Redefining the Hypersonic Frontier: CubeSats, Democratization, and Dual-Use Risk

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Benjamin Petsopoulos

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Technical Team Members:

Sydney Bakir	Franklin Escobar	Benjamin Petsopoulos
Cole Bixby	Nathan Kaczka	Cade Shaw
Max Cristinzio	Jason Morefield	Michael Wennemer
Luke Dropulic	Zachary Morris	Caleb White
	Arooj Nasir	

On my honor as a university student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISORS

Prof. MC Forelle, Department of Engineering and Society

Prof. Christopher Goyne, Department of Mechanical and Aerospace Engineering

Introduction:

Hypersonic flight (above Mach 5) is a key aerospace frontier, sought for national security applications due to its potential for high-speed, maneuverable platforms capable of potentially bypassing traditional inter-continental ballistic missile defense systems (U.S. Department of Defense, 2021) and holding civilian potential like high-speed travel (Naveen et al., 2024). Atmospheric reentry at these speeds involves extreme conditions (Benson, 2021), which historically required large, costly government programs. This landscape is changing with CubeSats; small, standardized satellites initially designed for educational missions. Now adapted as affordable platforms for hypersonic reentry research (Georgia Tech Research Institute, 2022), they allow university teams and smaller groups to gather vital flight data (HEDGE Team, 2025), democratizing access to this challenging field.

However, this accessibility creates a serious challenge. While CubeSats accelerate research, they also facilitate the development and potential spread of dual-use hypersonic technologies, capabilities applicable to both peaceful transport and advanced weaponry ("HyCUBE Overview | UMN SmallSat Program," 2025). This rapid innovation, now within reach of universities and companies, introduces specific risks: there's a heightened concern that governments might leverage easily obtainable university research primarily for military applications rather than broader societal benefit, particularly if the pathways for managing this dual-use information flow are unclear. Furthermore, private companies, including startups, now capable of entering this field, could potentially engage in irresponsible proliferation by selling sensitive technologies or data internationally without adequate oversight. These potential outcomes mean the pace of innovation risks outpacing existing international and national regulations, as well as established ethical guidelines (Ms. Helena Correia Mendon¸ca, Mrs.

Magda Cocco, & Ms. Cristina Miranda, 2018). This paper argues that current CubeSat-based hypersonic reentry projects, by enabling these new actors such as universities and private companies, reveal significant gaps in ethical and regulatory frameworks specifically concerning the management of dual-use aerospace technology. While the engineering is impressive, these experiments highlight an urgent need for governance approaches that can keep pace with rapid hypersonic innovation and address these emerging risks.

To support this claim, the paper will first review literature covering hypersonics, CubeSats, and dual-use governance. The methods section outlines the research approach combining technical case studies with policy analysis. The core analysis then examines specific CubeSat projects, linking technical achievements and problems with regulatory gaps and ethical questions. Finally, the conclusion synthesizes these findings, while addressing a key counterargument, arguing that managing these technologies responsibly is critical, and offers recommendations for future action.

Literature Review:

Hypersonic flight involves extreme aerothermodynamic challenges, especially during atmospheric reentry, generating intense heat and plasma (Benson, 2021). Historically, due to technical complexity and cost, hypersonic research and development (R&D) was dominated by state military programs and major space agencies, driven by strategic interests (U.S. Department of Defense, 2021) and the goal of high-speed transport (Naveen et al., 2024). This established hypersonic technology as inherently dual-use: advancements serve both military and potential civilian goals (Tracy, Wright, Global Security Program, Union of Concerned Scientists, & Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, 2020).

