitigation measures from the satellite operator community, and as well as regulatory measures that are needed at both the national and international level.[60]

Through the Satellite hub and the Industry and Technology hub the CPS has facilitated engagement with satellite industry leaders on the development of technical mitigation strategies, including satellite deployment procedures, reduction of satellite reflectivity, and coordination between satellite operations and astronomical observatories. In August 2024, for example, SpaceX and the U.S. National Science Foundation's National Radio Astronomy Observatory (NSF NRAO) announced the development of system which allows for dynamic coordination between SpaceX and key NSF observing instruments. The system enables real-time sharing of the NSF telescopes' current observation plans (covering attributes such as direction, frequency, and bandwidth) with SpaceX, allowing SpaceX to adjust transmissions properties in order to reduce interface.[61] The CPS has also engaged with both the ITU and

[57] See https://cps.iau.org/about/

[58] See https://cps.iau.org/news/launch-of-new-iau-centre-safeguarding-astronomy-from-satellite-constellation-interference/

[59] Statement by the International Astronomical Union (IAU) to The 60th session of the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space AGENDA ITEM 17: General Exchange of Views on Dark and Quiet Skies for Science and Society https://www.unoosa.org/documents/pdf/copuos/stsc/2023/Statements/16_PM/17_IAU_15_Feb_PM.pdf

[60] International Astronomical Union Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS), *Call to Protect the Dark and Quiet Sky from Harmful Interference by Satellite Constellations,* March 2024, https://cps.iau.org/documents/49/techdoc102.pdf

[61] See https://www.spacedaily.com/reports/New_Coordination_System_Allows_Satellite_Internet_and_Radio_Astronomy_to_Share_the_Sky_999.html

COPOUS, resulting in a COPUOS Scientific and Technical Subcommittee agenda item related to this issue.[62]

3.2 Review of the Space Legal Framework

In conducting their national space activities, states are bound by any applicable rules of international and national law, which include the Outer Space Treaties (3.2.1), those derived from a number of International Environmental and Climate Regime Treaties (3.2.2), as well as national requirements to assess the environmental effects of their activities (3.2.3). The following sections consider the international frameworks first, before considering the role of private standards and then national regulation, focusing again on the UK and the USA, but with reference also to country examples that merit further investigation.

3.2.1 The International Space Treaties

Access to, and exploitation of, outer space is governed by five international space treaties, of which four are directly relevant to this study:[63]

- 1967 Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and other Celestial Bodies (the 'OST', 114 ratifications, 22 signatories); [64]
- 1968 Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space ('ARRA', 100 ratifications, 23 signatories);
- 1971 Convention on International Liability for Damage Caused by Space Objects ('LIAB', 100 ratifications, 18 signatories);
- 1974 Convention on Registration of Objects Launched into Outer Space ('REG', 75 ratifications, 3 signatories)

These four treaties have attained wide-ranging state support, being ratified by the main spacefaring nations as well as those yet to establish an autonomous space capacity, by both developed and developing countries. This renders the treaties internationally 'representative' but also difficult, if not impossible, to clarify or up-date, amendment requiring the support of a majority of State parties,[65] with an accompanying likelihood of divergent State interpretations of key provisions. The ARRA, LIAB and REG allow international governmental organisations, such as the European Space Agency (ESA), to assume the duties and benefit from the rights established. The OST is a framework treaty, establishing key principles and requirements on

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[62] See https://cps.iau.org/news/united-nations-agrees-to-address-impact-of-satellite-constellations-on-astronomy/

[63] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 27 January 1967, 610 UNTS 205, 18 UST 2410, TIAS No 6347, 6 ILM 386 (entered into force 10 October 1967); The Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched Into Outer Space, 22 April 1968, 672 UNTS 119, 19 UST 7570, TIAS No 6599, 7 ILM 151 (entered into force 3 December 1968); the Convention on International Liability for Damage Caused by Space Objects, 29 March 1972, 961 UNTS 187, 24 UST 2389, 10 ILM 965 (1971) (entered into force 1 September 1972); the Convention on Registration of Objects Launched into Outer Space, 6 June 1975, 28 UST 695, 1023 UNTS 15 (entered into force 15 September 1976).

[65] OST Art. XV; ARRA VIII; LIAB, Art. XXV; REG IX.

the basis of which national space activities can take place, while the ARRA, LIAB and REG develop in more detail specific aspects of the OST.

The fifth treaty, the 'Moon Treaty', establishes a framework for the exploration of the Moon and other celestial bodies, but currently has only seventeen signatories, not including the United Kingdom (UK). In addition, the Agreement focuses on the Moon and other celestial bodies, which are explicitly stated not to include the Earth, so that its relevance for this study is currently limited.[66]

Given their international standing and binding nature, these four treaties are an attractive basis on which to found procedural and substantive environmental standards for space activities, including the return of space objects at the end of their life. On reading the treaties, however, it is not immediately apparent how this could be achieved. The treaties, drafted against the background of the Cold War, were motivated by two main objectives: firstly, to prevent space from becoming a new theatre of war, and, secondly, to ensure that space exploration and use was open to all, in particular, that 'first mover', more technologically advanced states, would not degrade or limit other states' access to space in the future. There were certainly concerns over radiation, arising both from nuclear tests in outer space, addressed, prior to the OST, by the Partial Test Ban Treaty of 1963,[67] and from the use of nuclear energy in space,[68] as well as contamination from extra-terrestrial matter brought back to Earth.[69] But beyond this, and despite being drafted at a time of growing environmental awareness,[70] the space treaties do not specifically address the environmental consequences of space activities for the Earth.

The limited express engagement with environmental protection is not, however, conclusive. The four treaties establish not only core freedoms to access and explore outer space but also conditions and constraints on the exercise of these freedoms. It is these conditions and constraints that can be employed to develop further certain substantive and procedural duties regarding custodianship of outer space and the Earth's environment. These include:

a) *Specific requirements to avoid certain harmful or damaging activities*

i) A **duty to avoid the harmful contamination** of outer space and certain **adverse changes to the Earth's environment** (Art. IX OST);

[66] Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, 5 December 1979, 1363 UNTS 3 (entered into force 11 July 1984), see Art.I.1.
[67] Treaty Banning Nuclear Weapons Tests in the Atmosphere, In Outer Space and Under Water (entered into force 10 October 1963) 480 UNTS 43.
[68] Failure of the 1964, Transit-5-BN-3 navigation satellite, which burned up on re-entry, led to the dispersal of plutonium fuel in the upper atmosphere, see NASA 'Safety and Radioisotope Power' at: Radioisotope Power Systems Safety and Reliability - NASA Science.
[69] Stephan Hobe; Kai-Uwe Schrogl; Bernhard Schmidt-Tedd (eds.) 1954; Rafael Moro-Aguilar, editor, translator; Rada Popova, Rada, editor, Cologne Commentary on Space Law (Madrid: Dykinson S.L.;2021), Article IX, p.324.
[70] For example, Rachel Carson's seminal study of pesticides, *Silent Spring* (US: Houghton Mifflin, 1962) was first published in 1962, five years before the adoption of the OST. For a chart contrasting space active nations in 1966 with those in 2020 see Union of Concerned Scientists, UCS Satellite Database, updated 1 May 2023, at: https://www.ucsusa.org/resources/satellite-database.

ii) **Launching State liability for damage** caused to another state, its natural or juridical persons, 'on the Earth, in air space or in outer space' (Art VII OST, developed further in LIAB);

b) Cross-Cutting Requirements and Principles

iii) A duty to **act in accordance with international law** (Arts. I and III OST);

iv) A duty act in the **interests and for the benefit of all countries** (Art. 1 OST);

v) A duty to have **due regard to the corresponding interests of all other States** (Art. IX OST);

c) Requirements relating to oversight, information sharing, and mutual assistance

vi) A duty to **authorise and 'continually supervise'** space activities (Art. VI OST);

vii) A duty to **inform the UN Sec. Gen, the public and scientific community** 'to the greatest extent feasible and practicable', of their space activities (Art. XI OST) and to undertake appropriate international consultations where their activities could cause potentially harmful interference (Article IX OST). National and UN Registers are required under the REG (Articles II-IV REG);

viii) **Mutual assistance** regarding the return of re-entered space objects and in addressing any resultant hazards (Article V ARRA) and where a space object presents a 'large scale danger to human life' or living conditions (Article XXI LIAB).

The analysis below focuses on those aspects of international space law that are most relevant to the issue of ablation, starting with an examination of the core freedoms established in the OST at section 3.2.1.1. The following sections 3.2.1.2 and 3.2.1.3 examine the requirements to avoid harm and compensate for damage (see a above), and the extent to which our understanding of these can, and should, be influenced by applying the three cross-cutting duties to act in accordance with international law, for the benefit of all countries, and with due regard for their corresponding interests (see b above). Sections 3.2.1.4 and 3.2.1.5 then consider the extent to which the State oversight, information-sharing and consultation requirements (see c above), currently assist in our understanding of ablation and their potential role in this context in the future. A final section 3.2.1.6 considers the limitations in the current international space law enforcement system.

3.2.1.1 Core Freedoms Established in the International Space Treaties: freedom to explore and use outer space.

The *key freedoms* set out in Article I OST are:

- the freedom for all states, on a basis of equality, to engage in the 'exploration' and 'use' of outer space; and
- 'free access to all areas of celestial bodies'.

Article VI OST confirms that space activities can be carried out not only by states and governmental agencies but also private entities, subject to appropriate oversight.

In order to accommodate future technological developments, avoid ongoing debate and facilitate agreement, the OST did not define a number of key terms. There is thus no definition of 'outer space', nor is there such a definition in any of the four subsequent international space treaties. The delimitation between outer space and airspace is, however, important, because different legal regimes apply to each.[71]

Article 1 of the Chicago Convention of 1944 provides that the airspace over the territory of a state is subject to that state's 'complete and absolute sovereignty'.[72] Aviation activities over the high seas, an area outwith national jurisdiction, are to be in conformity with the Convention, overseen by the International Civil Aviation Organisation (ICAO).[73] Given that the first launch of a man-made satellite into orbit took place in 1957, the absence of a specified upper limit to state sovereignty in the Chicago Convention is not surprising.[74]

In relation to outer space, Article I OST designates outer space as the 'province of all mankind', an area that is specifically stated to be incapable of national appropriation, whether by claim of sovereignty, use or occupation (Art. II OST).

With the development of space activities, the need to adopt a point of demarcation began to become more pressing. Scientific calculations in the fifties led to the determination of a theoretical line 100kms above sea level at which centrifugal forces replace aerodynamic lift and airflight is no longer possible.[75] This line, known as the 'Kármán Line' because of the contribution to its formulation of aeronautics engineer Theodore von Kármán, is not merely of scientific interest, but is also used for regime categorisation in certain laws and regulations. The Sporting Code of the World Air Sports Federation, for example, provides that only flights above 100km are considered astronautical flights,[76] while Australia employs the 100km threshold in its statutory definition of 'space objects', their launch and return.[77] Reference to a specific altitude is, however, relatively unusual, and is not always 100km.[78] Indonesia, for example, provides that outer space begins at 'approximately 100-110 kms',[79] while the US Federal Aviation Administration adopts 80kms, the top of the mesosphere, as the altitude

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[71] For discussion see M. Byers and A. Boley *Who Owns Outer Space?: International Law, Astrophysics, and the Sustainable Development of Space* (Cambridge Studies in International and Comparative Law. Cambridge University Press; 2023), 'Abandoned Rocket Bodies' at pp.114-129.
[72] Convention on International Civil Aviation, (entered into force April 4, 1947) 15 UNTS 295.
[73] Ibid., Art. 12.
[74] Jairo Becerra, Paula Pérez and Laura Duarte, 'Borders in Airspace and Outer Space' in Dimitri Endrizzi, Jairo Becerra, Eduardo Andrés Perafán Del Campo, Jaime Cubides Cárdenas, and Laura Cecilia Gamarra-Amaya (eds) *Frontiers – Law, Theory and Cases* (2023, Springer), p.72.
[75] S. Sanz Fernández de Córdoba, '100 km Line for Astronautics', 21 June 2004, at: https://www.fai.org/page/icare-boundary. The line, below this, was rounded up to 100kms as an easier reference point.
[76] Ibid.
[77] Space Launches and Returns Act 2018, as amended in 2023, C2023C00335 (C11), article 8.
[78] COPUOS, National legislation and practice relating to the definition and delimitation of outer space, 21 Feb. 2022, A/AC.105/865/Add.27, at: https://documents.un.org/doc/undoc/gen/v22/009/48/pdf/v2200948.pdf?token=msE37vfJPrTwRgAtPf&fe=true; Thomas Gangale, *How High the Sky? The Definition and Delimitation of Outer Space and Territorial Airspace in International Law* (2018, Beucher Germany) DOI 10.1163/9789004366022, at 313-320.
[79] Ibid. para 3.

above which an individual must travel, subject to specific conditions, in order to earn the title 'astronaut'.[80]

Wherever the line is drawn, it is apparent that not all 'space activities' occur in outer space. At least part of the launch and re-entry process typically takes place within airspace and thus jurisdiction of one or more States or over the High Seas. Legislation such as that enacted by Australia can be understood as designed to streamline the regulatory process by clarifying which activities fall within its domestic air and space legal regimes, not as a formal determination that outer space starts at 100km. This reflects a 'functionalist' approach, whereby the regulatory framework runs with the activity – space law covering launch to, operation of, return from, a specific altitude - not 'salami sliced' according to where specific aspects of a space activity occurs, according to a 'spatialist' approach.[81]

Within the UN, the Legal Sub-Committee of COPUOS has been exploring these issues since 1967 but there is as yet no international consensus on where outer space begins, or, indeed, whether there is a need for such a delimitation.[82] The Chair of the COPUOS Working Group examining this matter, proposed in 2017 that further consideration be given to agreeing a 100km boundary, accompanied by a special regime authorising passage through national airspace for space activities, including launch and re-entry.[83] Such passage would be conditional on it being peaceful, in conformity with international law, and respecting the territorial interests of any State or States concerned. In particular, such passage should not pose 'unjustified dangers to the local population *or the environment'*.[84]

This proposal was in part a recognition of increasing activity in the stratosphere, not only from satellite launches and re-entry, but also traffic in the form of suborbital vehicles, HAPS and stratospheric balloons. Such activities, if untracked or uncoordinated, could pose potential risks to other users of airspace, in the same zone or below, as well as to individuals on the ground. These concerns have led some academics to suggest the creation of a new intermediate 'near-space' zone, covering an area over 50km, thus above civil aviation, and below 120 km, the re-entry threshold for space systems.[85] The zone would be regulated in the same way as the High Seas, with a right for all States of innocent and peaceful passage, subject to compliance with safety and navigation rules established by the ICAO. The regime would be enforced by States, working in Flight Information Regions.[86]

[80] Chelsea Gohd, 'New FAA rules change who qualifies for commercial astronaut wings', Space.com, 27 July 2021, at: https://www.space.com/faa-commercial-astronaut-wings-rule-change.
[81] These approaches are discussed in detail in Gangale (2018).
[82] For a recent indication of the breadth of views in this area see: COPUOS, Report of the Legal Subcommittee on its sixty-second session, 20 to 31 March 2023, A/AC.105/1285, pp.13-15 and Michael Friedl, *The Copuos Briefing Book*, 2024 Edition (Secure World Foundation, Vienna), p.85. For commentary: Cologne Commentary (2021), p.188, para.16.
[83] COPUOS, 'Promoting the discussion of the matters relating to the definition and delimitation of outer space with a view to elaborating a common position of States members of Copuos', Legal Subcommittee, 9-20 April 2017 at: A/AC.105/C.2/L.302.
[84] Ibid. para 27.
[85] Paul Dempsey and Maria Manoli, 'Suborbital Flights and the Delimitation of Airspace vis-à-vis Outer Space: Functionalism, Spatialism and State Sovereignty', (2017) XLII *Annals of Air and Space Law* 198-238.
[86] Ibid.

Ablation occurs between 100km and 20 kms, the space object descending at speed through areas subject to state jurisdiction or over the high seas, where there is limited risk of damage to people or property from components that survive re-entry. If an 80km demarcation line is adopted, ablation could take place both in outer space and national airspace. There is currently little incentive for an individual state to assert control over another country's satellite ablating as it passes through its territory, save where this causes a danger to people or property, such as an aircraft. From another perspective, Azerbaijan noted in its response to a COPUOS questionnaire on delimiting outer space that 'the fact that most States do not complain about the passage of [re-entering] aerospace objects over their airspace does not signify their approval but is rather due to their not being informed about the passage or of any damage caused by it. As for the question of international customary law in relation to such passages, there is currently no such law'.[87] Ultimately, an understanding of where ablation occurs and what, if any, consequent damage arises, is essential when considering how, and by whom, environmental concerns resulting from re-entry can, and should, be addressed.

In relation to the regime applicable to activities in outer space, Article II OST characterises outer space as an area not subject to state appropriation. Article I OST also characterises these activities as 'the province of all mankind'. One influence behind this characterisation may have been the post war international scientific co-operation in the field, founded on the idea that 'space should be for all humanity'.[88] In addition, from at least the early sixties the US, and more reluctantly the USSR, could see the surveillance advantages of open access to space, unencumbered by domestic permissions for overflight. Other regimes were also discussed by way of analogy prior to adoption of the OST, which were not based on national jurisdiction: those relating to the High Seas, with its principle of open access, and Antarctica, the latter placed under international administration with an emphasis on collaborative scientific enquiry and a prohibition on militarisation, designed to defuse the tensions arising from contested territorial claims.[89]

Whether the inclusion of the phrase 'province of all mankind' in Article I OST adds anything to the stated freedom to use and explore outer space in the OST is not clear. The Cologne Commentary considers that the designation serves to emphasise that space activities must be undertaken for the benefit of the international community, not the sole interest of a single state, but this is already established in the 'benefits' clause in Article I OST and on this view would be largely redundant.[90] Arguably, the term reflects the 'enabling aspect' inherent in the concept of a 'global commons' that space should be a domain open to all, like the high seas.[91] Its links with the 'constraining aspect' of that concept, that such common areas require effective and co-ordinated regulatory oversight to ensure sustainable use,[92] is much more

[87] COPUOS, Questionnaire on possible legal issues with regard to aerospace objects: replies from Member States, A/AC.105/635/Add.17, question 7.
[88] M. K. Davis Cross, 'Outer Space and the Idea of a Global Commons' (2021) 35 *International Relations*, 384-40.
[89] M.J. Peterson, 'The Use of Analogies in Developing Outer Space Law' (1997) 51 *International Organisation*, vol. 51, no. 2, Apr. 1997, pp. 245–74 https://doi.org/10.1162/002081897550357.
[90] Cologne Commentary (2021) p.68.
[91] Goehring, John, 'Why Isn't Outer Space a Global Commons?' *Journal of National Security Law and Policy*, Vol 11:3, p.573 (2021); see also Geert van Calster, 'The Laws of Sustainable Development' in V. Mauerhofer et al.(eds.) *Sustainability and Law* (Springer Nature Switzerland; 2020), pp. 49-64.
[92] Typically applied to goods that are both rivalrous and non-excludable: Elinor Ostrom, "How Types of Goods and Property Rights Jointly Affect Collective Action." *Journal of Theoretical Politics*, vol. 15, no. 3, July 2003, pp. 239–70. https://doi.org/10.1177/0951692803015003002.

controversial. Although some commentators and administrations do categorise space as a global commons, the understanding of that term and state practice vary widely.[93] At the domestic level, for example, President Trump passed an executive order in April 2020, which stated expressly that the US did not view outer space to be a global commons, though previous administrations had adopted a contrary perspective.[94] A slightly different characterisation of 'common heritage of mankind' is applied to the Moon in Article 11.1 of the Moon Treaty, and the consequent implications for resource management and benefit sharing is one reason why the Moon Treaty has received limited international endorsement.[95]

3.2.1.2 A Direct Obligation to Prevent Environmental Damage, including atmospheric contamination, under the International Space Treaties? The Relevance of Article IX OST and the Overarching Principles Guiding Space Activities in International Law.

