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CHINA AEROSPACE STUDIES INSTITUTE

HYPERSONICS RESEARCH COLLABORATION

BETWEEN THE UNITED STATES AND THE PEOPLE'S REPUBLIC OF CHINA

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EXECUTIVE SUMMARY

This report draws on a dataset of all publications related to hypersonic technologies in the OpenAlex database between 2002-2020 in order to: (1) identify the institutions in the People's Republic of China (PRC) and the United States (US) that most often collaborate with each other on this topic; (2) identify patterns of US-PRC collaboration on this topic; and (3) investigate the relative impact of researchers in these PRC-US hypersonics research collaborations. It offers four key findings:

1) The PRC organizations with which US researchers collaborate on hypersonics include not only actual military organizations, such as the National University of Defense Technology, but also many organizations closely affiliated with the military, such as Beihang University. These collaborations have the potential to support PRC military research, indicating the need for appropriate screening mechanisms and careful due diligence before embarking on such collaborations.

2) There has been a significant amount of collaboration on hypersonics research between the US and the PRC, although in comparison to the overall volume of US hypersonics research, collaborations with the PRC represent a relatively small proportion. Collaborations with the PRC represent higher proportions of hypersonics-focused research in, for instance, the United Kingdom and Australia.

3) US-PRC collaboration in hypersonics research tends to focus on propulsion technology, with secondary foci on overall design technology, materials processing and manufacturing, and flight navigation, guidance, and control. Collaboration in publications on testing, verification, demonstration, and validation was relatively limited, potentially indicating that US-PRC research on hypersonics focuses on basic, rather than applied, research.

4) US researchers who collaborate with PRC researchers on hypersonic technologies tend to have higher research impact scores than their PRC counterparts. This indicates that the PRC may benefit more than the US from such collaborations.

Overall, while US collaborations with PRC institutions on hypersonics are relatively limited and at first glance do not appear to focus on testing applications of existing hypersonic technologies, they are still significant and often involve PRC military or military-affiliated institutions. Such research therefore has the potential to benefit the PRC military. Furthermore, US researchers in such collaborations tend to have higher research impact, indicating that the PRC may disproportionately benefit from working with them.

General Overview

In this report we provide a deep dive into hypersonics research collaboration between the United States (US) and the People's Republic of China (PRC). We employ an updated version of the dataset used in CASI's prior report, "An Exploratory Analysis of the Chinese Hypersonics Research Landscape." This updated dataset covers the period 2012 – 2020 and contains an additional 1,606 relevant articles for the period, producing a corpus of 14,979 hypersonics publications containing at least one Chinese author. In this work, US-PRC collaboration is defined as a research publication authored by at least one researcher from a PRC institution and one from a US institution.

We present US-PRC hypersonics research collaboration through the following analyses:

> **Collaborations measured against baselines over time:** Here we compare US-PRC collaboration trends to overall US hypersonics research trends, as well as to collaboration trends from the top five most prolific nations in hypersonics research.
>
> **A high-level topical breakdown of research publications:** Relying once more on the high-level taxonomy of hypersonics research introduced in BluePath's original hypersonics publication for CASI, we classify US-PRC research into several categories.
>
> **Presentation of US institutions with the greatest number of military-affiliated PRC collaborations:** This section presents a table of US institutions with the most exposure to PRC military-affiliated institutions in their hypersonics research.
>
> **Presentation of PRC military-affiliated research institutions most frequently collaborating with US institutions:** This section highlights the specific PRC military-affiliated institutions collaborating on the greatest number of research projects with US institutions.
>
> **Comparing the influence of PRC researchers and their international collaboration partners:** This section measures and compares the mean H-index within all hypersonics publications that involved collaboration with PRC researchers for each nation of interest.

Security Concerns: Collaboration with PRC Military Entities

Our analysis found that US institutions have collaborated with several PRC entities that are either closely associated with the People's Liberation Army (PLA) and the PRC military-industrial complex, or are outright arms of the Chinese military. Collaboration between US institutions and PRC entities of concern, while less frequent than other nations' collaborations with the PRC, did still occur on numerous occasions. For instance, the National University of Defense Technology (NUDT), the sixth-most common institutional partner for US researchers' collaborations in hypersonics research, is both a military academy directly subordinate to the PRC's Central Military Commission and one of the PLA's most important research institutions. NUDT conducts research on a wide range of military technologies, including hypersonic missiles.[1] The Australian Strategic Policy Institute (ASPI) has extensively documented how NUDT and other PLA universities partner with foreign academic institutions to collaborate on cutting-edge research, which is then used for military purposes. This includes one researcher who disguised his affiliation with a PLA university to conduct research on hypersonic flight vehicles in Norway.[2] NUDT has been included on the US Commerce Department Entity List since 2015 due to its military activities.[3] Given these facts, any dual-use research collaboration between US institutions and NUDT is at high risk of being put to military use.