This hypersonic field is changing significantly with the innovation of CubeSats. Originating around 1999 as a collaborative effort between California Polytechnic State University (Cal Poly) and Stanford University's Space Systems Development Laboratory, CubeSats were conceived as low-cost, standardized platforms primarily for educational purposes (Pemberton, 2022). They leverage modular designs and Commercial Off-The-Shelf (COTS) components, drastically reducing development costs and enabling affordable access to space via rideshare launch opportunities (Bowman, 2014). Initially limited to simple missions, CubeSat capabilities have rapidly advanced. This evolution has significantly contributed to the democratization of space research, lowering barriers to entry for universities, smaller companies, and even student groups. This democratization now extends into the previously exclusive domain of hypersonics: by utilizing the inherent orbital velocity of spacecraft (speed generated from the orbit of earth from high altitude), CubeSats provide a comparatively affordable means to conduct experimental hypersonic reentry missions. University initiatives like HEDGE at the University of Virginia (UVA) and HyCUBE at the University of Minnesota (UMN), alongside commercial entities like Varda Space Industries now use CubeSats' orbital velocity for relatively affordable hypersonic reentry experiments, collecting flight data on materials and aerothermodynamics (HEDGE Team, 2025; “HyCUBE Overview | UMN SmallSat Program,” 2025; “Space Born, Earth Bound - Varda Space Industries,” 2025). This change in the actor network involved in hypersonic research is a central reason why new governing regulations must be formed.

Gap 1: Inadequacy of the Outer Space Treaty for Governing Emerging Dual-Use Space Technologies: The 1967 Outer Space Treaty (OST), the foundation of space law, promotes peaceful exploration and bans orbital weapons of mass destruction (United Nations, 2002). However, drafted decades ago, it is not adequate for governing contemporary dual-use hypersonic reentry research via accessible CubeSats. Scholarship critiques its failure to address technological leaps and the rise of non-governmental actors (universities, private companies) unforeseen by its drafters (Ms. Helena Correia Mendon¸ca, Mrs. Magda Cocco, & Ms. Cristina Miranda, 2018). A key inadequacy is the ambiguity of peaceful purposes, a term the OST leaves undefined (Ferreira-Snyman, 2015, p. 496). The main interpretation equates peaceful with non-aggressive, allowing military support activities (surveillance, communications), while a stricter non-military interpretation has less state practice support (Ferreira-Snyman, 2015). This complicates regulating dual-use CubeSat research where scientific aims can overlap with military applications. Furthermore, the OST explicitly prohibits only nuclear/weapons of mass destruction in orbit (Article IV), leaving out specific regulation of conventional weapons or military systems during reentry (Ferreira-Snyman, 2015). While Article VI mandates state supervision of non-governmental entities, it offers little practical guidance for overseeing diverse new actors (Ms. Helena Correia Mendon¸ca, Mrs. Magda Cocco, & Ms. Cristina Miranda, 2018), whose activities complicate governance (Ferreira-Snyman, 2015). This blend of ambiguity, lack of specificity, and challenges supervising new actors highlights the need for updated frameworks addressing risks from accessible hypersonic research platforms.

Gap 2: Export Control Regimes: Export control systems, which are governmental regulations designed to restrict the transfer of certain goods, software, and technologies deemed critical for national security or foreign policy reasons, both multilateral ("The Wassenaar Arrangement," 2021) and national (United States Department of State, 2024), are designed to prevent the transfer of sensitive military and dual-use technologies. However, they run into significant problems with university-based CubeSat research. A large portion of academic research often qualifies for fundamental research exemptions, which is built on the idea of open dissemination of results (UVA Office of Research Security, 2025). There is a boundary between non-controlled fundamental research outputs and controlled technical data or development activities, and finding it is extremely hard, especially for rapidly evolving, cutting-edge technologies like hypersonics. Furthermore, existing regulations struggle to regulate the transfer of intangible technology, like algorithms, simulation software, and design methodologies which can be easily shared through publications, conferences, and over the internet. Since CubeSats (which are tangible hardware platforms but enable the creation and dissemination of critical intangible knowledge and data) are so easy to manufacture, they can easily outpace the processes required to update complex export control lists and regulations (Bauer, 2024).