The treaty article directly concerned with environmental protection is Article IX OST. This imposes distinct obligations on States in regard to their impact on 'outer space' and the Earth. In relation to the former, the study and exploration of outer space, including the Moon and other celestial bodies, is to be carried out in such a way as to avoid '*their* harmful contamination'. States are required, 'where necessary', to take 'appropriate measures' in this regard. Given, as noted above, the absence of agreement as to where 'outer space' begins, it is possible that some ablation, at least at the higher levels, takes place in 'outer space'. The Cologne Commentary affords 'contamination' a broad interpretation, 'covering all possible kinds, forms or instances of harmful interference in outer space, deliberate or unintentional alike', which could encompass ablating space objects and the related vapour and particulate contamination.[96] Because space activities are high risk, the Commentary also suggests that the obligation on States is an exacting one. In particular, the consequent duty to take 'all appropriate measures to prevent harm, or to minimise the risk thereof' extends not just to known risks but also imposes a continuing duty to identify potential risks. States cannot simply turn a blind eye to potential contamination but are required to undertake reasonable efforts to proactively inform themselves 'of factual and scientific components that relate to a contemplated activity'.[97]

In relation to contamination caused by ablation in domestic airspace, Article IX provides that States are to pursue their exploration in outer space so as to 'avoid adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter'. As with other key terms in the OST, 'extraterrestrial' is not further defined and if understood to mean something that originates from outwith the Earth's environment, its inclusion would greatly

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[93] See discussion by Davis Cross (2021), *Supra 123*; Pic, Pauline, et al., "Outer Space as a Global Commons: An Empirical Study of Space Arrangements" (2023) 17 *International Journal of the Commons*, pp. 288-301 https://www.jstor.org/stable/48756452. ; Olavo de O. Bittencourt Neto, 'Outer space as a global commons and the role of space law', in Kai-Uwe Schrogl, Christina Giannopapa, and Ntorina Antoni (eds.) *A Research Agenda for Space Policy* (Edward Elgar, 2021), pp.1-18; and J. Cayón, and S. Yousefian (2021) 'The Outer Space as a New Theater of Operations; Some Ethical-Legal Considerations' in J.M. Ramírez, B. Bauzá-Abril (eds) *Security in the Global Commons and Beyond. Advanced Sciences and Technologies for Security Applications* (Springer, 2021), 99-116.
[94] President Trump, for example, passed Exec. Order No. 13914, 85 Fed. Reg. 20,381 (Apr. 10, 2020).
[95] Goehring (2023) p. 7; Cologne Commentary (2021) pp.64-67.
[96] Cologne Commentary (2021), Article IX, paras.39-40.
[97] Ibid.

restrict the scope of this important environmental clause. NASA's Interagency Report on Orbital Debris adopts a limited interpretation, noting '[a]lthough parties are called upon to avoid adverse changes in the environment of the Earth resulting from the introduction of "extraterrestrial matter", it is unlikely that this clause was intended to cover matter originating on Earth'.[98] It may be relevant that Article VII of the Moon Treaty distinguishes harmful contamination of the Moon through the introduction of '*extra-environmental'* matter, which is broad enough to cover man-made items such as spacecraft, and damage to the Earth through the introduction of '*extraterrestrial* matter', the different terminology suggesting the latter covers only material originating in outer space.[99] Moreover, the Moon Agreement broadens this by adding the phrase 'or otherwise', which suggests that the drafters of the Moon treaty considered the reference to 'extraterrestrial' on its own to be unduly restrictive.

Is a more expansive interpretation of the OST possible? Article 31 of the 1969 Vienna Convention on the Law of Treaties requires treaties to be 'interpreted *in good faith* in accordance with the *ordinary meaning* to be given to the terms of the treaty *in their context* and *in the light of its object and purpose*'.[100] From an ordinary meaning perspective, definitions of 'extraterrestrial' extend not only to objects that originate outside the Earth or its atmosphere but also those that 'exist' or 'occur' in this domain, which could thus cover a satellite prior to re-entry.[101] The decision not to define key terms was, as noted, in part to facilitate agreement but also to enable the Treaty to evolve alongside technological capabilities as a framework act. This suggests that a dynamic approach to interpretation of Article IX OST is both legitimate and necessary. When drafted, although there was awareness that space debris could constrain access in the future, this was not a significant or pressing problem at that time.

In addition, there are indications that those who framed Article IX did not intend it to be solely restricted, in relation to protection of the Earth, to material originating in outer space. When the draft text of the treaty was presented to the UN General Assembly the accompanying summary of Article IX made reference simply to the avoidance of 'harmful contamination and adverse changes in the environment of the earth', without including the qualifying reference to extraterrestrial matter.[102] Moreover, the drafters had initially been concerned at the risks of radiation, a form of contamination derived from human activity, whose damaging impact is most likely to be felt on Earth. Academic commentary is divided on this matter, though with a body of opinion favouring a more restrictive interpretation. Joanne Wheeler, for example, interprets 'harmful contamination' as covering biological and radioactive materials but not space debris.[103] On the other hand, Roberts considers that 'extraterrestrial matter' in Article IX OST 'probably means materials brought back, intentionally or unintentionally, from the outer

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[98] NASA, Interagency Report on Orbital Debris, 1995. Nov. 1995. ntrs.nasa.gov, https://ntrs.nasa.gov/citations/20000011871, chap. 9, p. 46.
[99] Moon Agreement (1984) Art.VII.1.
[100] Vienna Convention on the Law of Treaties 1969 (entered into force on 27 January 1980) 1155 UNTS, p. 331
[101] The Oxford English Dictionary (Oxford; 2023 ed.) defines 'extraterrestrial' as an object 'that exists, occurs, or originates from beyond the earth; *esp.* designating life forms, spacecraft, etc., from another planet…'.
[102] Cologne Commentary (2021) para.17, p.308.
[103] Joanne Wheeler, 'Space Debris: Legal Framework, Issues Arising and New ISO Guidelines in 2010/2011.' in *Yearbook on Space Policy 2010/2011* (Vienna: Springer Vienna) pp. 253–265 at p.256.

space environment', and that 'an expanded definition could also include orbital debris'.[104] Not only would this ensure that all State parties conform to certain environmental standards and assessments, reducing the attraction of forum shopping, but that these apply at all stages of a space activity, whether these occur above or below some notional line dividing outer and air space.

These ambiguities and potential limitations are a major weakness in the international space regime, and a more developed environmental policy framework, beyond access and safety, is clearly desirable. As noted, however, amendment of the OST requires majority approval by State Parties under Article XV, which, given their diverse interests, appears unrealistic. Nevertheless, the three requirements that the OST imposes on any space activity, noted in the introduction to this section, could independently form the basis for certain environmental obligations.

The first, is the overarching requirement in Article IX itself, that States have 'due regard' 'in all their activities in outer space' to the corresponding interests of all other States (art. IX OST). The principle of 'due regard' is an established concept in the field of civil aviation and is employed in international conventions such as the 1982 UN Convention on the Law of the Sea.[105] In relation specifically to space law, the Cologne Commentary states that space activities, given their hazardous nature, should be carried out with 'a high standard of care and due diligence'.[106] In particular, the duty imposes on States an obligation to 'prove beyond reasonable doubt that everything possible was undertaken to prevent harm occurring'.[107] This is in line with the requirement in Principle 15 of the Rio Declaration, concerning the 'precautionary principle', that 'where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation'.[108] Byers and Boley argue that a failure to carry out an environmental impact assessment as part of the licensing process for a mega constellation would violate both the OST and customary international law.[109]

Arguably an 'activity in outer space' (another undefined term) includes the whole life cycle of a space project, even if the initial and final stages of that activity take place in national territory. And although the relevant 'corresponding interests' are not specified, since Article IX itself concerns environmental contamination from space activities, both environmental and safety considerations can reasonably be considered included within its ambit. In particular, given that the OST establishes the freedom for all states to access outer space, an increasing number of uncontrolled, ablating space objects pose risks for the launch and safe return of other space objects.[110] Article IX OST requires States to consult where their activities could

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[104] L. R. Roberts "Orbital Debris: Another Pollution Problem for the International Legal Community." (1996) *Florida Journal of International Law*, vol. 11, 1997 1996 p. 613.
[105] M. Byers and A. Boley, 'Mega-constellations and International Law' in *Who Owns Outer Space?: International Law, Astrophysics, and the Sustainable Development of Space*. (Cambridge Studies in International and Comparative Law. Cambridge University Press; 2023), PP.77-113.
[106] Cologne Commentary (2021) p.311.
[107] Ibid.
[108] The Rio Declaration on Environment and Development, UN 13 June 1992, A/CONF.151/5/Rev.1.
[109] See M. Byers & A. Boley (2023) at *Supra 140* at p.108.
[110] Any material that does not ablate on re-entry poses a potential risk for humans on the ground, for worrying examples see M. Byers and A. Boley, 'Abandoned Rocket Bodies', in *Who Owns Outer Space? International Law, Astrophysics, and the Sustainable Development of Space* (Cambridge University Press; 2023), 114-129.

cause 'potentially harmful interference' with other States' exploration and use of outer space and NASA considers that 'the generation of orbital debris could, depending on the circumstances, be viewed as falling within the scope of this provision'.[111]

The second is the requirement that space activities should be 'carried out for the benefit and in the interests of all countries' (art.1 OST) and it is relevant to note that the obligation is towards 'all countries' not just contracting States. Although this has been interpreted as affording States considerable latitude in determining the nature of the benefit to be conveyed,[112] there is an important difference between *benefits*, however broadly defined and indirect, and wide-scale environmental *damage*. Serious environmental damage, whether direct or indirect, cannot realistically be considered to benefit, or be 'in the interests of all countries.

Article 31.3 of the 1969 Vienna Convention states that, when interpreting a treaty, consideration should be given to any 'relevant rules of international law applicable in the relations between the parties'.[113] Sands concludes that Principles 21 of the Stockholm Declaration and 2 of the Rio Declaration, alongside, in the European context, the precautionary principle, are sufficiently well established to create customary legal obligations capable of giving rise to a free-standing legal remedy.[114] Principle 21 of the Stockholm Declaration provides that '…States have a responsibility to ensure that activities *within their jurisdiction or control* do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction'.[115] This formulation is important because it imposes not just on those States that have responsibility under the OST for the ablating space object, but also those States that have control over the airspace in which the ablation occurs, an obligation to take measures to address, at least, significant transboundary harm.[116] In addition, the international conventions and protocols relating to the climate and the atmosphere are also relevant in understanding the practical implications of this principle.[117]

The third, is the express requirement in Article III OST that State Parties should carry on activities in outer space 'in accordance with international law, including the Charter of the United Nations…'. This creates an explicit bridge with the international environmental treaties and established substantive and environmental principles, discussed above and at 3.2.3 below. The Cologne Commentary notes that the 'duty of control, preventive action and due diligence in outer space' is part of a more general customary duty in international law, explicitly

[111] See NASA, Interagency Report on Orbital Debris, 1995. Nov. 1995. ntrs.nasa.gov, https://ntrs.nasa.gov/citations/20000011871, chap.9, p.46
[112] Cologne Commentary (2021) pp.65-67.
[113] 1969 Vienna Convention.
[114] P Sands, J. Peel, A. Fabra, & R. MacKenzie (2018). 'General Principles and Rules.' in *Principles of International Environmental Law* (CUP, Cambridge; 2018), pp.197–251.
[115] Stockholm Declaration: Declaration on the Human Environment, U.N. General Assembly Resolutions 2994/XXVII, 2995/XXII and 2996/XXII of 15 December 1972, italics added.
[116] See further Sands et al. (2018) *supra 149* at pp.207-211, discussing the distinct principles to take action to prevent, to cooperate, and to act sustainably.
[117] See discussion at 3.2.3 below and Sands et al. (2018) *Supra 149* at pp.252-294; UN Framework Convention on Climate Change, 9 May 1992 (entered into force 21 March 1994) 1771 UNTS 107, art. 3(3).

recognised by the International Court of Justice in the case concerning the projected Gabcikovo-Nagymaros dam project.[118]

Conclusion.

Article IX requires States to avoid harmful contamination both in outer space and on the Earth. Key terms are, however, ambiguous and have been interpreted in such a way as to exclude the effects of ablation that occurs in domestic airspace or over the High Seas. An alternative, more expansive, interpretation is, however, possible, which requires space faring States to actively investigate and take appropriate measures to mitigate any significant damaging effects caused by their space activities to the environment of the Earth. Article IX requires not only the avoidance of contamination but also adoption of procedural measures to investigate and evaluate the risks involved in space activities.

Alongside the *avoidance requirements* in Article IX, States must have 'due regard' to the interests of all other States and act 'for the benefit and in the interests of all countries' (art. IX and I OST). Moreover, State activities in outer space must conform to international law (art. III OST), including customary international law, notably Article 21 of the Stockholm Declaration. Together, these articles impose on States a duty to *consider the environmental implications* of their space activities and to take steps to mitigate resultant significant damage. Article IX also requires *consultation on outer space activities* that could cause 'potentially harmful interference' with those of other States.

Although the international community has been actively addressing the challenges of space debris for continuing access to outer space, there has been much less engagement with the issue of Earth based contamination from space activities.[119] Indeed, the main mechanism used to resolve the problem of ongoing access has been the timely removal of non-functional space objects and their ablation, thereby subordinating environmental concerns to other sustainability objectives.[120] This may be partly due to ongoing scientific uncertainty as to the potential cumulative environmental impact of ablation, but also the inherent ambiguity of key terms in the OST; the lack of effective dispute resolution and enforcement mechanisms; and divergent political interests.

3.2.1.3 International Liability for Environmental Damage under Article VII OST and the Liability Convention.

Article VII OST and the subsequent 1972 Liability Convention ('LIAB') impose international liability on launching States for damage caused by their space objects. The LIAB, designed to further elaborate on Article VII and establish procedures for resolving disputes and awarding compensation, takes precedence over the more general OST, but there are contexts in which Article VII will continue to apply, for example, where the States involved in a dispute are not parties to the LIAB. Under Article VII OST 'launching States' are liable for damage caused by a space object or its component parts to another State or its natural or juridical persons. The LIAB similarly covers damage caused by 'space objects', and confirms that this includes launch vehicles and their component parts (art.1(d)). Since launch vehicles can ablate at a sufficiently high altitude, as well as cause terrestrial and marine pollution if they return to Earth,

118 *Hungary v Slovakia* (Judgement) (1997) ICJ Rep 7, para.140.
119 See 3.1.3.1.
120 Ibid. See also van Calster (2020) at 51-52.

this is an important clarification. Apart from this, however, 'space object' is not further defined. Given the intention behind the LIABC to address disputes arising from collisions both in space and on the Earth, it can be concluded that 'space object' covers both functional and non-functional objects, such as space debris.[121]

Both treaties define launching States as those States that launch or procure the launch of a space object into outer space, and those from whose territory or facility the space object is launched.[122] Liability remains with the launching State or States, even where ownership of a space object has been transferred, thereby complicating effective oversight, particularly at the end of life of a satellite.[123] Though it may be possible to determine which State is responsible for a specific ablating space object over a given territory, this will not always be possible, particularly where the object is a component part of a satellite or launch vehicle that has broken up; where the satellite itself has not been registered with the UN; or no details have been provided as to its final expected trajectory (see 3.2.1.5 below). The problem is particularly compounded in the context of ablation where the potential environmental damage stems not from any one act of ablation but the cumulative impact of numerous such events, attributable to the space faring nations, over many years.

Does the establishment of international liability under the space treaties cover *environmental* damage? Article VII OST does not define 'damage', but confirms that it can arise 'on the Earth, in air space or in outer space'. As the Treaty does not specifically limit the concept, the Cologne Commentary suggests 'damage' should be given a broad scope, extending to material and immaterial damage, to physical and other forms of injury, including loss of profits.[124] The duty is to reinstate the injured part to the position they were in before the damage. Under the LIAB, damage is defined as 'loss of life, personal injury or other impairment of health; or loss of or damage to property of States or of persons, natural or juridical, or property of international governmental organisations' (Art. I(a)), which does not appear to cover pure economic loss or immaterial damage. Article I LIAB does not make reference to where the damage occurs, but it is apparent from Article VII LIAB, considered further below, that, in line with Article VII OST, damage on the Earth, in air space and in outer space are all covered. As with Article VII OST, it has been suggested that a 'broad interpretation' of damage is warranted,[125] but the framing of Article I(a) LIAB indicates that there must be damage to property or persons, and a State bringing a claim will need to show that it has been so damaged or that it is acting on behalf an individual or entity similarly affected (Art. VIII LIAB).

Where environmental damage causes property damage or ill health, as is often the case, it falls within the express terms of Article 1(a) LIAB. In the only formal complaint so far brought

[121] Reflected in Alexander P. Reinert, '*Updating the Liability Regime in Outer Space: Why Spacefaring Companies Should Be Internationally Liable For Their Space Objects'*, (2020) 62 Wm. & Mary L. Rev., pp. 325-356 at p.335.
[122] OST Art.VII, considered at Cologne Commentary (2021) pp.242-246, and LIAB Art.I(c).
[123] For discussion of the ambiguities arising from multiple launching states see Reinert, n. *Supra 156*, at p.339.
[124] Cologne Commentary (2021) p.250.
[125] See William III Schwarzschild, 'Recent Treaties and Statutes.' (1972) 6 *Vanderbilt Journal of Transnational Law*, vol. 6, no. 1, Jan. 1972, pp.262-271, who suggests at p.268 that the scope of such a broad definition 'can be circumscribed by a narrow application of the principle of causation in a particular case'.

under the LIAB, however, Canada sought to recover the costs of cleaning-up radioactive waste caused by the crash of the Russian nuclear powered Kosmos 954 satellite.[126] The case ultimately settled, with Russia paying for half the clean-up costs, the total claim being considered excessive. On one view the cost of the clean-up was pure economic loss, necessary to prevent damage to property or health,[127] but not covered by the terms of the LIAB. Such loss would, however, be covered by the broader terms of Article VII OST. On another view, exposure to radioactivity changes the nature of materials and thus constitutes damage, even if not immediately apparent. Moreover, Canada brought its claim under the LIAB and Russia was ultimately willing to pay compensation.

Where the damage occurs to an *environment* beyond national ownership, such as outer space, there will be no one individual or state that can claim its property interests or those of its nationals have been affected under Article VII OST or Article VIII LIAB, save where there is consequential damage to, for instance, a space object or astronaut. Most ablation occurs below 100-83 kms, below, therefore, what is generally considered the point at which 'outer space' begins, and presumptively within national air space.[128] But though the vapour and particles released by ablation pollute the atmosphere in an area falling within State sovereignty, potential damage is to the air, clouds and ozone layer, regarded as a common resource, not subject to national appropriation.[129] If correct, this would limit the international space liability regime in relation to the immediate effects of ablation. Where, however, the impact on the ozone layer or climate can be shown to have then caused damage to the territory of a given State or human health, for instance, through drought, rising sea levels, or an increase in skin cancer rates, Article VII OST and the LIAB regime would come into play.