US institutions were also found to have collaborated on various occasions with other PLA entities. These include military academies such as the PLA Space Engineering University, as well as military research institutions. The latter present a particularly vexing problem, because their military affiliations are often not obvious at first glance. For example, the China Aerodynamics Research and Development Center (CARDC) was the second-most frequent PLA collaborator after NUDT, and the seventh-most common military-affiliated collaborator for US researchers overall (see Table 4 below). Despite its seemingly anodyne name, CARDC is in fact a PLA research institute which is heavily involved in the PLA's hypersonic weapons program. CARDC goes to great lengths to hide this affiliation, even having its military leadership appear in civilian clothing on its website.[i4]

In addition to PLA institutions, several examples of collaboration with PRC military companies appeared in the data. These included the Aerospace Research Institute of Materials and Processing Technology (ARIMPT) and China Academy of Space Technology (CAST), both subsidiaries of the military aerospace giant China Aerospace Science and Technology Corporation (CASC). CASC is the PRC's largest state-owned enterprise focused on rocket and ballistic missile technology.

As with CARDC above, these enterprises and their subordinate research institutes often mask their military affiliations behind anodyne-sounding names, assuming Western researchers will not investigate risky ties before agreeing to collaborate. This includes using different names in English that obfuscate military connections or missions, such as translating "Defense S&T Key Laboratory" as "National Key Laboratory."[5] Such examples demonstrate the urgent need for better

[i] Sources disagree as to whether CARDC's exact subordination is the Academy of Military Sciences or the PLA Strategic Support Force.

screening mechanisms and enhanced due diligence on the part of Western research institutions when considering scientific collaboration with PRC institutions.

Beyond explicitly military institutions, several other ostensibly civilian institutions on the list also raise significant concerns. These include the so-called "Seven Sons of National Defense" [国防七子], a consortium of seven universities that are known for their particularly close connections to the PLA and China's defense industry.[ii] These universities occupied the top five places on the list of collaborating institutions, and were found to collaborate with US institutions on a far greater overall scale than outright military institutions. However, despite their official status as civilian universities, research collaboration involving these entities is no less likely to be put to military use. Unlike most PRC universities, the Seven Sons are directly overseen by the State Administration for Science, Technology and Industry for National Defense (SASTIND), a PRC government body tasked with defense research and procurement, making their mission fundamentally military in nature. Thus, these universities contribute a disproportionately high amount of the PRC's military research and workforce. For instance, nearly three-fourths of researchers recruited by the PRC's major defense conglomerates in 2019 graduated from one of these seven universities.[6] Further, a 2021 BluePath Labs survey found that the majority of top-level PRC defense labs assigned to civilian universities were overseen by these seven institutions.[7] The military research conducted by these labs extends into hypersonic technologies. For example, a key defense lab for missile technology at Beihang University,[8] the number one entity on the list, has conducted research into improved guidance and accuracy for hypersonic flight vehicles.[9]

All members of the "Seven Sons" are listed in the US Commerce Department Entity List.[10] Further, in 2020, the US banned entry of scholars affiliated with these universities for study or research.[11] It is important to note, however, that PRC university cooperation with the PLA is by no means limited to just the Seven Sons. SASTIND currently has defense research agreements with dozens of civilian universities, including other consortiums such as the "Seven Sons of the Arms Industry," and over 150 PRC universities are credentialed to conduct classified defense research.[12] Thus, it is important that US universities have adequate screening mechanisms in place and conduct thorough due diligence before agreeing to collaborate on any potentially dual-use research with PRC universities.

The remainder of this report presents detailed analytics on US-PRC collaboration on hypersonic systems, based on a corpus of 14,979 technical publications published between 2012 and 2020. This data provides insights into specific collaborative relationships and provides benchmarks for US collaboration in comparison to other nations that have also done work with China on hypersonic technologies.

[ii] These are Beihang University, Beijing Institute of Technology (BIT), Harbin Engineering University (HEU), Harbin Institute of Technology (HIT), Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing University of Science and Technology (NUST), and Northwestern Polytechnical University (NWPU).

US and International Hypersonics Collaboration with the PRC

Within the total hypersonics corpus of 33,687 publications (14,979 of which contained PRC coauthors), the US ranked second with contributions to 6,523 publications (Table 1). Of these, 834 were identified as US-PRC collaborations (Table 2). The US leads top hypersonics research-producing nations in overall collaborations with China. However, the proportion of US hypersonics research that involves collaboration with the PRC is among the lowest of the top producers of hypersonics research (Table 2). Considering the US's high rate of hypersonics research article production for the period, PRC involvement into the US hypersonics research landscape is relatively limited (Figure 2).