Gap 3: Insufficient Frameworks for Responsible Innovation: While universities have Institutional Review Boards (IRBs) focused on human subjects protection and general research integrity policies, and professional societies like the American Institute of Aeronautics and Astronautics (AIAA) promote codes of ethics (American Institute of Aeronautics and Astronautics, 2025), a specific framework for managing the dual-use risks in sensitive fields like hypersonics, is non-existent. Unlike biology, which developed frameworks for Dual Use Research of Concern (DURC) to account for specific security threats (Evans, 2022) driven by public events like anthrax scares, the aerospace engineering community lacks a similar process. Historically, aerospace research risks were often managed via classification and export controls within state programs, a different type of context that lacks the public motivator such as anthrax seen in biology; consequently, we rely solely on individual researcher awareness and adherence to general ethical principles. This might not be enough because of the technical complexity and potential security implications of hypersonic capabilities (Air University (AU), 2025).

We will start with a basic technical review to understand what these CubeSat projects actually do, how they work, what data they collect during reentry (like heat and pressure measurements), and their limitations (like size or surviving the heat). This technical part helps us see the real-world context, which is important because it grounds the assessment of dual-use potential in actual capabilities and limitations, rather than pure speculation. We will integrate this technical understanding with the Social Construction of Technology (SCOT) framework (Bijker, Hughes, & Pinch, 1987). SCOT will allow us to examine how different relevant social groups, defined as any group or individual who attaches a particular meaning to the technology and influences its development or use (historically large state agencies, but now also university labs, student teams, and commercial startups), shape the meaning and development of CubeSat-based hypersonic research. We can analyze the flexibility of this technology: how different social groups can have different understandings and assign different meanings or problems/solutions to the same technology. Is it seen mainly as an educational tool, a low-cost scientific instrument, a road to commercial development, or potentially a proliferation risk? SCOT helps us understand how these varying interpretations, held by different social groups, influence the design and trajectory of the technology, interacting with technical characteristics like low cost and accessibility.

Methods:

This research employs a qualitative, mixed-methods design, integrating a technical review with a sociotechnical analysis using the Social Construction of Technology (SCOT) framework to examine the governance challenges surrounding CubeSat-based hypersonic reentry research.

Phase 1: Technical Review

A technical review established the necessary background by analyzing publicly available information (project-specific documents from HyCUBE, HEDGE, Varda; general CubeSat/hypersonic resources from NASA, DoD). The goal was to descriptively map the technology's capabilities (e.g., COTS use, sensor types), limitations (e.g., heat, power constraints), and key characteristics enabling broader participation (e.g., low cost, standardization) relevant to the identified governance concerns (dual-use data, controlled components). This analysis focused on understanding the technology, not performing original engineering assessments, selecting sources demonstrating democratized access to hypersonics.

Phase 2: Sociotechnical Data Collection and Analysis (SCOT Framework)

The SCOT framework guided the analysis of how CubeSat hypersonic research is socially shaped. This phase involved:

1. **Identifying Social Groups:** Recognizing the shift from primarily state actors to include universities, student teams, commercial startups (Varda), funding agencies like the Air Force Office of Scientific Research, and regulatory bodies.
2. **Mapping Interpretations:** Analyzing how these different groups interpret CubeSat-based hypersonic research (as a science platform, educational tool, commercial

service, defense technology, proliferation risk) based on mission statements, funding, and actions.

3. **Connecting Interpretations to Governance Gaps:** Linking the many/conflicting interpretations, enabled by the technology, directly to the gaps in governance. This step formed the link between the technology and the governance challenges.

This methodology, while acknowledging the limitations in relying on publicly available data, provides a structured approach to analyzing the connection between CubeSat technology, its diverse users, and governance gaps in the hypersonic domain.