Establishing the relevant causal link, involving the application of concepts such as remoteness and foreseeability, will be challenging in the context of ablation. As the Cologne Commentary notes '[n]ot all damage emanating from a space object will occur locally or immediately. Damage may be the result of a chain of events, stemming from the original incident caused by the space object, and may occur on Earth and in orbit. In certain cases, particularly with space debris, it may only appear after the lapse of time. … Where the causal chain or nexus is interrupted or broken, the damage is no longer the consequence of the space object.'[130] These observations are particularly pertinent in the context of ablation, where the damage is cumulative, the result of many individual events; and where the effect may only be felt many years later. The chemical reactions have still to be fully understood and it is possible that the link between the atmospheric pollution and ultimate Earth-based damage could be considered indirect or too remote. Untangling the extent to which damage is caused by the ablation of space objects and from other causes, such as meteorites entering the earth's atmosphere or other human activities, is a further complication.

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[126] Sraavya Poonuganti, 'It's Raining Rockets: Heightening State Liability for Space Pollution' (2023) 23 *Chicago Journal of International Law* pp.490-525, pp.499-501.

[127] Rosanna Deplano, 'The Peaceful Settlement of Space Disputes' in R. Buchan, D. Franchini, N. Tsagourias (eds)*The Changing Character of International Dispute Settlement: Challenges and Prospects* (2023; Cambridge University Press) pp.403-438 at p. 420, who notes the absence of actual damage.

[128] See 3.2.1.1 above.

[129] Fabienne Quilleré-Majzoub 'A qui appartiennent les nuages? Essai de définition d'un statut des nuages en droit international public' (2004) 50 Annuaire Français de Droit International, pp. 653-667.

[130] Cologne Commentary (2021) p.251.

A final requirement, alongside determining responsibility, the nature of the damage, and causation, is to establish the required level of fault. This is not clarified in Article VII OST but is addressed in the LIAB, which imposes:

i) absolute liability for damage caused on the surface of the earth or to aircraft in flight (Art. II), and

ii) fault based liability where the space object causes damage to another space object that is not on the surface of the earth, or to persons/property on board such a space object (Art. III).

The applicable fault regime, complicated by the absence of definitions, thus depends on where the damage occurs and what is damaged. Fault based liability under Article III LIAB could arise if an ablating space object were to collide with another space object during launch, or with a suborbital vehicle on its passage to or from Earth. Given that international guidelines encourage the rapid removal of space debris from lower Earth orbit, it is unlikely that a launching State would be held to be at fault solely on the basis that it allowed a space object to ablate. Fault requires either some deliberate wrongdoing, or recklessness or negligence as to a damaging outcome. The steps taken to notify the space-faring community in good time of the anticipated trajectory and timing of a satellite descent in order to minimise the risk of any such collision could, thus, be a relevant consideration in assessing fault.

The absolute liability regime of Article II LIAB applies to damage arising in two contexts. In relation to damage to aircraft in flight, ablation occurs well above the upper limit of domestic airflight, though there could be damage to aircraft in flight and persons or property on Earth from components that survive re-entry. In relation to damage to the surface of the Earth, the ablation process could result in metal or other particles falling to Earth and causing contamination, or, as discussed above, changes to the climate or depletion of the ozone layer that have longer term damaging effects on the Earth's surface or to human health. In the context of absolute liability, the fact that such damage could not have been foreseen, or that steps were taken to investigate, warn of, or minimise such damage, would not exclude liability. The only qualification to this is where the complainant State has itself deliberately or negligently contributed to the damage (Art. VI.I LIAB).

Article XXI LIAB, requires States to 'examine the possibility' of rendering 'appropriate and rapid assistance' to a State that has suffered damage caused by a space object that causes 'large scale danger to human life' or 'seriously interferes with the living conditions of the population or the functioning of vital centres'. The uncontrolled descent of a nuclear power source or the crashing of a satellite into a populated area, could clearly result in damage of this magnitude, but the broad wording could also encompass major environmental damage, of the type discussed above. Action is here, required, however, only once damage has been suffered, whereas the present concern is to prevent or minimise such damage in the future. State liability under international environmental law for transboundary harm is addressed in detail at 3.2. 3 below.

A final limitation of the outer space liability regime is the operation of the dispute resolution process in the LIAB, though alternative means of recourse, for instance before national courts or tribunals, are not excluded (Art. XI LIAB). This process, which initially relies on diplomatic negotiations, failing which a Claims Commission can be established at the request of either party, is widely considered ineffective, and it is unlikely that its existence will exert direct pressure on States in a collective responsibility situation such as this.[131] Claims for compensation are brought by States, not affected private parties, and diplomatic considerations may well affect the process (Art. VIII LIAB. In particular, a decision reached by a Claims Commission will only be binding if both State parties to the dispute agree (Art. XIX.2 LIAB). The only case to be brought under the LIAB to date was that relating to KOSMOS 954, discussed above, which ultimately settled. Claims must be brought no later than one year after the damage occurred or when the liable launching State is identified. If the damage is regarded as damage to the atmosphere, this is likely to exclude claims altogether, in that the ultimate damage to human health or to the surface of the Earth is likely to become apparent only many years later. Identifying the relevant launching States responsible for damage in this context is also problematic, though it is worth noting that launching States are jointly and severally liable by virtue of Article V LIAB. This could open the door to a process against all spacefaring nations for the cumulative environmental impact of their activities, leaving it to the States themselves to apportion liability among themselves under Article V.2 LIAB, possibly in line with the scale of national space activities.

3.2.1.4 A requirement that States take Earth-based environmental considerations into account when overseeing and authorising domestic space activities under Article VI OST?

Article VI OST provides that States are internationally responsible for national activities in outer space and must ensure that both governmental and non-governmental activities conform to the provisions in the OST. More specifically, they are *to authorise and 'continually supervise'* the activities of *non-governmental entities* 'in outer space', the former phrase suggesting that this obligation does not cease once the space object is no longer functional.

Article VI thus establishes the basis for national licensing regimes for space activities, in order to ensure compliance with the OST. Responsibility for the activities of international organisations, such as the European Space Agency (ESA), rests with the organisation itself and those State Parties that are also members of that organisation.

Responsibility relates to 'activities in outer space' and there are different views as to whether this extends beyond specific activities physically located 'in' outer space, or identified in the OST, namely the use and exploration of outer space, as well as launch.[132] The 2013 UN Resolution on national legislation relevant to the peaceful exploration of outer space, by using the term 'may', suggests that State oversight in relation to launch and return is desirable but not required.[133] The Cologne Commentary prefers the view, which it considers to be in line with the 'telos' of the OST, that where an activity extends to outer space, however defined, the OST applies, entailing state responsibility from launch to demise. Air law will also apply

[131] See Poonuganti (2023) at *Supra 161* and Reinert (2020) at *Supra 156*.
[132] Cologne Commentary (2021) pp.189-90. The Commentary, at p.191, notes that those States that do authorise non-governmental activities include launch, and in some cases only launch.
[133] UN General Assembly Resolution of the 11 December 2013, containing Recommendations on national legislation relevant to the peaceful exploration and use of outer space, A/RES/68/74, para.1. The preamble notes the need to 'minimise the potential harm to the environment' and that the scope of oversight may extend to the 'launch of objects into and their return from outer space', preamble and para.1.

to those parts of the activity that occur within air space.[134] A 'significant number' of the participants in the UNOOSA 2023 stakeholder study highlighted that space debris mitigation was an important criterion for licensing or authorisation, indicating that end-of-life is now being quite widely addressed in national licensing practice, albeit with a focus on timely removal from outer space as opposed to the impact of ablation.[135]

Article VIII OST provides that a State on whose registry a space object is recorded retains jurisdiction and control over the space object while it is in outer space. Ownership is not affected by the object's presence in outer space. A State that decided to remove or alter the trajectory of a space object for which it is not responsible, would thus be interfering with such control and the property rights of the owner of the space object. Any resulting damage could potentially lead to liability under the Liability Convention discussed further below.

The 'benefits' and 'due regard' principles, discussed above, impose on States an obligation to assess, and take appropriate measures to prevent, national activities in outer space causing significant harm to other countries or State Parties. By virtue of Article III OST, they must also ensure these activities comply with their international obligations, notably international environmental law. Many States, such as the UK, already build certain environmental considerations into their licensing procedures,[136] Licensing regimes variously involve environmental impact assessments, criteria around end of life disposal, and in one instance a specific licence for disposal of a launch vehicle on the sea bed.[137] But even for States committed to addressing global environmental challenges, absent further scientific study and investigation, the appropriate (precautionary) steps to take to address the risk of environmental harm from ablation are far from clear. Those states that do take a proactive approach could be disadvantaged in an increasingly global space economy, underlining the need for co-ordination, information sharing, and consistent application of scientifically robust international standards. It is also worth remembering that the requirement to authorise and continually supervise under Article VI OST only applies to non-governmental entities, and the practice of states in licensing governmental activities is mixed. This potentially limits access to information regarding a significant proportion of space activities, with implications for assessing the full impact of ablation.

3.2.1.5 The Potential for Enhanced Environmental Information Sharing Under Articles VIII and XI OST, and the Registration Convention.

A key objective of those who drafted the OST was to enhance co-ordination and transparency in space activities. This is reflected in Resolution 1721 XVI B, which preceded adoption of the OST, calling on states to report their satellite launches to COPUOS and for the Secretary-General to keep a public registry of the information provided.[138] States Parties to the OST are

[134] Cologne Commentary (2021) p.189.
[135] UNOOSA, *Registration of Objects Launched into Outer Space, Stakeholder Study*, November 2023 at https://www.unoosa.org/oosa/en/oosadoc/data/documents/2023/stspace/stspace91_0.html, p.21.
[136] The UK requires an environmental impact assessment to be carried out for spaceport and launch and return licences, while the grant of orbital operator licences under the Outer Space Act 1986 or Space Industry Act 2018 involves consideration of the impact of the proposed activity on the orbital environment, including end of life, see further section 3.2.5.1 below.
[137] UNOOSA (2023), *Supra 135* at p.21.
[138] UN General Assembly Resolution 1721 (XVI). International co-operation in the peaceful uses of outer space, 1085th plenary meeting, 20 December 1961.

now required by virtue of Article XI to inform the Secretary-General of the UN, the public and scientific community 'to the greatest extent feasible and practicable, of the nature, conduct, locations and results' of their space activities. The Secretary-General is required to then disseminate this information 'immediately and effectively', currently through the Index of Submissions by States under Article XI of the OST.[139] A number of States, notably the UK and the Netherlands, use this mechanism to keep the international community informed about the decommissioning of their space objects, passivation measures, date and time of disposal, and the orbital parameters of re-entry.[140]

The 1975 Registration Convention (REG) is more limited in scope than Article XI OST in that it relates to 'space objects' rather than 'space activities. It requires one of the launching states to record the launch of a space object into earth orbit or beyond in a national registry. The state of registry is then to notify the Sec-Gen of the UN with the information specified in Article IV REG regarding the space object and its launch, which is in turn to be recorded in a separate UN Registry of Objects Launched into Outer Space.[141]

The UN Registry is a useful, though incomplete, resource when seeking to assess the number of satellites that have been placed in orbit. It can be supplemented by ITU filings, which give an indication of intended future launches. The details specified in Article IV REG are quite limited and include the designator, date of launch, orbital information, and 'general function' of the object. Of particular interest for this study, the State of Registry is also required to inform the Secretary-General 'to the greatest extent feasible and as soon as practicable' of space objects it has previously notified 'which have been but no longer are in earth orbit' (Article IV.3). The State may also provide further information on a voluntary basis (Article IV.2), for instance whether the object carries a nuclear power source.

The disadvantage of the UN register is that the Convention only requires information to be provided after the launch, which is sometimes conveyed long after, or not at all. The number of States who have ratified the REG is below that for the OST and some States exempt space objects with defence or governmental purposes from authorization requirements altogether.[142] UNOOSA found that less than a third of parties to the REG do, or would, report when a space object is no longer in Earth orbit, even though required. In contrast, Article XI OST is not limited by a specific list and the requirement that information be provided to 'the greatest extent feasible and practicable' in relation to the nature, conduct, and the results of space activities, opens the door to a richer exchange of information. This is particularly so when Article XI is interpreted with reference to the 'benefits', due regard, and compliance with international law principles discussed above.

As early as 2007 the UN General Assembly was recommending consideration of furnishing additional information under the Convention regarding, inter alia, any change of status, the 'approximate date of decay or re-entry', and, 'where States are capable of verifying that information', the 'date and physical conditions of moving a space object to a disposal orbit'.[143]

[139] Accessible at: https://www.unoosa.org/oosa/en/treatyimplementation/ost-art-xi/index.html.
[140] See, information provided by the UK on the decommissioning of communications satellite AMC-18 at: https://www.unoosa.org/res/osoindex/data/documents/gb/a/aac_1051319_html/AC105_1319E.pdf
[141] The Register is available at: https://www.unoosa.org/oosa/en/spaceobjectregister/index.html.
[142] UNOOSA (2023) *Supra 135* at p.22.
[143] UNGA Resolution 62/101 of 17 December 2007 at: https://www.unoosa.org/pdf/gares/ARES_62_101E.pdf.

States that have provided information to COPUOS on the development of the reporting requirements have been broadly supportive of enhancing the information made available under Article XI OST and greater standardization, possibly through a more detailed template and searchable depository.[144] From an ablation perspective, further information regarding specific materials used in a space object, weight, expected life span, re-entry alignment and procedures, would all be valuable.

By way of completeness, it is worth mentioning that Article VIII OST and Article V of the Rescue Agreement (ARRA) make provision for the exchange of information regarding a space object, or component part thereof, when found outside the territory of the State of registry, and for its return. The State of registry is required to provide information about the object if so requested prior to return (Art. VIII OST). If a Party to the Rescue Agreement has reason to believe an object or component part could be hazardous or of a 'deleterious nature' it can 'notify the launching authority, which shall immediately take effective steps…to eliminate possible danger of harm' under the direction and control of the notifying State (Art. V ARRA).

3.2.1.6 Means of Interpretation and Enforcement of International Space Law

The four main international space treaties establish important parameters for space activities but were drafted before the development of private space activities and at a time of very different technological capabilities and policy priorities. There are consequently 'gaps' in the coverage of certain current concerns, in particular, the environmental impact of space activities. The treaties also include a number of open-ended principles and key terms, such as 'fault' and 'extraterrestrial', that are open to divergent interpretations.[145] Some of these gaps and ambiguities could be addressed through treaty amendment, but, as previously noted, this is not a realistic option, given conflicting national strategic interests and current political tensions.[146]

Soft law recommendations, declarations and guidelines can be used to provide greater certainty and coordination in the application of the treaty provisions but to date guidance on Earth-related contamination aspects of space activities has been limited.[147] The separation of the legal and scientific working groups within COPUOS, the limited institutional scope for industry participation, and reliance on consensus to adopt decisions, which affords every member of the Committee in effect a power of veto, all impede the ability of COPUOS to respond in a timely and coordinated fashion to technical and industrial developments. This has led some commentators to suggest, as a minimum, an honest appraisal of the limitations of the existing framework,[148] or, more ambitiously, consolidation of the existing international treaties and creation of a strengthened global space organisation or agency[149].

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[144] Luxembourg/Germany, 'Dedicated Tools and Practices for Enhanced Information Sharing', COPUOS
[145] Vienna Convention on the Law of Treaties, 23 May 1969 (entered into force 27 January 1980) 1155 UB+NTS 331.
[146] OST Art.XV, ARRA Art.VIII, LIAB Art. XXV, REG Art.IX.
[147] See 3.2.4 below.
[148] D. Kendall and G. Brachet, 'COPUOS: Current and Future Challenges' (2023) 48 *Air and Space Law*, Special Issue, pp.7-18.
[149] F. Gaspari and A. Oliva (2019) 'The Consolidation of the Five UN Space Treaties into One Comprehensive and Modernized Law of Outer Space Convention: Toward a Global Space

The system for resolving disputes relating to the OST and other space treaties is widely considered inadequate.[150] The LIAB has yet to be pursued to a Claims Commission and is unlikely to influence State licensing practices in the context of cumulative, long term environmental damage (see 3.2.1.3 above). It reflects a more general preference for diplomatic resolution and State freedom to decide whether or not to commit to a binding dispute resolution regime.[151]

Article III OST brings into play international law and the UN Charter, which, in Article 33, lists the various means of dispute resolution to be applied by parties where a dispute is likely to endanger international peace and security.[152] These include both non-binding mechanisms, such as negotiation and mediation, and, subject to the agreement of the parties, binding mechanisms, such as arbitration and adjudication. Reference may also be made to the General Assembly and Security Council in such a context (Article 35, see also Article 37).

The International Court of Justice (ICJ) has competence to give advisory opinions on legal questions raised by duly authorised UN organs and specialised agencies.[153] Although COPUOS is an organ of the UN it is not listed as having such competence, nor is it an agency, unlike UNESCO, the ICAO and the ITU, which can seek advice on legal questions falling within their remit, if authorised by the Assembly General. The ICJ also has competence to settle legal disputes referred to it by states and contentious cases can be brought by all state members of the UN either by agreement, or where provided specifically in the relevant treaty.[154] The OST and other international space treaties do not make such provision. Recourse is also possible where a state declares that it accepts the compulsory jurisdiction of the ICJ, on a basis of reciprocity, regarding the interpretation of a treaty and any question of international law. This could potentially open the way to proceedings, though to date no space related claim has been so referred to the ICJ and Deplano has observed that 'States do not support the prospect of treaty interpretation by international institutions on space law matters'.[155]

State compliance with their international space law commitments thus depends on their good faith implementation of these provisions in domestic law and recognition in their relations with other States and international organisations. State responsibility under the OST for 'national activities', means that many of the principles in the OST are built into domestic licensing regimes. The UK Space Industry Act 2018, for example, establishes a detailed licensing regime, encompassing safety, security and sustainability requirements, breach of which can

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Organization' in G.D. Kyriakopoulos and M. Manoli (eds) *The Space Treaties at Crossroads* (Springer 2019).

[150] J. Frohloff, 'Per Arbitrum Ad Astra', (2020) 37 *Journal of International Arbitration*, p. 721; F. Tronchetti, 'The PCA Rules for Dispute Settlement in Outer Space: A Significant Step Forward' (2013) 29 Space Policy, p. 181 at 182, though contrast with Rosanna Deplano, 'The Peaceful Settlement of Space Disputes' in R. Buchan, D. Franchini, N. Tsagourias (eds).*The Changing Character of International Dispute Settlement: Challenges and Prospects* (2023; Cambridge University Press) at pp.403-438.

[151] Deplano (2003), Ibid.

[152] UN Charter, 26 June 1945 (entered into force 24 October 2045) 1 UNTS 16.

[153] Statute of the International Court of Justice, signed 26 June 1945 (entered into force 24 October 1945) arts. 65-68.

[154] Statute of the ICJ (1945), arts. 34-38.

[155] Deplano (2023) *Supra 150* at p.424.

lead ultimately to suspension of the licence or prosecution for a criminal offence.[156] Domestic implementation can thus give the international regime 'teeth' but implementation is variable, the mixed approaches to registration have been noted, and different national rules and expectations can lead to forum shopping.

The LIAB does not exclude other means of dispute settlement and private actions for breach of contract or in tort/delict before domestic courts are possible. Arbitration also remains an option and the Permanent Court of Arbitration has developed specific rules for space-related disputes, with, among other adaptations, specialist arbitrators, experts, and specific rules relating to the handling of commercially sensitive information. Although this could be used to clarify certain provisions of the space treaties, for instance, the concept of 'fault' in the LIAB, to date this facility has not been used. This could be because arbitration here is relatively expensive but also, paradoxically, because it leads to binding awards.[157]

In conclusion, the available dispute resolution mechanisms are unlikely to resolve whether international space law applies to environmental damage of a kind potentially resulting from ablation.