Table 1. Top 10 most prolific nations in hypersonics research (2012 – 2020)

Rank	Country	Article Count
1	People's Republic of China	14,979
2	United States	6,523
3	Russian Federation	1,431
4	United Kingdom	1,238
5	India	1,197
6	Germany	935
7	Japan	819
8	Australia	814
9	France	667
10	Italy	584

Table 2. Top 10 most prolific collaborators with PRC in hypersonics research (2012 – 2020)

Rank	Country	Article Count	Percentage of Total
1	United States	834	12.8%
2	United Kingdom	540	43.6%
3	Australia	299	36.7%
4	Canada	180	44.2%
5	Germany	150	16%
6	Singapore	146	75.6%
7	Japan	109	13.3%
8	France	88	13.2%
9	Sweden	75	48.7%
10	Italy	58	10%

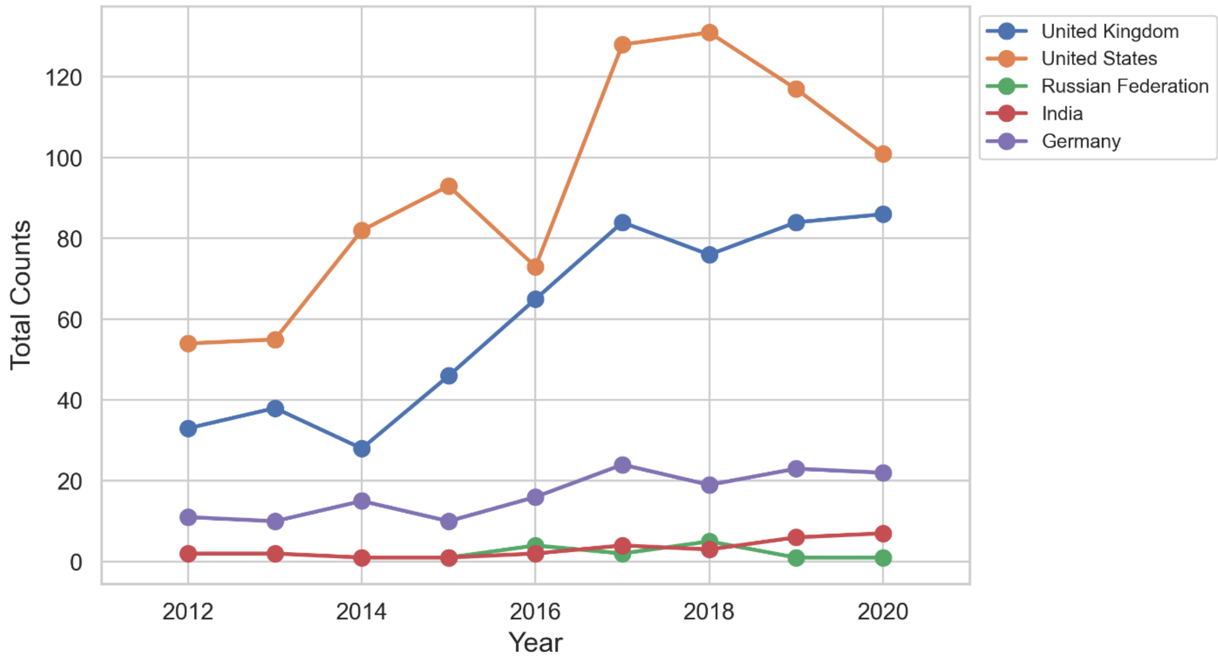

Figure 1. Total number of documents featuring collaboration between the PRC and other countries.