Analysis:

CubeSats' lower cost, standardization, use of COTS components, and rapid development cycles significantly reduce barriers to entry for hypersonic research compared to traditional, large-scale government programs (Benson, 2021). This technical shift enables the emergence of new relevant social groups in the hypersonic field, including universities (e.g., University of Minnesota (UMN) HyCUBE, University of Virginia (UVA) HEDGE), student teams, and commercial startups (e.g., Varda Space Industries), alongside traditional state actors. Figure 1 visually contrasts these approaches, highlighting the dramatic differences in actors, goals, budget scale, development timelines, hardware complexity, and openness norms between legacy state-led efforts and these newer CubeSat initiatives.

Feature	Traditional State-Led Programs	Emerging CubeSat-Based Initiatives
Primary Actors	DoD, NASA, Large Contractors	Universities, Student Teams, GTRI, Startups
Typical Goals	National Security, Prestige, Large-Scale Science	Education, Tech Demo, Commercial Service, Defense R&D Support
Budget Scale	Billions USD	Thousands to Millions USD
Development Cycle	Many Years to Decades	1–5 Years
Hardware	Custom, Complex, Large Vehicles	CubeSat Buses (3U/6U), COTS, Small Payloads
Openness Norms	Classified / Restricted	Open (Academic Norms) or Proprietary

Figure 1. Comparative Table of Hypersonic Research Approaches

SCOT analysis reveals that these new groups often possess different primary goals (education, fundamental science, commercial service development) compared to the state military and space agency actors central to the era when the 1967 Outer Space Treaty (OST) was drafted (United Nations, 2002). This misalignment creates tension with the OST's state-centric assumptions and ambiguous provisions.

This is particularly evident regarding the OST's peaceful purposes clause (Article IV), which stipulates that the Moon and other celestial bodies be used exclusively for peaceful purposes, but lacks a precise definition for activities in Earth orbit beyond banning weapons of mass destruction. Legal interpretations vary, often distinguishing between prohibited aggressive actions and permitted non-aggressive military support (Ferreira-Snyman, 2015). CubeSat projects collecting reentry data (e.g., aerothermal loads, plasma effects on HyCUBE) generate information valuable for both civilian spacecraft design and military applications. For instance, reentry data can inform civilian Thermal Protection System (TPS) design improvements, Computational Fluid Dynamics (CFD) model validation, reentry trajectory planning, and space weather research, while also providing insights useful for military Hypersonic Glide Vehicle (HGV) aerodynamic refinement, Reentry Vehicle (RV) targeting and thermal design, missile materials development, and understanding plasma effects on communications and potential countermeasures. SCOT highlights interpretive flexibility here: the university group (UMN) frames the work primarily as fundamental science and education, while a funder like the Air Force Office of Scientific Research (AFOSR) likely sees strategic defense value (“HyCUBE Overview | UMN SmallSat Program,” 2025). The OST's vagueness provides little clear guidance for navigating these dual-use scenarios involving non-state actors.

Furthermore, the OST's requirement for state authorization and continuing supervision (Article VI) over all national space activities becomes practically challenging. This principle holds states responsible for overseeing the activities of their non-governmental entities to ensure treaty compliance. However, the sheer volume, relatively low cost, and rapid development cycle of university or commercial CubeSat projects (as shown in Figure 1) make continuous, detailed governmental oversight difficult to implement effectively compared to supervising a few large national missions. The technical accessibility enabled by CubeSats stresses the OST's supervisory model, revealing a key limitation in applying Cold War-era international law to democratized space activities (Ms. Helena Correia Mendon¸ca, Mrs. Magda Cocco, & Ms. Cristina Miranda, 2018).

The expansion of university-based CubeSat hypersonic research, often encouraged by defense funding (e.g., AFOSR support for HEDGE, HyCUBE), creates friction with national export control systems like the US Export Administration Regulations (EAR). These projects involve students and researchers gaining hands-on experience with technologies and concepts potentially relevant to controlled items (e.g., reentry vehicle shapes, advanced materials, guidance algorithms) (United States Bureau of Industry and Security, 2013).