3.2.2 Other International Sectoral Regimes Potentially Relevant to Ablation

3.2.2.1 Nuclear Activities in Space

Concern over radiation contamination stemming from nuclear tests after the Second World War led to the Partial Test Ban Treaty, covering atmospheric and marine tests, in 1963.[158] Article 1 prohibits not only nuclear weapon test explosions but also requires States to prevent 'any other nuclear explosion, at any place' under its jurisdiction or control:

(a) in the atmosphere; beyond its limits, including outer space; or under water, including territorial waters or high seas; or

(b) in any other environment if such explosion causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted.

The 1963 Treaty thus covers radiation contamination released into the atmosphere by the explosion of a nuclear-powered satellite on re-entry. The Treaty was followed in 1996 by the Comprehensive Nuclear-Test-Ban Treaty, which has still to obtain the necessary signatures to come into force.[159]

Nuclear power remains a valuable energy source for satellites stationed in high orbits or spacecraft heading for distant celestial bodies, and, as the KOSMOS 954 case illustrated, also entails significant environmental risks if re-entry occurs. To minimise these risks, the UN

[156] See CAA, Spaceflight Enforcement Policy, CAP 2987, 1 May 2024.
[157] Deplano (2023), *Supra 150.*
[158] Treaty Banning Nuclear Weapons Tests in the Atmosphere, in Outer Space and Under Water, 8 August 1963 (entered into force 10 October 1963) 480 UNTS 43.
[159] Comprehensive Nuclear-Test-Ban Treaty, 24 September 1996 (not yet in force) at: https://digitallibrary.un.org/record/4028139?v=pdf.

General Assembly adopted Resolution 47/68,[160] which establishes goals for radiation protection, safety assessments, and information sharing. In particular, the Resolution limits use of nuclear reactors to interplanetary missions and high orbits, with deployment in low Earth orbits only possible if, after completion of the operational part of the mission, the nuclear reactor is stored at a sufficiently high orbit to allow for radiation decay (Principle 3.2.(a)). In consequence, satellites or space craft with nuclear reactors should not, save where there is some malfunction or accident, re-enter the Earth's atmosphere and be subject to the effects of ablation.

The Resolution specifies that nuclear reactors are to use only highly enriched uranium 235 as fuel. It also emphasises the continuing relevance and application of key provisions in the OST, notably Articles VI and VII on State responsibility and liability, as well as the compensation regime established in the LIAB. The Scientific and Technical Subcommittee of COPUOS, together with the International Atomic Energy Agency, have also developed a Safety Framework for Nuclear Power Source Applications in Outer Space, which provides additional guidance on governmental, management and technical considerations for States and International intergovernmental organisations, such as the ESA, developing space nuclear power applications.[161]

3.2.2.2 International Air Traffic Regulation

As discussed at 1.1.2, States have sovereignty over the airspace above their territory, though there is no agreed point of demarcation between airspace and outer space, where state sovereignty is excluded by Article II OST. Ablation occurs, however, below 100km, that is below what most States would consider airspace, the exact area and intensity of burning depending on the angle and speed of re-entry of the space object. Air law and space law are subject to entirely different regulatory regimes, helpfully detailed by Dempsey and Manoli.[162] As with space law, air law is governed by a series of international agreements, though these are more extensive in scope and detailed in terms of provision, covering fields such as safety, navigation, registration, liability, security and criminal activity.[163] In the space law context these concerns are largely left to be developed by individual States as part of their licensing processes. In particular, space law imposes oversight and liability on States, whereas under air law liability rests with the airline or operator.

The relevance of these rules to ablation is questionable on two counts. Firstly, the ablation process takes place above operational zone for commercial air traffic, rendering largely irrelevant the safety and navigation requirements in treaties such as the 1944 Chicago Convention on Civil Aviation.[164] Secondly, an ablating satellite is not an 'aircraft', the focus of the international air law agreements. Though not defined in foundational treaties such as the Chicago Convention, Annex 7 of the Chicago Convention defines an 'aircraft' as '[a]ny machine that can derive support in the atmosphere from the reactions of the air…'. The

[160] UNGA Resolution 47/68, Principles Relevant to the use of Nuclear Power Sources in Outer Space', A/AC.105/C.1/2014/CRP.3.
[161] See COPUOS, 'Defining the Organizational Structure that Implements a Space Nuclear Power Source Mission Application', 5 February 2014, A/AC.105/C.1/2014/CRP.3.
[162] Dempsey and Manoli (2017).
[163] Ibid.
[164] Convention on International Civil Aviation, signed 7 December 1944, (entered into force 4 April 1947) 15 UNTS 295.

existence of wings and horizontal take off is not conclusive. From a functionalist perspective, this definition does not cover satellites and their component parts, in that they are not designed, at least in their operational phase, to derive any support from the air. From a 'spatialist' perspective, satellites are destined for outer space and are thus more appropriately considered space objects than air craft.

A further consequence is that the presumptive freedom of transit though another State's airspace, granted by Article 5 of the Chicago Convention to non-scheduled civil aircraft services, would not apply. Absent the establishment of a customary international law right of transit, a State would thus have the right to deny an ablating space object access to its airspace. A key question requiring further examination is thus whether such a customary international right of transit for de-orbiting space objects in the upper atmosphere has been established and, if not, the extent to which it is feasible to notify states in advance of ablation events likely to occur in their air space in order to obtain the necessary consents. If States do have the right to control ablation events occurring in their air space, then a further question is whether this creates international responsibility to assess and address the risks of significant transboundary pollution, for instance, under Principles 21 of the Stockholm declaration and 2 of the Rio Declaration.[165] Although the damage occurs in national airspace its impact is on the atmosphere, the air and clouds, considered a common resource. The situation is further complicated where ablation arises in the airspace over the high seas and is not, therefore, subject to national jurisdiction. It is worth noting that Article 12 of the Rio Declaration states that '[u]nilateral actions to deal with environmental challenges outside the jurisdiction of the importing country should be avoided. Environmental measures addressing transboundary or global environmental problems should, as far as possible, be based on an international consensus.'[166]

On the other hand, certain launch vehicles, spacecraft components and sub-orbital spacecraft could be classified as aircraft, bringing into play the body of air law. The 1952 Rome Agreement provides for liability for damage caused to persons 'on the surface' by foreign aircraft in flight or things falling from them but does not cover indirect damage or any consequences that stem from legal air flight activities (Article 1).[167] Recognition of the potential overlap between international air law and space law, with their very different regimes, representation and standard-setting processes, led to a period of heightened co-ordination between the ICAO, the UN agency charged with overseeing international air law, and UNOOSA, through a series of symposia, culminating in 2017.[168]

The role of the ICAO is of interest, not only because of its distinct composition and competences but also because of its direct role in addressing air pollution arising from air transport. As discussed further below, the ICAO has established emission limits for aircraft

[165] Stockholm Declaration (1972); Rio Declaration (1992).
[166] Rio Declaration (1992).
[167] Convention on damage caused by foreign aircraft to third parties on the surface, 7 October 1952 (entered into force 4 February 1958), 310 UNTS 181.
[168] COPUOS, Use of space technology in the United Nations system: Cooperation between the United Nations Office for Outer Space Affairs and the International Civil Aviation Organization, 18 June 2019, A/AC.105/2019/CRP.14, which envisages, inter alia, adoption of a memorandum of understanding between the two organisations. For detailed discussion of air law and sub-orbital flights see Stefan Wedenig, Suborbital Point-To-Point Flights—Applicability of Air Navigation Law and Aviation Criminal Law, McGill University (Canada) ProQuest Dissertations & Theses, 2021. 29274698.

engines to protect air quality near to airports and a Carbon Offsetting and Reduction Scheme for International Aviation.[169] Though the Carbon Offset scheme is limited, it highlights both the ability of the ICAO to support the negotiation of what, from 2027, will be binding standards, and the absence of similar requirements developed in the context of international space activities.[170]

3.2.2.3 The Radio Regulations and Management of the Electro Magnetic Spectrum

As with the ICAO (but unlike UNCOPUOS), the International Telecommunication Union (ITU), which governs the allocation of global radio spectrum and satellite orbits, is a specialized UN agency. Serving as the gatekeeper for information and communication technologies, it works towards establishing coordinated and universal access to digital technologies. The agency is made up of 193 Member States alongside over 1000 companies, international and regional organizations, and educational institutions.

The agency acts as the only regulatory institution which manages and registers the radiofrequency spectrum needed for satellites to function for their mission operations and communication to ground stations. It facilitates the management of the radio-frequency spectrum, the development of policy and regulatory frameworks concerning telecommunications and ICT, emergency telecommunications, and more.[171] Satellite filings are issued by nations on behalf of organizations following the ITU's Constitution, Convention, and Radio Regulations. Registrations of satellites are recorded in the Master International Frequency Register (MIFR), [172] which details the frequency assignments, as well as information as notified under article 11 of the Radio Regulations (RR). The preamble to the RR provides that the ITU is to 'facilitate equitable access to and rational use of the natural resources of the radio-frequency spectrum and the geostationary-satellite orbit', while Article 4 states that 'Member States shall endeavour to limit the number of frequencies and the spectrum used to the minimum essential to provide in a satisfactory manner the necessary services. To that end they shall endeavour to apply the latest technical advances as soon as possible'.[173] This is relevant when considering the contribution that controls over the number of satellites in orbit could have on future atmospheric and terrestrial pollution levels.

In the UK, the notifying administration is Ofcom, which manages the submission of all satellite fillings to the ITU for organizations registered in the UK, British Overseas Territories, the Channel Islands and Isle of Man. An understanding of the ITU filing system is crucial for research into ablation, particularly regarding e concerns over information sharing, transparency, limitations on the number of satellites, and understanding the true scale of objects existing in orbit and re-entering.

Determining the exact number of satellites is far from an exact science and predictions as to future launches can be inaccurate. As Falle et. al. (2023) describes, this can occur for a

[169] See Sands et al. (2018), supra, p. 275.
[170] Ibid.
[171] ITU (2023). Handbook on small satellites 2023. Retrieved from https://www.itu.int/dms_pub/itu-r/opb/hdb/R-HDB-65-2023-PDF-E.pdf
[172] ITU (2024). Master Frequency Register (MIFR). Retrieved from https://www.itu.int/en/ITU-R/terrestrial/broadcast/Pages/MIFR.aspx
[173] Radio Regulations, 2020 edition, at: https://www.itu.int/en/publications/ITU-R/Pages/publications.aspx?parent=R-REG-RR-2020&media=electronic.

number of reasons such as over-filling,[174] from companies choosing to spread out their satellite constellations between multiple fillings, and/or companies having multiple nations file for the same satellite constellation.[175] Further complicating the issue is the diverging policies on ITU filings between nations-opening up avenues for companies to make use of flag-of-convenience nations to bypass more stringent regulations.[176]

The ITU constitution allows a) recognized operating agencies, scientific or industrial organizations and financial or development institutions which are approved by the Member State concerned; b) other entities dealing with telecommunication matters which are approved by the Member State concerned; and c) regional and other international telecommunication, standardization, financial or development organizations; to participate in the Union's activities (Article 19).[177] This enhances the representative nature of the ITU, considered a potential point of reference for any future development of the framework for the international regulation of outer space.[178] The ITU participates in the UN Inter-Agency Meeting on Outer Space Activities (UN-Space), set up in the mid-seventies to promote collaboration in the use of exchange of information and co-ordination regarding matters relating to space technology and its applications.[179]

3.2.3 International Environmental Law

This section considers whether international environmental laws regarding the ozone and climate, capture environmental harm caused by space activities. It concludes that, while general international law may indirectly regulate certain aspects of space activities, the result is a patchwork of obligations with significant gaps in terms of environmental protection.

3.2.3.1 Customary rules and principles of International Environmental Law

The Outer Space Treaty (OST) emphasises that activities in exploring and using outer space must be in accordance with International Law,[180] extending the customary rules of International Environmental Law (IEL) to earth pollution derived from space activities.[181] One of the primary principles of IEL is the principle of prevention of transboundary harm, which, as enshrined in the Stockholm Declaration[182] and Rio Declaration[183], requires States to ensure

[174] Falle, A., et. al. (2023). One million (paper) satellites. Retrieved from https://outerspaceinstitute.ca/osisite/wp-content/uploads/One-million-paper-satellites-Accepted-Version-.pdf
[175] Ibid
[176] Ibid
[177] 1994 Constitution and Convention of the ITU, Kyoto, 1994 at: https://www.itu.int/itudoc/gs/consconv/index.html.
[178] Kendall and Brachet (2023) p.17.
[179] Meetings are annual, details at https://www.unoosa.org/oosa/en/ourwork/un-space/index.html.
[180] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies (adopted 27 January 1967, entered into force 10 October 1967) 610 UNTS 205 (OST), art 3.
[181] Carl Q Christol, 'International Liability for Damage Caused by Space Objects' (1980) 74 (2) American Journal of International Law 346-371, 353.
[182] UNGA 'United Nations Conference on the Human Environment' Res 2994 (XXVII) (15 December 1972) UN Doc A/RES/2994 (Stockholm Declaration), Principle 21.
[183] 1992 Rio Declaration on Environment and Development (14 June 1992) UN Doc A/CONF.151/26 (vol I) (Rio Declaration), Principle 2.

that activities in their territory or under their control do not harm the environment of other States or areas beyond national jurisdiction (ABNJ).

3.2.3.2 The Principle of Prevention of Transboundary Harm

The principle has been recognised as a customary rule[184] and is mentioned in various international treaties.[185] Since the State on whose registry an object launched into outer space is carried retains jurisdiction and control over such object, the principal *prima facie* applies to the States undertaking space activities. However, applying it to the ablation of space debris is particularly challenging.

The obligation of due diligence underpins the principle of prevention of transboundary harm,[186] which is considered an obligation of conduct, not one of result.[187] Due diligence requires States to notify, warn, inform, or consult States potentially affected by environmental harm and to undertake environmental impact assessments (EIA).[188]

The current scientific knowledge suggests that the ablation of space debris could potentially cause ozone depletion, upper atmospheric pollution, climate change, and marine degradation .[189] Traditionally, the principle has been applied to cases of immediate and direct harm, while the potential harm from ablation is more diffuse and long-term, making it difficult to attribute the harm to any single instance of ablation. Conducting an EIA as part of due diligence to determine the risk of significant environmental harm due to ablation is a challenge. The unpredictable re-entry of space objects combined with the long-term and diffuse nature of ablation makes conducting a comprehensive and accurate EIA an onerous task.

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184 *Case Concerning Pulp Mills on the River Uruguay* (*Argentina v Uruguay*) (Judgement) [2010] ICJ Rep 14, para 101; *Certain Activities Carried Out by Nicaragua in the Border Area (Costa Rica v Nicaragua) and Construction of a Road in Costa Rica along the San Juan River (Nicaragua v Costa Rica)* (Judgement) [2015] ICJ Rep 665, para 104.

185 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (adopted 29 December 1992, entered into force 30 August 1995) 1046 UNTS 120, preamble; Convention on Long-range Transboundary Air Pollution (adopted 13 November 1979, entered into force 16 March 1983) 1302 UNTS 217, preamble; United Nations Convention on the Law of the Sea (adopted 10 December 1982, entered into force 16 November 1994) 1833 UNTS 3 (UNCLOS), art 192; Vienna Convention for the Protection of the Ozone Layer (adopted 22 March 1985, entered into force 22 September 1988) 1513 UNTS 293, preamble; Convention on Biological Diversity (adopted 5 June 1992, entered into force 29 December 1993) 1760 UNTS 79 (CBD), art 3; United Nations Framework Convention on Climate Change (adopted 9 May 1992, entered into force 21 March 1994) 1771 UNTS 107 (UNFCCC), preamble.

186 *Case Concerning Pulp Mills on the River Uruguay* (n 5).

187 Pierre-Marie Dupuy, 'Reviewing the difficulties of codification: on Ago's classification of obligations of means and obligations of result in relation to state responsibility' (1999) 10 European Journal of International Law 371, 379-380.

188 Jutta Brunnée, 'Harm Prevention' in Lavanya Rajamani and Jacqueline Peel (eds), *The Oxford Handbook of International Environmental Law* (2nd edn, OUP 2021) 275; *Certain Activities Carried Out by Nicaragua in the Border Area (Costa Rica v Nicaragua) and Construction of a Road in Costa Rica along the San Juan River (Nicaragua v Costa Rica)* (n 5).

189 Robert Ryan and others, 'Impact of Rocket Launch and Space Debris Air Pollutant Emissions on Stratospheric Ozone and Global Climate' (2022) 10 (6) Earth's Future e2021EF002612; Aaron C Boley and Michael Byers, 'Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth' (2021) 11 Scientific Reports <https://doi.org/10.1038/s41598-021-89909-7> accessed 4 August 2024; Samantha M Tracy and others, 'Stratospheric aerosol injection may impact global systems and human health outcomes' (2022) 10 (1) Elementa: Science of the Anthropocene <https://doi.org/10.1525/elementa.2022.00047> accessed 7 August 2024.

Further, the process of notifying and consulting the affected States is complicated as the direct impact of ablation primarily occurs in ABNJ, such as the ozone layer, atmosphere, and oceans, which are all global commons, whereas further or indirect impacts of ablation such as climate change affects States themselves.[190] As a result of the indeterminate extent of the harm of ablation caused in ABNJ and to States, notifying and consulting with all potentially affected States through an international institution becomes a necessity. As the existing legal frameworks do not prescribe a specific international institution for addressing potential environmental harm from ablations, simultaneous notification and consultation processes in multiple international forums to discuss different aspects arising from a single issue need to be undertaken, which is a classical problem of fragmentation of international law.

Further, to satisfy the due diligence obligation, a State engaging in the ablation of space debris is dutybound to adopt appropriate rules and measures[191] to impose environmental restrictions on all space operators in their jurisdiction who plan to ablate space debris. Hence, the State must ensure that the domestic preventive requirements concerning ablation meet the standards of ‘best available techniques/technologies’ (BATs) and ‘best environmental practices’ (BEPs).[192] Currently, there are no internationally recognised BATs or BEPs aimed at reducing the impact of ablation on Earth’s environment against which the domestic measures can be evaluated.

It is currently unclear whether a failure of States undertaking ablation to fulfil the procedural obligations alone would constitute a breach of the principle in the absence of actual significant environmental harm.[193] Assuming the application of the principle is deemed intrinsic to undertaking ablation, determining compliance with the principle will be challenging as proving tangible, significant environmental harm from ablation is arduous due to the nature of potential harm.

Even when one succeeds in arguing for the application of the rule of prevention of transboundary harm, manoeuvring the technical difficulties, it will be a hurdle to hold any State responsible for the violation of the principle. Typically, only a State has the authority to bring action against another State for the breach of international law which caused a violation of its rights. Theoretically, any State may bring an action against the wrongdoing State in case of environmental harm in ABNJ stemming from a breach of international law, claiming the

[190] Leslie-Anne Duvic-Paoli, ‘Prevention and Protection of the Environment: Spatial Scope’ in The Prevention Principle in International Environmental Law Cambridge University Press 2018) 240.
[191] *Case Concerning Pulp Mills on the River Uruguay* (n 5) para 197.
[192] Leslie-Anne Duvic-Paoli (n 11) 209.
[193] See, *Case Concerning Pulp Mills on the River Uruguay* (n 5) para 282; *Certain Activities Carried Out by Nicaragua in the Border Area (Costa Rica v Nicaragua) and Construction of a Road in Costa Rica along the San Juan River (Nicaragua v Costa Rica)* (n 5); *Certain Activities Carried Out by Nicaragua in the Border Area (Costa Rica v Nicaragua) and Construction of a Road in Costa Rica along the San Juan River (Nicaragua v Costa Rica)* (Separate opinion of Judge ad hoc Dugard) [2015] ICJ Rep 665, para 10; *Certain Activities Carried Out by Nicaragua in the Border Area (Costa Rica v Nicaragua) and Construction of a Road in Costa Rica along the San Juan River (Nicaragua v Costa Rica)* (Separate opinion of Judge Donoghue) [2015] ICJ Rep 665, para 9; Jutta Brunnée (n 9) 276; Leslie-Anne Duvic-Paoli, ‘The Frontiers of Prevention?: Reparation and Compliance Control’ in The Prevention Principle in International Environmental Law (Cambridge University Press 2018) 337.

violation of *erga omnes* obligations, which are obligations that any State owes to the international community as a whole.[194]

Although the classification of the duty of States to protect the marine environment as an *erga omnes* obligation is established,[195] the status of the duty to prevent atmospheric pollution and degradation as an *erga omnes* obligation is intensely debated among scholars.[196] Despite recognising atmospheric pollution and degradation as a 'common concern of humankind,' the International Law Commission contends that they do not entail an *erga omnes* obligation.[197] As such, it is highly uncertain whether any State can claim *locus standi* before an international court or tribunal in a legal action against the wrongdoing State for breaching the rule of prevention of transboundary harm with respect to the global atmosphere.

3.2.3.3 Precautionary Principle

The precautionary principle stipulates the need for States to enact measures to avoid environmental degradation when presented with evidence of a threat of severe or irreversible harm.[198] The principle appears in various international instruments,[199] and the International Tribunal of the Law of the Sea has repeatedly applied the principle in multiple instances[200] and has held that this "obligation applies in situations where scientific evidence concerning the scope and potential negative impact of the activity is insufficient but where there are plausible indications of potential risks."[201]

The applicability of this principle in situations of lack of complete scientific certainty wherein the activity in question can lead to irreversible harm sets it apart from other principles of international environmental law. To trigger the precautionary principle, the scientific certainty of threatened harm must be perceived as reasonably plausible to cause undesirable

[194] See, UNGA 'Responsibility of States for Internationally Wrongful Acts' Res 56/83 (28 January 2002) UN Doc A/56/589 (ARSIWA) art 48; Leslie-Anne Duvic-Paoli, 'The Frontiers of Prevention?: Reparation and Compliance Control' in The Prevention Principle in International Environmental Law (Cambridge University Press 2018) 342.
[195] *Responsibilities and Obligations of the States Sponsoring Persons and Entities with Respect to Activities in the Area* (Advisory Opinion, 1 February 2011) ITLOS Reports 2011, para 180
[196] See, Leslie-Anne Duvic-Paoli, 'The Frontiers of Prevention?: Reparation and Compliance Control' in The Prevention Principle in International Environmental Law (Cambridge University Press 2018) 340-341.
[197] United Nations Draft guidelines on the protection of the atmosphere (2021) Adopted by the International Law Commission at its seventy-second session, submitted to the General Assembly (A/76/10, para 40), Yearbook of the International Law Commission, 2021, vol. II, Part Two, Comment 3 to the Preamble.
[198] Jesse Cameron Glickenhaus, 'Potential ICJ Advisory Opinion: Duties To Prevent Transboundary Harm from GHG Emissions' (2015) 22 NYU Environmental Law Journal 117, 149.
[199] Vienna Convention for the Protection of the Ozone Layer (adopted 22 March 1985, entered into force 22 September 1988) 1513 UNTS 293; Montreal Protocol on Substances that Deplete the Ozone Layer (adopted 16 September 1987, entered in force 1 January 1989) 1522 UNTS 3; Convention on Biological Diversity (adopted 5 June 1992, entered into force 29 December 1993) 1760 UNTS 79 (CBD); United Nations Framework Convention on Climate Change (adopted 9 May 1992, entered into force 21 March 1994) 1771 UNTS 107 (UNFCCC); Agenda 21 (14 June 1992) UN Doc A/CONF.151/26 (vol II); 1992 Rio Declaration on Environment and Development (14 June 1992) UN Doc A/CONF.151/26 (vol I) (Rio Declaration).
[200] *South Bluefin Tuna* (*N.Z. v Japan; Australia v Japan*) (Provisional Measures, 2 August 1999) ITLOS Reports 280, para 79; *Responsibilities and Obligations of the States Sponsoring Persons and Entities with Respect to Activities in the Area* (Advisory Opinion, 1 February 2011) ITLOS Reports 2011, para 132.
[201] *Responsibilities and Obligations of the States Sponsoring Persons and Entities with Respect to Activities in the Area* (n 17) para 131.

consequences.[202] The scientific uncertainty over the environmental impact of ablation seemingly makes it a perfect scenario to apply the precautionary principle. However, the current lack of precise scientific understanding of the impact also makes it difficult to determine the appropriate measures necessary to avoid any environmental degradation.

3.2.3.4 The Ozone Treaty

Stratospheric ozone in Areas Beyond National Jurisdiction (ABNJs) is protected under the **Montreal Protocol on Substances that Deplete the Ozone Layer** ("Montreal Protocol"), and its parent convention.[203] Generally recognised as a successful exercise in governing an environmental problem of the global commons, the Montreal Protocol establishes legally binding targets for reducing the production and consumption of ozone depleting substances ("ODS"), in particular chlorofluorocarbons ("CFCs").[204] Given universal ratification and a stringent non-compliance procedure, the Montreal Protocol has been hugely effective in reducing emissions under its purview.

Scholars have already pointed out the inappropriateness of the Montreal Protocol in addressing the emissions from rockets or spacecraft into the stratosphere.[205] Despite frequent amendments to bring other ODS within its scope, the Montreal Protocol currently does not appear to cover ozone depletion caused by satellite ablation or rocket launches for two main reasons.

Firstly, risks to the ozone layer from space activities may fall outside the scope of the Montreal Protocol. The so-called ozone-depleting potential ("ODP"), which is the metric used to identify substances for phase-out, only captures emissions at the Earth's surface, which disqualifies the emissions directly injected into the stratosphere, as well as the thermal ablation of satellites at the top of the mesosphere. Although the Montreal Protocol's Quadrennial Assessment of Ozone Depletion (2022) recognises the significant risk of methane rocket propellants in the future,[206] it does not recognise emissions from space activities falling back on earth. The "production" of ODS as defined under the Montreal Protocol does not cover substances released into the stratosphere due to the ablation of aluminium satellites.[207]

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[202] See, Jacqueline Peel, 'Precaution' in Lavanya Rajamani and Jacqueline Peel (eds), The Oxford Handbook of International Environmental Law (2nd edn, OUP 2021) 305; Ole W Pedersen, 'From Abundance to Indeterminacy: The Precautionary Principle and Its Two Camps of Custom' (2014) 3 (2) Transnational Environmental Law 323, 327.

[203] Montreal Protocol on Substances that Deplete the Ozone Layer (adopted 16 September 1987, entered into force 1 January 1989) 1522 UNTS 3 (Montreal Protocol); Vienna Convention for the Protection of the Ozone Layer (adopted 22 March 1985, entered into force 22 September 1988) 1513 UNTS 293 (Vienna Convention)

[204] Paolo Galizzi and Kerry Gillich, 'Atmospheric and Air Pollution' in Erika J Techera and others (eds), *Routledge handbook of international environmental law* (2nd edn, Routledge 2021) 213.

[205] Martin Ross, Darin Toohey, Manfred Peinemann & Patrick Ross, "Limits on the Space Launch Market Related to Stratospheric Ozone Depletion" (2009) 7:1 *Astropolitics* 50-82.

[206] World Meteorological Organization, 'Scientific Assessment of Ozone Depletion 2022', GAW Report No. 278, < https://csl.noaa.gov/assessments/ozone/2022/downloads/2022OzoneAssessment.pdf >, at pp. 3 & 49.

[207] See Montreal Protocol art 2 in conjunction with annex A; Scot W Anderson, Julia La Manna and Korey J Christensen, 'The Development of Natural Resources in Outer Space', *Journal of Energy & Natural Resources Law* 37.2 (2019): 227-258.

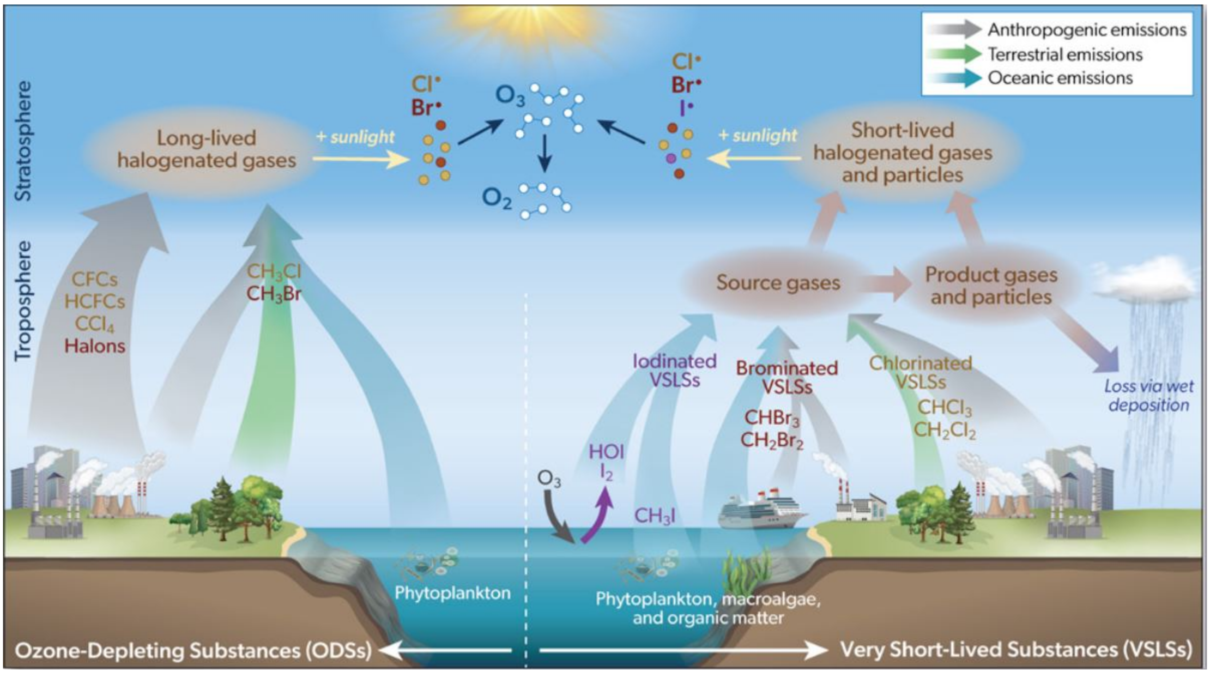

Figure 24. (taken from 'Scientific Assessment of Ozone Depletion 2022', p. 83): Emissions derived from space fall outside the Ozone Treaty's legal imaginary

Secondly, space objects and space by-products are not included in the Annexes of the Montreal Protocol. Annex D regulates product-denominated categories, such as refrigerators, air conditioners, insulation boards, panels and pipe covers. Annex D excludes the objects commonly integrated in space objects, namely: solar panels, thrusters, shields, payloads, etc. Equally, the chemical elements commonly found in space objects are not regulated by Annexes A, B, C E and F of the Montreal Protocol. CFRP, metal oxides, gases and other chemicals, such as Alumina (Al_2O_3), which can catalyze the destruction of ozone (O_3) in the mesosphere, are not "Controlled substances" regulated by the Montreal Protocol Annexes.

For satellite re-entry to be included within the scope of the Montreal Protocol, the Meetings of the Parties to the Montreal Protocol would have to adjust or amend the Protocol and Annex F, by a qualified two-third majority vote of the Parties present and voting.[208] Given the past flexibility of the Montreal Protocol in adapting to emerging threats to the ozone layer, applying the regime to ablation through future amendments would be desirable and feasible. As of yet, the non-applicability of the Montreal Protocol to space activities largely leaves the environmental impacts of rocket launches in a legal void.[209]

Importantly, lack of knowledge about the precise impact of satellite re-entry on ozone depletion does not constitute sufficient grounds to inhibit regulation; the Montreal Protocol has a history of regulating potentially harmful substances in face of scientific uncertainty.[210] Following Bakker, this constitutes evidence that states have historically taken a precautionary approach

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[208] Rule 40, "Rules of Procedure for Meetings of the Parties to the Montreal Protocol" found in Annex I of the report of the First Meeting of the Parties, online: <https://ozone.unep.org/treaties/montreal-protocol-substances-deplete-ozone-layer/rules-of-procedure>.
[209] Martin Ross and James Vedda, 'The Policy and Science of Rocket Emissions' 2018) Centre for Space Policy and Strategy, The Aerospace Corporation 2, 5.
[210] Alan Boyle and Catherine Redgwell, *International Law and the Environment* (4th edn, OUP 2021) 175.

to protecting the atmosphere from ozone depletion.[211] This may be relevant insofar as the application of the precautionary principle renders causation unnecessary, the mere existence of an environmental risk being sufficient to warrant regulatory attention.

This legal opinion on the relevance of the precautionary principle was confirmed by the International Tribunal for the Law of the Sea, stating in its Advisory Opinion, that in failing to apply the precautionary principle by negating to take appropriate measures to prevent damage, notwithstanding the insufficiency of scientific evidence about the relevant potential harm but where there are 'plausible indications of potential risk', a state would fail to fulfil its due diligence obligation.[212]

Beyond the Montreal Protocol, atmospheric pollution is addressed by the **Convention on Long-Range Transboundary Air Pollution** ("CLRTAP"). Concluded under the auspices of the United Nations Economic Commission for Europe on the Protection of the Environment ("UNECE"), the CLRTAP and subsequent protocols regulate air pollutants such as nitrogen oxides and heavy metals.[213] The broad definition of air pollution under the CLRTAP renders it useful for regulating a wide range of pollutants. Notably, for 2020 onwards, the Gothenburg Protocol enshrines binding emission reduction obligations for major pollutants, including Black Carbon.[214] Similar to the Montreal Protocol, the Convention constitutes a dynamic (regional) regime responsive to emerging threats to the atmosphere. Given its history of regulating emerging threats through additional protocols, greater engagement with the environmental consequences of space activities would equally be desirable under the CLRTAP framework.

For the purposes of the CLRTAP, (a) "Air Pollution" means the introduction by man, directly or indirectly, of substances or energy into the air resulting in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other legitimate uses of the environment, and "air pollutants" shall be construed accordingly; (b) "Long-range transboundary air pollution" means air pollution whose physical origin is situated wholly or in part within the area under the national jurisdiction of one State and which has adverse effects in the area under the jurisdiction of another State at such a distance that it is not generally possible to distinguish the contribution of individual emission sources or groups of sources.[215]"

Could these definitions encompass the type of harm to the upper atmosphere likely to result from space activities? Some scholars believe so: "As CLRTAP applies specifically to the type of harm likely to be caused by commercial space flight, it seems suited to regulate the new industry. Unfortunately, like the Outer Space Treaty and the Liability Convention, an efficient enforcement mechanism is lacking and LRTAP contains no rule on State liability as to

[211] Christine Bakker, 'Protecting the Atmosphere as a "Global Common Good": Challenges and Constraints in Contemporary International Law' in Christine Bakker, The Protection of General Interests in Contemporary International Law (OUP 2021) 177.
[212] ITLOS, *Responsibilities and obligations of States sponsoring persons and entities with respect to activities in the Area* (Request for Advisory Opinion submitted to the Seabed Disputes Chamber), 1 February 2011.
[213] Convention on long-range transboundary air pollution (adopted 13 November 1979, entered into force 16 March 1983) 1302 UNTS 217 (CLRTAP).
[214] Yulia Yamineva and Seita Romppanen, 'Is Law Failing to Address Air Pollution? Reflections on International and EU Developments' (2017) 26 Review of European, Comparative & International Environmental Law 189, 193.
[215] CLRTAP art 1(b).

damage.[216]" One additional difficulty is that CLRTAP was designed to regulate emissions from major stationary sources (for example, power plants) and mobile sources (for example, vehicle emissions originating from a State's territory).[217] The problem is that ablation's air pollution originates outside of the area under the national jurisdiction of one State, and occurs in the mesosphere and the stratosphere in an Area Beyond National Jurisdiction (ABNJ).[218] If ablation occurs mostly outside the jurisdiction or control of a State, and since there are no clear rules on the conduct of States or their nationals in the upper layers of the atmosphere, the effectiveness of the CLRTAP in regulating the emissions of end-of-life satellites in the mesosphere and stratosphere is questionable.

In the absence of clear rules on the protection of the atmosphere from gases and chemicals originating in ABNJs, the ILC *Draft Guidelines on the Protection of the Atmosphere* encourage States to adopt a comprehensive view of their international legal obligations in relation to the protection of the atmosphere. In particular, Guideline 9 promotes "the interrelationship among relevant rules on the protection of the atmosphere and other relevant rules of international law (…), which should be interpreted and applied in order to give rise to **a single set of compatible obligations, in line with the principles of harmonization and systemic integration**, and with a view to avoiding conflicts. (…) States should, to the extent possible, when developing new rules of international law relating to the protection of the atmosphere and other relevant rules of international law, endeavour to do so in a harmonious manner.[219]" This interpretation is consistent with Article 31, paragraph 3 (c) of the 1969 Vienna Convention on the Law of Treaties, which is intended to guarantee a "systemic interpretation", requiring "any relevant rules of international law applicable in the relations between the parties" to be taken into account, meaning that rules should not be considered in isolation of general international law.[220] Discussions on the international legal obligations of States in regard to the protection of the atmosphere are ongoing before the ICJ in preparation of Obligations of States in respect of Climate Change (Request for Advisory Opinion).[221]

3.2.3.5 The Climate Regime

Ablation can contribute to the release of carbon dioxide ("CO2"), a greenhouse gas ("GHG") which contributes to climate change. Even though the contribution of GHG to the atmosphere from space activities is significantly small compared to other anthropogenic activities, projections suggest that the volume of GHG from space activities may constitute significant transboundary climate harm in the future. It is therefore important to consider the applicable

[216] Jennifer Friedberg, "Bracing for the impending rocket revolution: how to regulate international environmental harm caused by commercial space flight." Colo. J. Int'l Envtl. L. & Pol'y 24 (2013): 197.
[217] ICJ, Obligations of States in respect of Climate Change (Request for Advisory Opinion), PART IV: Development of international law (documents received from the Secretariat of the United Nations) 30 June 2023, PART IV (B): Protection of the atmosphere, p. 254.
[218] CLRTAP art 1(b).
[219] Draft Guidelines on the Protection of the Atmosphere, adopted by the International Law Commission at its seventy-second session, in 2021, and submitted to the General Assembly as a part of the Commission's report covering the work of that session (A/76/10, para. 39), Yearbook of the International Law Commission, 2021, vol. II, Part Two.
[220] C. McLachlan, "The principle of systemic integration and article 31 (3) (c) of the Vienna Convention", International and Comparative Law Quarterly, vol. 54 (2005), p. 279.
[221] See Part IV B Protection of the atmosphere, Obligations of States in respect of Climate Change (Request for Advisory Opinion) – online: https://www.icj-cij.org/sites/default/files/case-related/187/187-20230630-req-06-02-en.pdf

rules derived from international climate law, which could mitigate the risks posed by ablation for the climate.