SCOT analysis again reveals conflicting interpretations between relevant social groups. Universities, as a group, strongly value open dissemination and academic freedom, often operating under the fundamental research exemption (FRE) within the EAR, which generally allows research results intended for publication to be shared broadly without requiring export licenses (United States Bureau of Industry and Security, 2013). Defense funding agencies (like AFOSR), however, invest in this research precisely for its potential strategic value and access to emerging talent (“HyCUBE Overview | UMN SmallSat Program,” 2025). CubeSats, by making advanced experimental research feasible within university labs, do work that blurs the line between non-controlled fundamental research and potentially controlled technical data or development activities. Figure 2 provides concrete examples of typical CubeSat research tasks (CAD design, CFD simulation, material tests) and how they can simultaneously serve educational/fundamental purposes while potentially generating data related to controlled technologies under the EAR (e.g., related to missile components or guidance, ECCN 9A101).

University CubeSat Activity	Fundamental Research Aspect	Potential EAR-Controlled Development
CAD design of reentry shape	Physics education, student training	Optimizing shape for controlled missiles (ECCN 9A101)
CFD simulations	Publishing flow model insights	Refining military-relevant reentry dynamics
Control algorithm dev	Exploring control theory	Algorithms for precision reentry/missile accuracy
Thermal material tests	Publishing material properties	Qualification data for missile components
Sensor integration	Engineering education	Specific data for controlled performance
Publishing detailed results	Academic freedom	Potential deemed export risk if shared internationally

Figure 2. Ambiguity Between Fundamental Research and Export-Controlled Development.

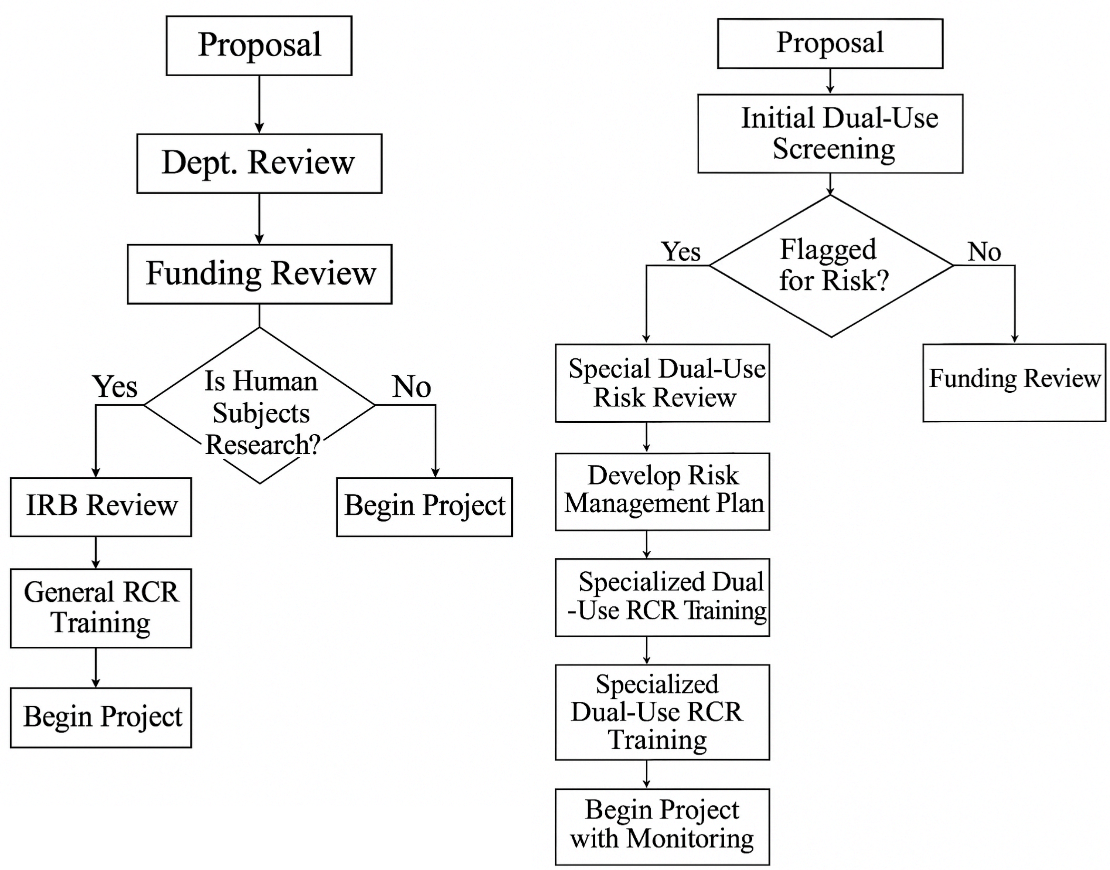
This ambiguity creates significant compliance challenges and risks unintended knowledge transfer or deemed export violations (transfer of controlled information to foreign nationals within the US).