In recent years, a body of international treaties has emerged to regulate State behaviour in order to protect the world's climate. These treaties – the **United Framework Convention on Climate Change** (UNFCCC), the Kyoto Protocol and the **Paris Agreement** constitute the UN Climate Change Regime. The foundational objective of the UNFCCC is to stabilise the greenhouse gas concentrations in the atmosphere at a level preventing dangerous anthropogenic interference with the climate system.[222] The Paris Agreement later specified this purpose, committing to the long-term goal of keeping the global average temperature "well below" 2 degrees Celsius, with an aspiration to limit increases to 1.5 degrees Celsius.[223]

In contrast to the unsuccessful Kyoto Protocol, the Paris Agreement's Nationally Determined Contributions (NDCs) follow a "bottom-up" approach, allowing States considerable flexibility in determining how they wish to "contribute" to achieving the overall 2-degree objective.[224] These provisions lack substantive obligations, while the Agreement's non-binding provisions do not sufficiently motivate states to improve their NDCs.[225] Even with the complete implementation of the current NDCs, global mean warming by 2100 would still reach approximately 2.7 degrees Celsius above pre-industrial levels.[226]

The UNFCCC regime has largely been a disappointment in regulating the potential climate impacts from space activities. Since substantive commitments under the international climate regime are largely voluntary, it may come as little surprise that states have omitted radiative forcing effects from space activities in their greenhouse gas inventories.[227] In the absence of substantive emission reduction obligations, states are not required to address the climate impact of space launches under the international climate change regime.[228]

3.2.3.6 Preventing risks to the albedo effect

The potential dispersion of aluminium oxide into the stratosphere during ablation is feared to increase the Earth's natural albedo effect in the stratosphere, thereby spiralling into an uncontrolled solar geoengineering experiment by unintentionally interfering with the climate system.[229] The UNFCCC and its subsequent Conferences of the Parties seek to achieve

[222] United Nations Framework Convention on Climate Change (adopted 9 May 1992, entered into force 21 March 1994) 1771 UNTS 107 (UNFCCC), art 2.
[223] Paris Agreement (adopted 12 December 2015, entered into force 4 November 2016) 3156 UNTS 79, art 2 (a).
[224] Daniel Bodansky, "The Paris Climate Change Agreement: A New Hope?" in American Journal of International Law Vol. 110 No. 2 (2016), 304.
[225] W. P. Pauw et al., "Beyond headline mitigation numbers: we need more transparent and comparable NDCs to achieve the Paris Agreement on climate change" in Climatic Change Vol. 147 No. 1 (2018).
[226] Niklas Höhne et al., "The Paris Agreement: resolving the inconsistency between global goals and national contributions" in Climate Policy Vol. 17 No. 1 (2017), 20.
[227] UNFCCC, 'National Inventory Submissions 2023', https://unfccc.int/ghg-inventories-annex-parties/2023.
[228] Christine Bakker, 'Protecting the Atmosphere as a "Global Common Good": Challenges and Constraints in Contemporary International Law' in Christine Bakker, The Protection of General Interests in Contemporary International Law (OUP 2021) 177.
[229] Aaron C Boley and Michael Byers, 'Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth' (2021) 11 Scientific Reports <https://doi.org/10.1038/s41598-021-89909-7> accessed 11 August 2024.

"stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system…".[230]

The Vienna Convention on the Law of Treaties requires State parties to interpret treaties in accordance with the ordinary meaning of the terms in their context and in the light of the treaties' objects and purposes.[231] As such, on a plain reading, the UNFCCC and its legal instruments appear ill-equipped to alleviate the risks to the climate system posed by ablation as neither of the potential risks directly impact the atmospheric concentration of greenhouse gases. Although it can be argued that the potential risks of ablation themselves are anthropogenic interferences with the climate system, the regime of the UNFCCC cannot be interpreted to deviate from its objective in an effort to regulate ablation due to its climate risks.

Outside of the UNFCCC, the Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques[232] (ENMOD treaty) is a key international instrument that aims to directly regulate environmental modifications, such as solar and marine geoengineering techniques.[233] As the name suggests, the ENMOD treaty specifically focuses on regulating the modification of climate for military and other hostile purposes. Hence, the ENMOD treaty cannot be used to deal with the potential risk to the climate from the ablation of space objects, since the latter does not qualify as climate modification for military and other hostile purposes.

Past efforts were made to build cooperation and understanding among States concerning weather modification for peaceful purposes. The UN General Assembly recognised the importance of advancing atmospheric science and technology and recommended States to build cooperation to better understand climate and weather modifications.[234] Further, the Governing Council of the UN Environment Programme (UNEP)[235] also recommended that States build cooperation among themselves concerning weather modifications. Additionally, States were recommended to conduct an EIA prior to weather modification activities when they could affect areas outside their national jurisdiction and to ensure no damage occurs to the environment of other States or of ABNJ. Regardless, it is important to note that both these international instruments are non-binding, and the UNEP decision only applies to intentional weather modifications.

Major uncertainties have been expressed concerning the potential negative consequences of the increase in the Earth's natural albedo effect on biodiversity and ecosystems.[236] However,

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[230] United Nations Framework Convention on Climate Change (adopted 9 May 1992, entered into force 21 March 1994) 1771 UNTS 107 (UNFCCC), art 2.
[231] Vienna Convention on the Law of Treaties (adopted 23 May 1969, entered into force 27 January 1980), art 31(1).
[232] Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques (adopted 10 December 1976, entered into force 5 October 1978) 1108 UNTS 151.
[233] Jesse L Reynolds, 'Solar Geoengineering Could Be Consistent with International Law' in Benoit Mayer and Alexander Zahar (eds), Debating Climate Law (Cambridge University Press 2021) 271.
[234] 'International co-operation in the peaceful uses of outer space', UNGA Resolution 1721 (XVI) C (20 December 1961) para 1(a).
[235] UNEP Governing Council, 'Provisions for co-operation between States in weather modifications' Decision 8/7/A (1980) UN Doc A/35/25.
[236] Secretariat of the Convention on Biological Diversity, 'Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters' (September 2012) CBD Technical Series No 66, 44-51 <https://www.cbd.int/doc/publications/cbd-ts-66-en.pdf> accessed 11 August 2024.

the Convention on Biological Diversity (CBD), which governs the conservation of biodiversity, does not provide for measures to mitigate or prevent the risks ablation may pose to biodiversity. Hence, the Conference of Parties (COP) under the CBD adopted a decision explicitly prohibiting the misadventures of climate geoengineering that may affect biodiversity[237]. However, since the COP decision is deemed non-binding, States are at liberty not to comply with the COP decisions.

The London Convention[238] and Protocol,[239] governing the aspects of dumping waste to prevent marine pollution may not be ideal for tackling the problem of ablation as their narrow definition of 'dumping' excludes disposal of waste incidental to the normal operation of aircraft, which could arguably include spacecraft. Although an Amendment to the Protocol that aims to regulate deliberate intervention in the marine environment to manipulate natural processes, which may include solar geoengineering, was approved over a decade earlier,[240] it has yet to enter into force as only three States have ratified the Amendment out of the 36 required.[241]

3.2.3.7 Prevent risks of increasing incidence of thunderstorms

One additional potential risk of ablation is the increasing thunderstorm in stratosphere by affecting the conductivity of atmosphere. In turn, thunderstorms may increase the risks of extreme weather patterns, such as tropical cyclones, which intensify the risks of flooding and associated impacts. This has increased the vulnerability of low-lying human settlements in many parts of the world. Worldwide, distribution and impacts of thunderstorms have been associated with floods, which generate human and economic losses. In extreme cases, thunderstorms can lead to mortality and economic losses, with severe risks associated to the regions of the developing world, where gaps in warning systems have been identified in Africa, some parts of Latin America and in Pacific and Caribbean Island states.[242]

The applicable rules for disaster loss reduction are set out in the Sendai Framework for Disaster Risk Reduction adopted by UN Member States in 2015. The Sendai Framework establishes global early warnings objectives to "Substantially increase the availability and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030.[243]"

The Sendai Framework mainly focuses on reducing disaster risks from natural and human-induced hazards on Earth. The Framework emphasises a comprehensive approach, including understanding risks, strengthening disaster risk governance, investing in risk reduction, and

[237] Conference of Parties to the Convention of Biological Diversity Decision X/33(2010) (18-29 October 2010) (UN Doc UNEP/CBD/COP/ DEC/X/33).
[238] Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (adopted 29 December 1992, entered into force 30 August 1995) 1046 UNTS 120.
[239] London Protocol to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (adopted 7 November 1996, entered into force 24 March 2006) 36 ILM 1.
[240] Resolution LP.4(8) on the Amendment to the London Protocol to Regulate the Placement of Matter for Ocean Fertilization and Other Marine Geoengineering Activities (adopted 18 October 2013).
[241] Jesse L Reynolds (n 5) 269.
[242] WMO Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970–2019), WMO-No. 1267, Geneva, 2021.
[243] United Nations Office for Disaster Risk Reduction, Sendai Framework for Disaster Risk Reduction 2015-2030, Geneva, 2015.

enhancing preparedness for effective response and recovery.[244] However, the Framework was not designed to directly address the ablation-related risks. Although the Sendai Framework can be used more indirectly to promote scientific enquiry into assessing the climate-related risks from ablation, it lacks the ability to promote a collaborative effort between international bodies with varied expertise that is needed to decipher the intricacies behind the potential risks from ablation. The current fragmented regulatory frameworks do not allow for systematic data collection related to the ablation of space activities or a comprehensive study assessing its potential impact.

The absence of a comprehensive Earth-Space regulatory framework leaves significant gaps to be filled in both assessing and managing the risks posed by ablation. Furthermore, the lack of a framework requiring the sharing of information about the details of ablation activities, such as their exact locations, along with an incomplete understanding of climate-related risks, results in insufficient early warning systems, a lack of preventive measures, and the failure to integrate these risks into wider climate policies and governance.

3.2.4 Role of Guidelines and Private Standards

In space governance, non-binding guidelines have become the de facto approach to capturing international agreements, due to the difficulty of amending, or agreeing specific interpretations of, binding multilateral treaties. Guidelines include such documents as the UN COPUOS Long-Term Sustainability guidelines and the IADC guidelines on space debris mitigation, discussed above. While building the consensus to develop international guidelines for responsible space operations is still hard work, the end result is guidance that can help the space community operate in space safely and effectively.

Commercial industry and governments also work together to codify industry and government best practices in the form of international standards. Notable Standards Development Organizations or SDOs include the International Organization for Standardization or ISO, the Consultative Committee for Space Data Systems or CCSDS, and others. It is important that the standards developed are widely adopted and reflect not only current best practices but are also achievable and verifiable with market relevance.

Applying standards promotes consistency in the goods and services supplied. In particular they can offer assurance regarding matters such as quality, interoperability, efficiency, reliability, safety, and ecological responsiveness.[245] Rather than establishing completely new and innovative dimensions, standards typically build on pre-existing technologies and allow for smooth updating and improved versions, in a way that international regulation finds challenging. Furthermore, standards ensure a common framework that can facilitate knowledge sharing and promote innovation; thereby avoiding duplications in research and development.[246]

[244] United Nations Office for Disaster Risk Reduction, 'Sendai Framework for Disaster Risk Reduction 2015-2030' (18 March 2015) UN Doc A/CONF.224/CRP.1, para 20.
[245] UK GOV (2020). Guidance: Standardisation. Retrieved from https://www.gov.uk/guidance/standardisation
[246] Ibid

The International Organization for Standardization or ISO is a non-governmental international organization which bridges the gap between global experts on the production of items and management of the processes involved[247]. This can range from technical specifics concerning materials, processes, services, systems, or products. Founded in 1946 and officially recognised in 1947, ISO has promoted the publication of standards in a range of areas including space. The ISO has established a network of 172 national standard bodies across the world, which, in the United Kingdom, an ISO member, goes under the name the British Standards Institution or BSI. The BSI publishes its own standards, often as the UK implementation of ISO standards. For example, BS ISO 27852:2024 is the implementation of ISO 27852:2024.

The BSI is a non-profit organisation, initially established in 1901,[248] responsible for the UK publication of international and European standards.[249] The BSI has signed a Memorandum of Understanding (MoU) with the UK Government, recognising it as the UK National Standards Body.

The ISO International Standards are not legally binding (contractual, legal or statutory).[250] Among the hierarchy of norms, ISO standards lie below the authority of national standards, which the users of standards should consider first and foremost. As legislation can change within the lifetime of a standard, standards rarely make reference to specific laws.[251] Additionally, in the case of BSI, the institution has no monitoring or supervisory role. This can create problems, in that it enables claims of compliance with standards to be made, even if false or inaccurate.[252] Although standards have no legal authority, regulators and governments can make use of standards, such as those of the ISO, in developing regulations. As standards such as these are developed with the involvement of global experts, through a rigorous system employing technical committees,[253] they carry strong weight and can thus provide support for government policies and regulation[254]. Lastly, compliance with international and national standards enables an organisation to demonstrate evidence of due diligence, potentially relevant in areas such as export controls, financing and licensing.[255]

[247] International Organisation for Standardisation (2024). About iso. Retrieved from https://www.iso.org/about
[248] International Organisation for Standardisation (2024). BSI: United Kingdom. Retrieved from https://www.iso.org/member/2064.html
[249] UK GOV (2020). Guidance: Standardisation. Retrieved from https://www.gov.uk/guidance/standardisation
[250] International Organisation for Standardisation (2024). Foreword - Supplementary information. Retrieved from https://www.iso.org/foreword-supplementary-information.html#:~:text=ISO%20International%20Standards%20and%20other,comply%20and%20which%20take%20precedence.
[251] British Standards Institution (2024). Standards and regulation. Retrieved from https://www.bsigroup.com/en-ID/Standards/Information-about-standards/Standards-and-regulation/
[252] Ibid
[253] International Standardization Organisation (2018). My iso job: What delegates and experts need to know. Retrieved from https://www.iso.org/files/live/sites/isoorg/files/archive/pdf/en/my_iso_job.pdf p. 13
[254] UK GOV (2020). Guidance: Standardisation. Retrieved from https://www.gov.uk/guidance/standardisation
[255] British Standards Institution (2024). Standards and regulation. Retrieved from https://www.bsigroup.com/en-ID/Standards/Information-about-standards/Standards-and-regulation/

The ISO has established numerous international standards relevant to the atmospheric ablation of space objects. These include, but are not limited to, the following standards, listed and grouped based on common themes:

Relevant Themes	Standards
Sustainability and space debris	**ISO 27852:2024**: Space systems - estimation of orbit lifetime[256] **ISO/TR 18146:2020:** Space systems - space debris mitigation design and operation manual for spacecraft[257] **ISO/TR 18146:2020:** Space systems - space debris mitigation design and operation manual for spacecraft[258] **ISO/TR 20590:2021:** Space systems - space debris mitigation design and operation manual for launch vehicle orbital stages[259] **ISO 23312:2022:** Space systems - detailed space debris mitigation requirements for spacecraft[260] **ISO 23020:2021:** Space systems - determination of test methods to characterize material or component properties required for break-up models used for Earth re-entry[261]
Spacecraft design and components	**ISO/TR 20891:2020:** Space systems - space batteries - guidelines for in-flight health assessment of lithium-ion batteries[262] **ISO 17546:2024:** Space systems - lithium ion battery for space vehicles - design and verification requirements[263] **ISO 16454:2024:** Space systems - structural design - stress analysis requirements[264] **ISO 10786:2011:** Space systems — structural components and assemblies (note: to be replaced soon by ISO/DIS 10786)[265]

[256] International Organization for Standardization. Retrieved from https://www.iso.org/standard/85364.html
[257] International Organization for Standardization. Retrieved from https://www.iso.org/standard/77688.html
[258] International Organization for Standardization. Retrieved from https://www.iso.org/standard/77688.html
[259] International Organization for Standardization. Retrieved from https://www.iso.org/standard/81216.html
[260] International Organization for Standardization. Retrieved from https://www.iso.org/standard/75221.html
[261] International Organization for Standardization. Retrieved from https://www.iso.org/standard/74336.html
[262] International Organization for Standardization. Retrieved from https://www.iso.org/obp/ui/en/#iso:std:iso:tr:20891:ed-1:v1:en
[263] International Organization for Standardization https://www.iso.org/standard/83872.html
[264] International Organization for Standardization. Retrieved from https://www.iso.org/standard/85534.html
[265] International Organization for Standardization. Retrieved from https://www.iso.org/standard/46099.html

	ISO 10794:2018: Space systems — programme management — Material, mechanical parts and processes[266] **ISO 17851:2016:** Space systems — Space environment simulation for material tests — General principles and criteria[267]
Space mission planning	**ISO 19971:2018:** Space systems - spacecraft and launch vehicle combined operation plan (COP) at launch site - General format[268] **ISO 17666:2016:** Space systems - risk management [269] **ISO 16126:2014:** Space systems - assessment of survivability of unmanned spacecraft against space debris and meteoroid impacts to ensure successful post-mission disposal[270]
Other	**ISO 14222:2022:** Space environment (natural and artificial) — Earth's atmosphere from ground level upward[271]

Unfortunately, ISO standards are not publicly accessible, due to the costs associated with the development, publication and maintenance of standards[272]. They incur a fee to obtain either PDF/ePub access or paperback versions. While a sample is provided, this contains very limited information. This is a general drawback, that limits information accessibility and knowledge transfer, particularly for smes.

Despite this drawback, some BSI standards are are available through university (Edinburgh) subscription services and offer insights regarding the landscape of standardisation in the UK. Similarly to ISO however, BSI's are not openly accessible and need to be purchased, limiting its broader application and study to smes and other stakeholders. The table below details space related standards grouped according to common themes[273]:

Relevant Themes	Standards
Sustainability and space debris	**Draft BS ISO 16126:** Space systems - Survivability of unmanned spacecraft against space debris and meteoroid impacts for the purpose of space debris

[266] International Organization for Standardization. Retrieved from https://www.iso.org/standard/72935.html
[267] International Organization for Standardization. Retrieved from https://www.iso.org/standard/60820.html
[268] International Organization for Standardization. Retrieved from https://www.iso.org/standard/66775.html
[269] International Organization for Standardization. Retrieved from https://www.iso.org/standard/69239.html
[270] International Organization for Standardization. Retrieved from https://www.iso.org/standard/55720.html
[271] International Organization for Standardization. Retrieved from https://www.iso.org/standard/77492.html
[272] International Organisation for Standardisation (2024). General faqs. Retrieved from https://www.iso.org/footer-links/frequently-asked-questions-faqs/general-faqs.html
[273] Drafts of BS ISO standards are included as well. These remain open for public comment.

	mitigation[274]
Spacecraft design and components	**BS ISO 16454:2024:** Space systems - Structural design - Stress analysis requirements[275] **BS ISO 17546:2024:** Space systems - Lithium-ion battery for space vehicles - design and verification requirements[276] **Draft BS ISO 20188:** Space systems - Product assurance requirements for commercial satellites[277] **Draft BS ISO 15104:** Space systems - Environmental testing for spacecraft thermal control materials[278] **Draft BS ISO 14622:** Space systems - Structural design. Loads and induced environment[279] **Draft BS ISO 14620:** Space systems - Safety requirements. Part 4: Spacecraft assembly, integration, and test[280] **Draft BS ISO 10786:** Space systems - Structural components and assemblies[281] **Draft BS ISO 10785:** Space systems - Bellows - Design and operation[282]
Space mission planning	**PD ISO/TR 23689:2024:** Space environment (natural and artificial) - Space weather information for use in space systems operations[283] **Draft BS ISO 20892:** Space systems - Launch complexes modernization process - General requirements[284]

274 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/bs-iso-16126-space-systems-survivability-of-unmanned-spacecraft-against-space-debris-and-meteoroid-impacts-for-the-purpose-of-space-debris-mitigation?version=standard

275 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/space-systems-structural-design-stress-analysis-requirements-1?version=tracked

276 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/space-systems-lithium-ion-battery-for-space-vehicles-design-and-verification-requirements-1?version=tracked

277 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/space-systems-product-assurance-requirements-for-commercial-satellites?version=standard

278 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/bs-iso-15104-space-systems-environmental-testing-for-spacecraft-thermal-control-materials?version=standard

279 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/bs-iso-14622-space-systems-structural-design-loads-and-induced-environment?version=standard

280 British Standards Institution (2024).

281 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/bs-iso-10786-space-systems-structural-components-and-assemblies?version=standard

282 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/bs-iso-10785-space-systems-bellows-design-and-operation?version=standard

283 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/space-environment-natural-and-artificial-space-weather-information-for-use-in-space-systems-operations?version=standard

284 British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/bs-iso-20892-space-systems-launch-complexes-modernization-process-general-requirements?version=standardhttps://knowledge.bsigroup.com/products/bs-iso-20892-space-systems-launch-complexes-modernization-process-general-requirements?version=standard

Other	**BS ISO 27852:2024:** Space systems - Estimation of orbit lifetime[285] **BS ISO 26900: 2024:** Space data and information transfer systems - Orbit data message[286]

An important observation is that information on the disposal of space objects or components, re-entry mechanisms, and consideration of atmospheric ablation are largely absent. For example, BS ISO 17546:2024 on lithium batteries does not cover the disposal or the recycling of batteries, which is a matter of particular concern in the case of atmospheric ablation. While BS ISO 27852:2024 includes mention of re-entry, as well as atmospheric drag models, which help predict atmospheric density and ultimately orbit lifetime, specifics are missing on the end-of-life process after the expiration a space object's orbital lifetime. These gaps show the current lack of information and technical insight regarding this aspect of space activity. Not only does this underline the need for further research but also efforts to include end of life considerations in standards in the future.

Applying standards that encompass atmospheric ablation would encourage industry to develop related products and services and spark dialogue. Moreover, the development of ISO standards, involves the participation of international ISO members who, during its technical and policy meetings, can bring their technical understanding of atmospheric ablation to the table. Lastly, standards can help bridge the divide between legislators and regulators on the one hand and industry and business stakeholders on the other.

3.2.5 Incorporation of Sustainability Considerations and Environmental Standards in the National Regulation of Space Activities

Effect is given to the international rules discussed above primarily through domestic law. In the sections that follow we consider the extent to which the UK and US incorporate sustainability and environmental considerations in their regulation of the space sector, notably through their licensing and oversight regimes. We also briefly consider the example of France, an example of a country that has established quite far-reaching environmental assessment requirements for space activities. This leads us to conclude that a more detailed and comprehensive examination of national practice is called for in order to determine the strengths and weaknesses of specific approaches and how best to accommodate concerns over ablation into the domestic regulatory context.

3.2.5.1 UK Space regime concerning requirements to assess environmental effects

Two statutes govern the licensing in the UK of space activities. The 2018 Space Industry Act 2018 governs the award of licences for activities carried out in the UK, or involving the launch from a ship with a British flag wherever this takes place. Five specific licences are granted under the 2018 Act: spaceport operator licence; launch operator licence, return operator licence; orbital operator licence; and range control operator licence. Further guidance on the

[285] British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/space-systems-estimation-of-orbit-lifetime-2?version=tracked
[286] British Standards Institution (2024). Retrieved from https://knowledge.bsigroup.com/products/space-data-and-information-transfer-systems-orbit-data-message?version=tracked

operation of the statute is contained in the Space Industry Regulations 2021,[287] alongside regulations on accident investigations and appeals, and additional guidance on the licensing framework.[288] The Outer Space Act 1986 regulates activities carried out overseas by UK entities; these include procuring an overseas launch of a space object or the operation by a UK entity of a satellite in orbit from an overseas facility.

Licences under the 1986 Outer Space Act (the 'OSA) and the 2018 Space Industry Act (the 'SIA') are granted by the CAA and recorded in a publicly accessible registry.[289] Companies seeking a licence to operate a spaceport or provide launch services under the 2018 Act are required to submit an assessment of environmental effects ('AEE'), but this is not required when applying for an orbital, return, or range control operator licence, where common requirements relating to safety and national security apply.[290]

The regulator is, however, required to 'take account of' any environmental obligations set by the Secretary of State and any international commitments of the UK, notably those relating to debris mitigation, when exercising its licensing powers more generally under SIA (S.2(2) SIA). Guidance given by the Secretary of State in 2021 under section 2(2) recognises that among the main likely environmental effects of UK spaceflight activities **are 'the effects of spaceflight emissions on climate change and on levels of ozone in the upper troposphere and stratosphere.'**[291] The stated environmental objectives thus include minimising the 'emissions contributing to climate change resulting from spaceflight activities', and the regulator is expected to ensure that space flight emissions do not undermine the UK's legally binding carbon budget commitments.[292] In relation to the ozone layer, the government considered at this time that space flight would have a 'trivial' impact compared to that of other industries, but that, where possible, technologies that reduce such impact should be encouraged.[293] In relation to air quality the main concern is with local air quality and human health, rather than an impact higher up in the atmosphere. The guidance, clearly requires that consideration be given to the broader environmental effects of space activities, and mitigating measures are to be taken where possible, but the guidance remains rather unspecific, with a tendency to evaluate impact from a relative perspective, rather than as a distinct contribution.

The regulator also has a wide power to add conditions to the grant of all licences under SIA as specified in schedule 1, or as the regulator 'thinks appropriate' (s.13 SIA). Schedule 1 includes conditions:

[287] The Space Industry Regulations 2021, SI 792, with a key focus on safety and security.
[288] In particular, CAA, Applying for a Licence under the Space Industry Act 2018, CAP 2209, 2024 (2nd ed,).
[289] Civil Aviation Authority, Licences granted and registers of space objects, at: https://www.caa.co.uk/space/what-happens-next/licences-granted-and-registers-of-space-objects/
[290] CAA, Applying for a Licence under the Space Industry Act 2018, CAP 2209, 2024 (2nd ed.) at para.4.62.
[291] Department for Transport, Guidance to the regulator on environmental objectives relating to the exercise of its functions under the Space Industry Act 2018. Given by the Secretary of State under section 2(2)(e) of the Space Industry Act 2018, 2021, at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/995153/guidance-to-the-regulator-on-environmental-objectives-relating-to-the-exercise-of-its-functions-under-the-space-industry-act-2018.pdf.
[292] For the various carbon budget requirements see government guidance at: https://www.gov.uk/guidance/carbon-budgets.
[293] Department of Transport (2021), p.13.

- relating to **space debris mitigation guidelines** (para.1);
- governing the **disposal of any payload in outer space on the termination of operations** and **requiring the licensee to notify the regulator as soon as practicable of its final disposal** (para.11);
- **designed to ensure compliance with the UK's international agreements** and agreements with other countries; and
- requiring the licensee **to conduct the licensee's activities in such a way as (a) to prevent the contamination of outer space or adverse changes in the environment of the earth**, and (b) to avoid interference with the activities of others in the peaceful exploration and use of outer space (para.14).

Before including such conditions, the regulator is required to consult specific bodies, which again reflect health and safety rather than environmental concerns (s. 13.6 2018 Act) and a readjustment to include environmental representation would seem desirable.

For orbital licences, where an AEE is not required, an applicant must still furnish extensive technical information.[294] This includes information about the selected launch company and whether the applicant considered sustainability factors when selecting that company, the arrangements for monitoring the space object during its operations, and responsibility for disposal. Of specific interest from an ablation point of view are requirements to provide information on design characteristics, such as the power system, as well as plans for end of life in case of mission failure, anticipated de-orbit plans, including payload deactivation, expected mass at end of life and surface area, predicted de-orbit duration, re-entry corridor and associated timelines, component survivability expectations, etc. Although a specific set of questions directly address sustainability, the focus is on preventing space debris, encouraging compliance with the existing space debris mitigation guidelines, and protecting the orbital (as opposed to the Earth's) environment.[295] One question is, however, highly relevant for this study, namely whether, and if so how, sustainability considerations have influenced the mission design and operations. Though ablation is, once again, not an expressly identified concern, it is apparent that much of the information to be provided is potentially relevant in assessing the environmental impact of satellite re-entry and in encouraging satellite operators to reflect on how they can reduce their environmental footprint. The technical question set could also be developed to record further relevant data that would assist in assessing the overall impact ablation.

As indicated above, an AEE is only required in relation to spaceport and operator licences.[296] To date, the CAA has granted only two spaceport licences and one launch licence. One of these spaceport licenses was for SaxaVord spaceport (Shetland Space Centre Limited). The other spaceport license and launch license were granted to Spaceport Cornwall (Cornwall Airport Limited) and Virgin Atlantic respectively, based on a combined assessment of environmental effects (AEE), submitted as part of their applications. This combined AEE was commented on and considered by the CAA and, in light of the Aarhus Convention. was also

[294] CAA, Technical Question Set, V2.1 16 February 2024.
[295] Ibid, pp.51-54.
[296] See CAA, Guidance for the Assessment of Environmental Effects, CAP 2215, 29 July 2021.

circulated for public comment.[297] The scope of the AEE is explained in the executive summary, which states that the: '[a]ssessment of Environmental Effects addresses the potential environmental effects of the United Kingdom (UK) Civil Aviation Authority (CAA) issuance of a spaceport operator licence to Spaceport Cornwall and a launch operator licence to Virgin Orbit, LLC (Virgin Orbit) to conduct launches from Spaceport Cornwall located at Cornwall Airport Newquay and the issuance of a spaceport licence to Spaceport Cornwall to support Virgin Orbit launch operations.'[298]

The scope of the AEE extends to "indirect effects", defined as those effects '…caused by the action and are later in time or farther removed in distance but are still reasonably foreseeable. Indirect effects may include growth inducing effects and other effects related to induced changes in the pattern of land use, population density or growth rate, and related effects on air and water and other natural systems'.[299]

Does this enable consideration of ablation as an indirect effect? In the Scoping of Assessment section (Chapter 4), the AEE states that the Mission Profile, identified as launch to end-of mission, includes the timing and location of jettisoned components. However, ablation impacts were not considered to be indirect effects or part of the Mission Profile (as seemingly ablation would be considered part of the "end-of-mission" stage"). In Table 15, it is evident that ablation was left out of the scoping exercise in so far as its impact occurs in "airspace":

Table 15. Summary of proposed activities and scoping status

AIRSPACE			
Carrier aircraft/LauncherOne transit to rocket drop point		X	Existing activity: does not differ from any other aircraft in transit, nor does it impose additional risks.
Release of LauncherOne from carrier aircraft over Atlantic Ocean.	X		New activity within airspace.
Sonic boom from LauncherOne over Atlantic Ocean SW of Ireland	X		New activity within airspace.
Reentry of stage 1 and fairings over Atlantic Ocean west of Portugal.	X		New activity within airspace: deposition of rocket debris into the ocean.
Rocket trajectory past Stage 1 and Fairings Reentry AHA/SHA		X	Altitude of rocket after 100 seconds of flight would be >25,000 m (82,000 ft) MSL and there would be no impacts to receptors along the subsequent trajectory.

The AEE also considered air quality. At 4.2.78 the AEE stated that '[w]ith regards to high altitude (i.e., >10,700 m [35,000 ft] MSL) emissions from the proposed LauncherOne operations, air quality significant effects can only occur where there are sensitive environmental receptors that maybe harmed (or benefit) as a result of changes in air quality. At the altitude where the rocket will be released there are no receptors and so no significant effects can occur. Therefore, any air quality effects associated with the LauncherOne rocket

[297] See Public Consultation on the Assessment of Environmental Effects: Virgin Orbit and Spaceport Cornwall - Civil Aviation Authority - Citizen Space (caa.co.uk); copy of CAA comments on AEE can be accessed here: virginorbitandspaceportcornwalljointassessmentofenvironmentaleffectspublicconsultationresponses.pdf (caa.co.uk); see also CAA launches consultation on environmental effects of first UK space launch from Cornwall | Civil Aviation Authority (caa.co.uk)
[298] Assessment of Environmental Effects Virgin Orbit, LLC LauncherOne Operations from Spaceport Cornwall, Cornwall Airport Newquay, United Kingdom July 2022 virgin-orbit-spaceport-cornwall-aee--13jul22--1.pdf (caa.co.uk). p. ES-1.
[299] page 4-1.

itself are scoped out of this assessment. However, Section 5.2 (Climate) addresses air quality impacts associated with GHG emissions within the affected airspace.'

The CAA AEE guidance does specifically require the assessment of climate change impacts.[300] The Spaceport Cornwall/Virgin AEE assessed such effects with reference to the Guidelines for Ecological Impact Assessment in the UK and Ireland (Charted Institute of Ecology and Environmental Management 2019). In terms of the assessment itself, para.5.21 of the AEE states that consideration is given 'to greenhouse gas (GHG) emissions from proposed Spaceport Cornwall and Virgin Orbit operations. The assessment does not consider the climate change impacts associated with the ongoing operations that can currently be undertaken at CAN under existing licenses'. It is apparent from the table below that no consideration was given to ablation in Scope 1 to 3 emissions, probably on account of a failure to consider the complete life-cycle of a satellite.

Table 16. GHG Emission scopes for the climate assessment

Scope	Definition	Items Scoped in the Climate Assessment
Scope 1	Direct GHG emissions that occur as a direct result of proposed Spaceport Cornwall operations.	• Assembly of LauncherOne in processing hangar. • Insertion of payload in LauncherOne in processing hangar. • Installation of TEA-TEB canisters, load fuel, connect TGOS, and condition LOX, GN2, and GHe for LauncherOne.
Scope 2	GHG emissions from the generation of purchased electricity consumed by Spaceport Cornwall operations.	• On site consumption of grid electricity in assembly process. • Consumption of electricity as fuel for vehicles and GSE.
Scope 3	All indirect GHG emissions. Scope 3 emissions are a consequence of the activities of Spaceport Cornwall but are from sources not owned or controlled by them (i.e., Virgin Orbit). Includes all high-altitude emissions including radiative forcing effects.	• Fuelling of LauncherOne with RP-1 and complete loading of LOX, GHE, GN2. • Propellants (LOX, GN2, GHe) arriving from offsite and transfer to commodity storage trailers on Echo Apron. • Deployment of propellant loading equipment (GSE trailers) and commodity conditioning on Echo Apron. • Release of LauncherOne from Cosmic Girl at 35,000-40,000 ft MSL over Atlantic Ocean SW of Ireland. • Emissions from RP-1 fuel burnt by LauncherOne rocket during flight operations. • Visitors in vicinity of CAN to observe takeoff of Cosmic Girl/LauncherOne.

At para 5.2.15 the AEE states that '[a] Lifecycle Analysis and Whole Life Carbon Assessment has been undertaken for all activities relating to Spaceport Cornwall (proposed launches and ancillary activities associated with launch operations) by the University of Exeter (Yan 2022; available at: https://spaceportcornwall.com/sustainability). The lifecycle analysis is based on the best available data at the time of writing and is valid and sufficient in meeting the AEE requirements.'

The Spaceport Operator Carbon Impact – A Life Cycle Analysis[301] report states that it 'provides a holistic assessment of the life cycle greenhouse gas (GHG) emissions from planned launches and ancillary activities associated with launch missions at the proposed Spaceport Cornwall between 2022 and 2027, using an attributional life cycle assessment

[300] 18937 (caa.co.uk) , at para 4.1.
[301] Dated July 2022, prepared by Professor Xiaoyu Yan of Environment and Sustainability Institute, University of Exeter Penryn Campus, Penryn, Cornwall.

(LCA) methodology'.[302] … The attributional life cycle assessment (LCA) methodology is used to provide a comprehensive coverage of all upstream processes related to the launches and ancillary activities. This indicates that the AEE assesses carbon emissions associated with activities at the facility, but not the downstream impacts/processes of planned space activities emanating from the facility from 2022 to 2027.

Although the AEE also considers the effects of RF (Radiative Force) of emissions at high-altitude (in atmosphere), including those of black soot, it only relates to emissions from launches and not ablation. At para 5.2.22 the AEE states that 'the radiative forcing (RF) effects due to emissions at high altitude are quantified given their importance in climate impacts of aviation activities and space missions. No ozone depleting gases or CFCs will be used in Spaceport Cornwall or Virgin Orbit activities.' This appears to be an omission, if emissions from ablation are accepted as containing ozone depleting substances.

Review of the Spaceport Cornwall/Virgin AEE, has thus established that:

- There was no specific mention of ablation.
- The impacts of debris from the licensed activities were only considered in relation to the marine environment and mammals.
- Downstream assessment of the impact of emissions as part of the carbon life-cycle assessment was not considered.

The failure of the AEE to adequately consider and propose mitigation measures concerning ablation, appears to stem from the fact that the CAA's does not specifically require such an assessment in its guidance, nor does it direct applicants to engage in such an assessment by making appropriate comments during the consultation phase.[303] Hence, a regulatory gap currently exists in the UK space regime concerning the assessment of ablation in applications for spaceport and launch licences under the AEE assessment regime.

In relation to the OSA, a number of specific provisions are designed to prevent or minimize environmental damage. Under section 5(2) the regulator has power to grant a licence only when satisfied that the licensee will comply with the UK's international obligations (da(ii)); and will **conduct its activities in such a way as to 'prevent the contamination of outer space or adverse changes to the environment of the earth'** (e(i)). Section 5 also enables the introduction of terms in a licence 'governing the disposal of the payload in outer space on the termination of operations under the licence' and requiring 'the licensee to notify the Secretary of State as soon as practicable of its final disposal' (g).

There is thus potential, under both the OSA and SIA, for consideration of environmental considerations, not just in relation to the sustainability of outer space but also the Earth (s.13 and Sch.1, para.14(a) SIA; s.5(2)(e)(i) OSA). To date, however, the main focus has been on debris mitigation and orbital congestion, so that further development of the licensing conditions to engage with end-of-life environmental pollution could be explored. In this regard, it is relevant to note the recent UK Supreme Court ruling in *R v Surrey County Council and others*,

[302] Spaceport-Cornwall-Carbon-Impact-report_UoE-2022_final-draft-2022-07-19.pdf (spaceportcornwall.com), executive summary.
[303] CAA, Guidance for the Assessment of Environmental Effects, CAP 2215, 29 July 2021

which considered the scope of environmental impact assessments under UK planning law in relation to a proposed oil extraction development.[304] The Supreme Court considered that the 'extraction of oil…would initiate a causal chain that would lead to the combustion of the oil and release of greenhouse gases into the atmosphere'.[305] Moreover 'the fact that an environmental impact will occur or have its immediate source at a location away from the project site is not a reason to exclude it from assessment. There is no principle that, if environmental harm is exported it may be ignored'.[306] Although the licensing of spaceports and launch operations are subject to a distinct licensing scheme, these observations seem relevant in this context. In assessing the environmental impact of both spaceport and launch operations, the potential long-term cumulative effects of satellites planned to be launched from a UK facility ablating in the upper atmosphere should be examined.

The UK Government's Space Regulatory Review 2024, involving a collaboration among DSIT, the UKSA, DBT and Dft, identified 7 priority regulatory outcomes and 17 recommendations for supporting activities.[307] The report addresses some of the points raised above by calling for a review of the existing UK regulatory framework for space, both primary and secondary legislation, in order to enhance co-ordination across regulators and government departments. It also underlines the importance of international engagement, supporting the development of domestic and international cross-regulator associations, working towards aligned regulatory frameworks that prioritise sustainability and cross-border trade. In particular, the report notes the importance of a regulatory framework that supports the development and adoption of sustainability standards and rewards sustainable activities. Alongside this report, the UKSA has been consulting on measures to support sustainable space practices, notably financial and insurance incentives, and the development of a space sustainability roadmap.[308] The 2024 Review identifies, albeit in broad outline, how the existing framework could be developed to support sustainable practices within a competitive environment and provides a mature reflection on priorities and challenges for UK space regulation in the future.