Moreover, hypersonic research relies heavily on intangible knowledge, modeling techniques, simulation software, control algorithms, design methodologies, which is inherently difficult to track and control compared to physical hardware. SCOT highlights that academic norms, prioritized by university-based social groups, emphasize rapid and wide dissemination of such knowledge through publications, presentations, and online databases. CubeSats exacerbate this by enabling faster design-build-test-publish cycles. This rapid generation and dissemination of potentially sensitive intangible knowledge, driven by academic practices, can easily outpace the necessarily slower bureaucratic processes required to update complex export control lists (like the Wassenaar Arrangement lists or the EAR's Commerce Control List) to address emerging technological concerns (“The Wassenaar Arrangement,” 2021; United States Bureau of Industry and Security, 2013).

While universities possess general research ethics policies (U.S. National Science Foundation, 2024) and professional societies like AIAA offer codes of conduct (American Institute of Aeronautics and Astronautics, 2025), these often lack the specificity needed to address the distinct dual-use risks inherent in hypersonics, particularly when national security funding is involved. Students and academic researchers on projects like HEDGE and HyCUBE are now directly engaging with technologies of significant defense interest, often enabled by military funding sources (e.g., AFOSR).

SCOT analysis reveals that these newer university groups often lack the strict internal compliance programs and specific procedures for assessing dual-use risks that are typical in large defense contractors or government labs (Air University (AU), 2025). The involvement of defense funding creates an ethical tension between the academic norm of openness and the awareness of the research's potential military applications or misuse. This situation presents several challenges: it allows military-relevant technology to be developed in open academic settings potentially subject to less scrutiny than traditional defense projects; it can create conflicts of interest for researchers balancing publication goals with security awareness; and it raises concerns about transparency and the risk of unintentionally contributing to weaponization.

Relying on general ethical principles alone is insufficient for researchers and students developing potentially weaponizable technology in an open university setting. Figure 3 illustrates a typical, simplified university ethics review process, often focused primarily on human subjects research via IRB review, with general Responsible Conduct of Research (RCR) training for others. In contrast, Figure 4 depicts a hypothetical, more robust process incorporating dedicated dual-use screening and risk management. The lack of widespread adoption of processes like the one envisioned in Figure 4 within the aerospace research community highlights the current procedural gap.



Figures 3 & 4. Comparing Standard vs. Updated Ethics Review Processes for Dual-Use Aerospace Research.

This ethical gap is very real for projects accepting military funding. General codes offer little specific advice on navigating dilemmas such as:

- How much technical detail is appropriate to publish openly?
- Should collaborations be pursued with certain international entities?
- How should student involvement in potentially sensitive aspects be managed?

- What procedures should be in place if research yields unexpected, highly sensitive results?

The lack of a widely adopted, aerospace-specific framework for responsible conduct in dual-use research forces researchers to navigate these difficult ethical decisions, potentially leading to inconsistent practices and increasing risks as CubeSats draw even more diverse actors into the hypersonic field.

Conclusion:

The integration of accessible CubeSat platforms into hypersonic reentry research represents a significant technological and social shift in the aerospace domain. This paper has argued that while this widening access fosters innovation and provides valuable educational opportunities, it simultaneously exposes and exacerbates critical gaps within existing regulatory and ethical frameworks, which are largely designed for an earlier era of state-controlled, large-scale technology development. Our analysis, combining technical insights with the Social Construction of Technology (SCOT) framework, illustrated how the characteristics of CubeSats, leveraged by diverse new actors including universities and commercial startups, directly challenge the applicability and effectiveness of international space law, national export controls, and established norms of responsible conduct in aerospace engineering.

Acknowledging the benefits of this shift, faster innovation cycles, reduced testing costs, valuable workforce training, is important. A perspective emphasizing these advantages might suggest that focusing heavily on regulatory gaps could stifle the very progress CubeSats enable in both civilian and defense spheres, arguing perhaps that the proliferation risks from small-scale projects are negligible compared to state programs. However, this perspective risks minimizing the complex relationship between innovation, security, and governance. The potential downstream consequences of unmanaged diffusion of dual-use hypersonic knowledge, lowering barriers for advanced weapon development, increasing international instability, or enabling non-state threats, cannot be dismissed solely based on platform size. Responsible governance should be viewed not as an obstacle to innovation, but as a necessary enabler for its sustainable and ethical development.

Addressing the identified gaps is inherently complex, and the relative lack of comprehensive solutions likely comes from multiple factors rather than simple oversight. Competing national interests (balancing security concerns with economic competitiveness and scientific leadership), the inherent difficulty in crafting regulations for rapidly evolving, intrinsically dual-use technologies, disagreements on appropriate international forums, and the sheer momentum of existing legal and bureaucratic systems all contribute to the challenge. Recognizing this complexity is crucial. Proactively engaging with these governance challenges is necessary not to halt progress, but to foster a more broad, ethically informed framework where the benefits of CubeSat-based research can be pursued responsibly, mitigating risks before they escalate and potentially trigger overly restrictive reactions or damage international trust.

Revised Future Steps / Recommendations:

Acknowledging that many stakeholders are likely aware of these challenges, moving forward requires coordinated effort amongst all actors. Potential pathways include:

International Dialogue & Legal Clarification: Focused discussions, potentially within forums like the UN Committee on the Peaceful Uses of Outer Space (COPUOS) or dedicated expert groups, are needed to explore clearer interpretations or supplementary agreements for the Outer

Space Treaty regarding dual-use activities by non-state actors, especially concerning reentry. Overcoming political differences to achieve consensus will always be a significant hurdle.

National Regulatory Adaptation: Agencies managing export controls (e.g., US Dept. of Commerce BIS for EAR, Dept. of State DDTC for ITAR) should continue evaluating how concepts like fundamental research and development apply to university-based research involving cutting-edge aerospace technologies like hypersonics.

Institutional Governance (Universities): Research institutions, particularly those involved in sensitive aerospace areas, should consider developing and implementing specific institutional policies, review processes (potentially involving specialized dual-use review committees beyond standard IRB/Export Control checks), and targeted training addressing dual-use risks. This requires institutional commitment and resources.

Community Norms & Ethics (Professional Societies): Organizations like AIAA can play a key role by facilitating dialogue, developing best practices, and potentially evolving codes of ethics to offer more specific guidance on navigating dual-use dilemmas encountered in contemporary aerospace research and development.

Education & Culture (Researchers/Educators): Creating a culture of awareness regarding dual-use responsibilities and introducing more discussions on security implications, ethics, and export controls into engineering curricula and research group practices is essential for long-term responsible innovation.

Funding Agency Leverage: Funding bodies, especially defense agencies supporting academic work, could explore incorporating dual-use risk assessment and mitigation planning as criteria for funding eligibility or project requirements, incentivizing responsible practices.

These steps are interconnected and require long-term engagement from all relevant social groups. The goal is not simply to impose restrictions, but to build a more adaptive and ethically robust governance ecosystem capable of supporting responsible innovation in an era of increasingly accessible advanced technology.

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