3.2.5.2 United States

In the United States, requirements for EIAs are set by the National Environmental Policy Act (NEPA) and it's implementing regulations (including those set by the Council on Environmental Quality). NEPA requires federal authorities and agencies to "evaluate the potential effects on the environment of proposed major federal actions prior to taking those actions and to obtain information from the public to inform the decision-making process."[309] This includes licensing of certain commercial activities, where public interest and public safety is concerned. In general agencies satisfy this requirement by preparing an environmental assessment or an

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[304] *R (on the application of Finch on behalf of the Weald Action Group) (Appellant) v Surrey County Council and others (Respondents)* [2024] UKSC 20.
[305] Ibid, para.79
[306] *R v Surrey County Council* (2024) para.93.
[307] HM Government, DSIT, Space Regulatory Review 2024. A Targeted Review of Space Regulations, Research Paper No. 2024/007, May 2024
[308] UKSA, Consultation on Orbital Liabilities, Insurance, Charging and Space Sustainability, updated 5 March 2024 at: https://www.gov.uk/government/consultations/consultation-on-orbital-liabilities-insurance-charging-and-space-sustainability/consultation-on-orbital-liabilities-insurance-charging-and-space-sustainability
[309] United States Government Accountability Office (GAO), "Commercial Space Transportation How FAA Considers Environmental and Airspace Effects," April 2024 https://www.gao.gov/products/gao-24-106193

environmental impact statement, or both. However, agencies can apply a “categorical exemption” to a type of activity “if the proposed action is in a category the agency has already determined does not normally have significant environmental effects”[310] Figure 25 summarizes the process for implement NEPA’s requirements.

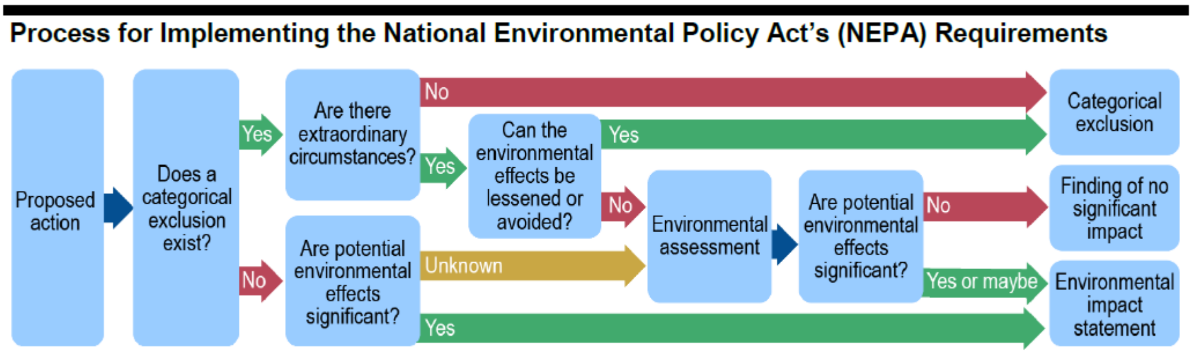

Figure 25. The NEPA Processes, *As Summarized By GAO (Source: GAO, 2024)*

In the United States licensing and oversight for commercial space activities is distributed through several federal agencies. Commercial space launch and reentries (not including satellite disposal at end of life) are licensed through the Federal Aviation Administration (FAA); while commercial spacecraft operators requiring use of the radio frequency spectrum are licensed through the Federal Communications Commission (FCC). End of mission disposal of spacecraft is typically addressed through an operator's space debris mitigation plan, subject to requirements of FCC licensing (or National Oceanic and Atmospheric Administration – NOAA, for those operators required to have such licensing). This section briefly reviews the current application of NEPA requirements in these two licensing authorities – and suggests a gap exists relative to the potential review for adverse impacts of atmospheric ablation of reentering space craft.

For commercial space launch and re-entry activities, the FAA is the cognizant licensing authority in the United States. It has determined that NEPA requirements apply to these activities, and currently considers environmental impacts that would result from an activity (launch and/or vehicle re-entry) before issuing a license. Depending on the facility from which a launch occurs, NASA or the US Air or Space Force may be involved in conducting and reviewing any environmental impact assessment or statement. In conducting NEPA reviews the FAA has identified 14 environmental impact categories for review, as shown in Table 17, below.[311]

Table 17. The FAA's Environment Impact Categories. Source: GAO, 2024

Environment Impact Category
Air quality

[310] United States Government Accountability Office (GAO), “Satellite Licensing FCC Should Reexamine Its Environmental Review Process for Large Constellations of Satellites,” Nov. 2022. https://www.gao.gov/products/gao-23-105005
[311] United States Government Accountability Office (GAO), “Commercial Space Transportation: How FAA Considers Environmental and Airspace Effects,” April 2024. https://www.gao.gov/products/gao-24-106193

Biological resources (including fish, wildlife and plants)

Climate

Coastal resources

Certain public and private lands

Farmlands

Hazardous materials, solid waste and pollution prevention

Historical, architectural, archaeological and cultural resources

Land use

Natural resources and energy supply

Socioeconomics, environmental justice and children's environmental health and safety risks

Water resources (including wetlands, floodplains, surface waters, groundwater, and wild and scenic rivers

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Several of these categories appear relevant to atmospheric ablation, including air quality and climate. The FAA has established "significance thresholds for 6 of the 14 impact categories."[312] These categories have quantitative thresholds. For the other 8 categories the evaluation is based on certain factors, including whether the activity would "adversely affect human health and environment." A U.S government audit of the FAA's consideration of environmental effects of its licensed activities conducted in 2023 reports that the FAA has in general "determined that the potential effects of current launch and re-entry activities are not significant overall."[313] It is unclear whether the FAA has evaluated atmospheric ablation of re-entering launch vehicles and other licensing re-entries as part of its environmental review processes.

In contrast to the FAA, the Federal Communications Commission currently applies a categorical exemption of NEPA requirements to its licensing of satellites, exempting consideration of impact on the terrestrial environmental as part of regulatory review.[314] This policy was upheld by a US federal court in July 2024.[315] The FCC's application of this categorical exemption dates to 1986, and has not been systematically reviewed or updated since then. U.S. government auditors have argued that in light of changes in the space sector, including the advent of large satellite constellations, that this exemption should be reviewed.[316] As of July 2023, the FCC, which operates an independent agency within the U.S. federal government, has thus far not reviewed the exemption.[317] In July 2024, the Council on

[312] See "How FAA Considers Environmental and Airspace Effects" at Supra 329

[313] Ibid

[314] United States Government Accountability Office (GAO), "Satellite Licensing FCC Should Reexamine Its Environmental Review Process for Large Constellations of Satellites," Nov. 2022. Accessed Aug 1, 2024. [Online]. https://www.gao.gov/products/gao-23-105005

[315] International Dark-Sky Association, Inc. v. FCC, No. 22-1337 (D.C. Cir. 2024), Accessed Aug 2, 2024. [Online]. https://www.cadc.uscourts.gov/internet/opinions.nsf/85945DC61537163285258B58004F3AF9/$file/22-1337-2064317.pdf

[316] United States Government Accountability Office (GAO), "Satellite Licensing FCC Should Reexamine Its Environmental Review Process for Large Constellations of Satellites," Nov. 2022. Accessed Aug 1, 2024. [Online]. https://www.gao.gov/products/gao-23-105005

[317] See https://www.gao.gov/products/gao-23-105005#:~:text=Recommendation%202)-,Open,of%20the%20Commission's%20categorical%20exclusions.

Environmental Quality published revised regulations for implementing NEPA.[318] The FCC had previously stated that it plans to develop proposed procedures after adoption of the final CEQ rule.

There is the theoretical potential for ablation to be considered in several categories identified by the FAA, including air quality and climate, as well as the potential for such assessment to be included in the revision of the FCC's procedures. However, the current status quo means that ablation is not being considered by either of the mentioned US authorities as part of their respective licensing regimes.

3.2.5.3 France

Under French jurisdiction, space activities are covered by the following:

- Law No 2008-518 of 3 June 2008, relating to space operations (LOS);[319]
- Decree No 2024-625 of 28 June 2024, relating to space operations authorisation;
- Order of 28 June 2024, relating to the composition of the three parts of the authorisation file;
- Order of 28 June 2024, relating to technical regulations;
- Decrees No 2022-233 and No 2022-234 of 24 February 2022, relating to space data, defence considerations and the authorisation and management of space operations;
- Decree No 2017-1619 of 27 November 2017, publishing the agreement between the Government of the French Republic and the European Space Agency on the Guiana Space Centre and associated services;

These laws govern space activities conducted by French entities, both public and private. Operators are subject to an authorisation from the French Ministry of the Economy on the basis of a number of factors, including environmental criteria. Authorisation files include three parts:

- The administrative part of the authorisation is where the applicant is to be identified;
- The technical part includes a description of the space operation, systems and procedures envisaged.
- The third part describes the payload mission and its characteristics.

Space operators must obtain authorisation from the French government before carrying out space activities, which includes an assessment of the potential environmental impact of the proposed space operation.[320]

[318] See https://www.federalregister.gov/documents/2024/05/01/2024-08792/national-environmental-policy-act-implementing-regulations-revisions-phase-2

[319] "LOI N° 2008-518 Du 3 Juin 2008 Relative Aux Opérations Spatiales (1)." *2008-518*, juin 2008. https://www.legifrance.gouv.fr/loda/id/JORFTEXT000018931380/

[320] In French Guyana, EIA procedures have been marred in controversy: a spaceport construction, which required a prior EIA under the authority of the National Centre for Space Research, led to the extinction of an amphibian red-listed by the International Union for the Conservation of Nature. Judicial proceedings at the Tribunal de Cayenne are ongoing. Guyane Nature Environnement,

The updated decree on space activities requires applicants for an authorisation to conduct an environmental impact assessment.[321] Art 7 requires the launcher to conduct an environmental impact study addressing, *inter alia*, damage linked to the fall of elements expected to detach from the launcher; damage linked to the controlled or uncontrolled re-entry of launcher elements placed in an Earth orbit. Art 16 requires the applicant to carry out the impact study of the planned operation on the terrestrial environment and to describe the measures taken to moderate the negative impacts on the environment. The content of this impact study must be related to the foreseeable impacts and the direct or indirect temporary and permanent effects of the planned operation on the environment. Additionally, Art 17 requires applicants for an authorisation to adopt an environmental damage prevention plan, which demonstrates that the materials and energy sources chosen for the space object are not likely to create environmental damage; the plan for preventing risks induced by the fall-out of the space object or its fragments; if applicable, the planetary protection plan.

For re-entries, the description in the authorisation file must include:

- a re-entry authorisation issued by the authorities responsible for the landing site;
- a description of the critical systems and sub-systems for the rescue mission;
- a description of the landing site and its facilities; and
- re-entry trajectories, flight sequence and triggering events, provisional date and re-entry window.

French law covers, environmental damage up to EUR750 million. According to the French Insurance Code, the insured can only be compensated up to the amount of the loss. Consequently, the insurer's maximum liability is determined by the value of the insured property. The producer is liable as soon as a defect in its product causes damage without the victim having to prove fault on its part. However, the victim must prove the causal link between the product defect and the damage. In the case of ablation, it is not clear whether dissemination of satellite by-products during re-entry can ever be linked by direct causation to the damage of a victim on earth. Furthermore, ablation is the normal procedure of an end-of-life satellite re-entry and in this case the satellite would not be considered defective.

The latest French amendments to their 2008 LOS anticipate upcoming harmonisation of EU Space Law. In September 2023, the European Commission announced a proposed legislation aimed to establish a "common framework" among eleven national regulations currently governing space activities across the EU member state. The European Commission is exploring the adoption of a EU Space Law founded on three fundamental pillars: safety, resilience and sustainability of space operations and systems.

Communiqué de presse, «Rejet de validation de la convention judiciaire au dépend du CNES qui prévoyait une amende de 10 000 € pour un préjudice écologique estimé à 10 Millions € », online : https://federation-gne.fr/actu/non-classe/communique-de-presse-historique-en-guyane-le-rejet-de-validation-de-la-convention-judiciaire-au-depend-du-cnes-qui-prevoyait-une-amende-de-10-000-e-pour-un-prejudice-ecologique-estime-a-10-million/

[321] Arrêté du 23 février 2022 relatif à la composition des trois parties du dossier mentionné à l'article 1er du décret n° 2009-643 du 9 juin 2009 relatif aux autorisations délivrées en application de la loi n° 2008-518 du 3 juin 2008 modifiée relative aux opérations spatiales, JORF n°0048 du 26 février 2022, Texte n° 9, online : https://www.legifrance.gouv.fr/eli/arrete/2022/2/23/ECOJ2206380A/jo/texte

3.2.6 CONCLUSION

The main findings in this report are that:

- the potential impact of ablation on the re-entry of space objects has to date received extremely limited attention both at international and domestic levels;
- international space and environmental laws do not directly address ablation, but both space and environment regimes require that information be shared and a precautionary approach adopted where activities could potentially cause significant harm;
- information exchange could be enhanced through further development of the UN Registry, while the precautionary principle calls for further collaborative study on the effects of ablation involving different re-entry scenarios and materials, in order to enable an informed response;
- where action is warranted, divergent approaches at the state level can lead to forum shopping and deregulatory pressures, pointing to the desirability of international guidance and standards;
- space governance is polycentric without a central organising regulatory body and the development of international standards or guidelines has proved slow and difficult; consideration should thus be given to also working with selected regional, inter-governmental and non-governmental organisations, in order to bring together scientific and legal experts from both the space and environmental fields.

The importance of 'sustainability' is now well embedded within international and many national space policies. The concept has, however, been interpreted conservatively: as supporting the role of space activities in providing information on climate change and other environmental or health challenges; and as requiring that outer space remains an open environment for present and future generations, with a focus on space congestion and debris removal. Where the re-entry process has been addressed, the focus has been on the risks to life or property posed by components that survive the ablation process, not the direct or indirect environmental consequences of ablation itself.

Two factors, in particular, lie behind this:

- The most obvious is that it is only relatively recently that the potential environmental significance of ablation has been recognised. Evidence of potential negative effects has not been considered particularly concerning given the limited scale of space activities compared to, for example, civil air traffic. With the recent development of commercial space activities, notably the launch of small satellite constellations with a limited life span, this perception is changing.
- Space activities, perhaps because they are considered to take place 'out there' and involve highly specialised technical industries, have tended to be subject to subject-specific legal regimes and regulations, both at international and national levels. Space 'exceptionalism' discourages drawing the necessary connections between space and other policy fields, in particular, environmental protection.

These observations underscore the need, not only for further scientific and technical investigation into the operation and effects of ablation, but also reconsideration of existing policy and regulatory frameworks. In particular, there is **need for a richer conceptualisation of what 'sustainability' means in the space context**, and a **more holistic policy perspective that addresses both 'space-based' and 'earth-based' implications of outer space activities**. **Dialogue between the scientific, technical and legal communities is essential** in order to assess what is currently required, ethically as well as legally, given the current state of knowledge.

A preliminary legal question, which requires further examination, is whether there is a customary right of transit for re-entering space objects through the air space of another state or over the high seas. Although there is no agreed altitude at which air space gives way to outer space, ablation wholly or mainly occurs within what is generally understood to be air space. Given that states have sovereignty over the airspace above their territory, this could open the way for states to set conditions on, or otherwise control, ablation events occurring in that domain.

This would not exclude the application of international space law, which requires States to authorise and 'continually supervise' the activities of non-governmental entities (Art. VI OST). The space law regime contains, however, a number of significant gaps and ambiguities. It does not include an explicit general obligation to avoid Earth-based environmental damage; the nature of the State responsibility to oversee domestic space activities is not further specified; there is considerable scope for variance in state approaches to information sharing, particularly regarding the final phase of a satellite's life; while the weak enforcement framework means that uncertainties remain unresolved. In particular, it is doubtful whether the cumulative damaging effects of ablation fall within the scope of the Liability Convention.

Despite these limitations, the OST requires States to have 'due regard' to the interests of all other States, placing on space-faring nations **an obligation to investigate the potential damaging environmental effects of national space activities and adopt appropriate preventive or mitigating policies**. In addition, states are required to **share information about their activities 'to the greatest extent feasible'** with the UN, the public and scientific community.

The extent to which states evaluate environmental effects as part of their licensing procedures varies considerably as does the information provided to the UN for recording in the UN registry. **Further study to determine and recommend best practice in relation to domestic space EIAs is desirable as is consideration of how the information reporting and recording requirements at UN level could be enhanced to address ablation**, for example, by including relevant aspects of the material composition and weight of space objects and planned orientation at re-entry.

Article III OST establishes an express bridge with international environmental and customary law, where a similar picture emerges to that in the international space law field. Review of the treaties adopted to address depletion of the ozone layer, climate change and other environmental challenges reveal that they either do not cover ablation or, at best, do so in a contestable and incomplete way. The specific focus on atmospheric pollution and ability to address emerging threats in treaties such as the Montreal Protocol nevertheless suggest that international environmental law could form a promising framework within which to address the environmental effects of ablation. Although amendment of the space law treaties is not currently realistic, **further consideration should be given to whether environmental conventions such as the Montreal Protocol could be amended to include specific space activities, and, if so, the best way to initiate such a process**.

Alongside treaty law, international environmental law encompasses two customary law principles: **the principle of prevention of transboundary harm** and **the precautionary principle**. The former requires States to notify, warn, inform or consult States potentially affected by environmental harm and to undertake environmental impact assessments, particularly challenging in a context such as ablation where damage is cumulative and indirect. The obligation to notify, warn, inform or consult has parallels with the information sharing requirements in the space treaties and could further support the case for more granular information exchange and systematic recording of space activities.

Similarly, the precautionary principle has parallels with the principle of due regard in international space law, requiring States to take appropriate action when faced with evidence of potentially severe or irreversible harm. What action should be taken, given the current state of knowledge is not, however, so clear. **One answer is that the precautionary principle requires, as a minimum during an initial stage of uncertainty, that space-faring states engage in further research, as in this project, to obtain a clearer understanding of the chemical and aerodynamic processes at play.** Given the collective nature of the problem this should be on a collaborative basis, to avoid duplication, with input also from the private sector. Further exploration of the practical implications of the ‘due regard’ and precautionary principles is desirable, in that, despite weaknesses in the system of enforcement, these binding international principles can be referenced to encourage good faith engagement by states and industry with transboundary environmental concerns.

Where it is established that action is required to address potential significant environmental harms it will be necessary **to determine the venues and actors best able to develop standards or guidance** and the **regulatory strategies most likely to realise the environmental goals. States act as the gateway to space and thus are well positioned to incentivise sustainable practices, for instance through supporting responsible investment and design, and/or requiring certain standards be met at the licensing stage; but in a competitive international market cannot act in isolation. Private actors can drive innovation and support responsive standard setting.** Consideration must also be given to the perceived legitimacy of any such process and the appropriate forum in which competing policy objectives can be addressed. **Standards/guidance could relate to such matters as the recommended orientation of space objects on re-entry; the use or avoidance of certain materials; design features affecting break-up on re-entry; alongside criteria designed to optimise orbital use, incentivise collaboration, and limit duplication**.

Further consideration of how these recommendations can be taken forward in policy development is included in TN01.

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