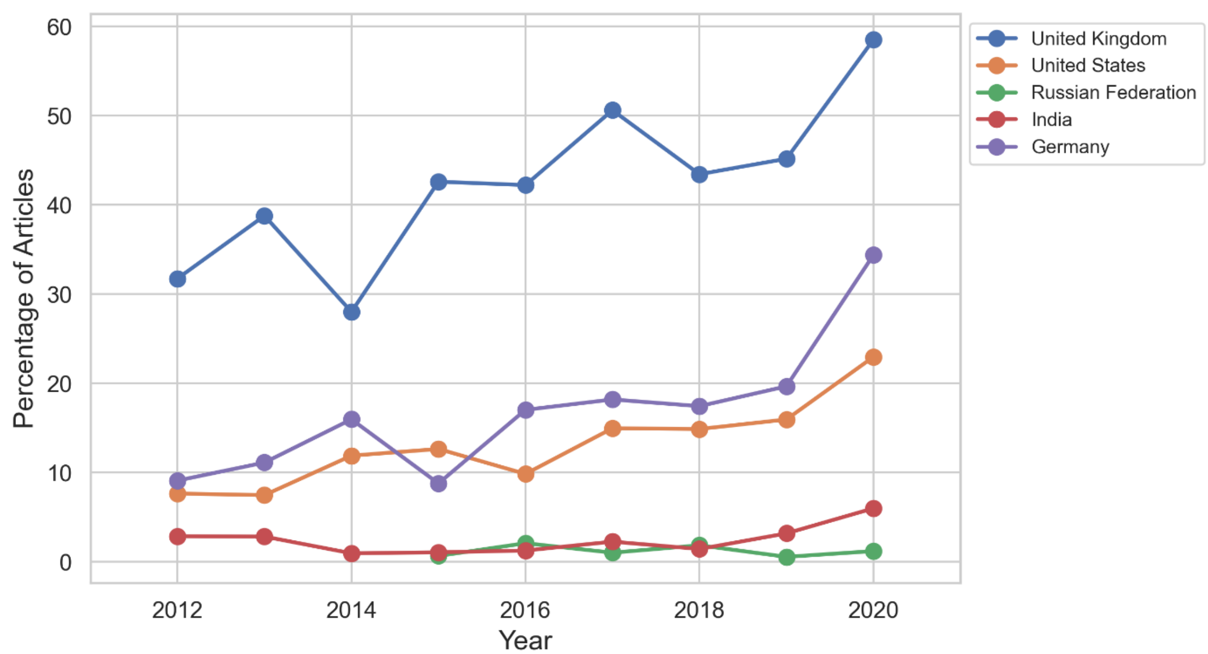

Figure 2. Percentage of articles produced in collaboration with the PRC from 2012 – 2020. These trends indicate that US hypersonics research does not involve an abnormal degree of collaboration with PRC institutions.

Overall, US scientists are not outliers in their hypersonics collaborations with PRC peers (Figure 3). They rank second out of the top five producing nations, close in value to third-place Germany.

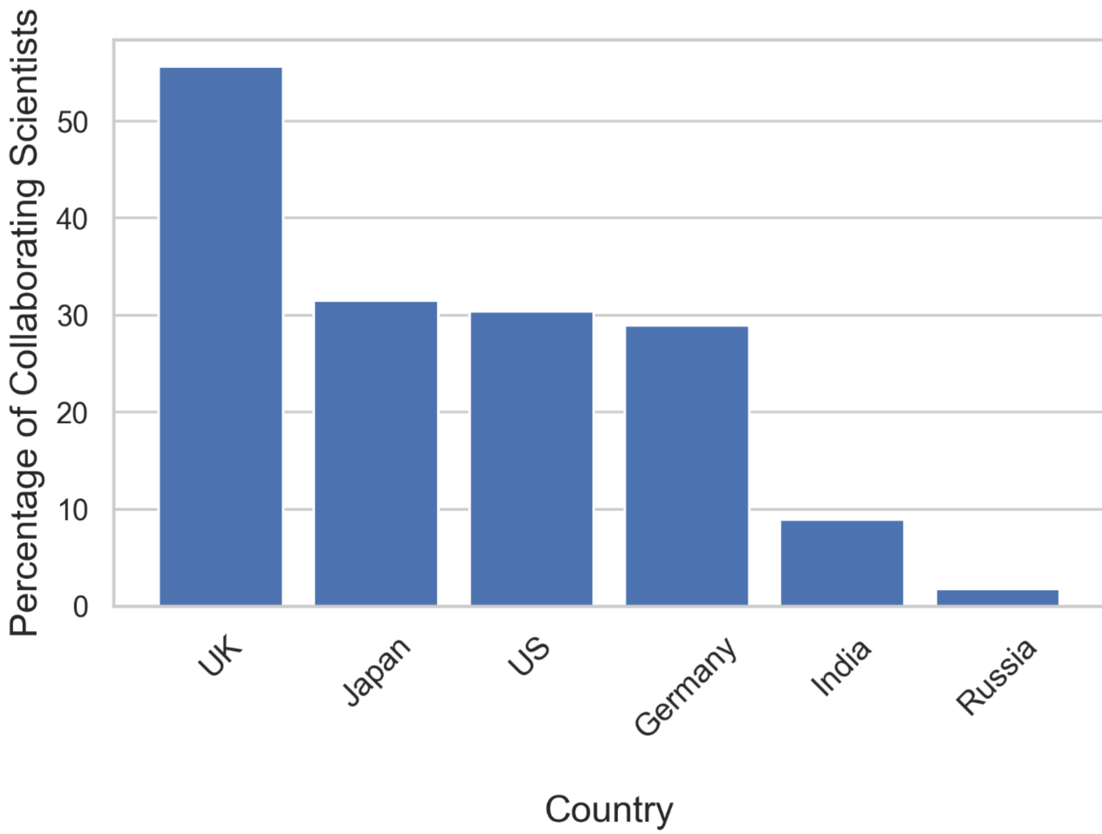

Figure 3. Proportion of scientists within full-country hypersonics corpuses that appear in a research article with a PRC collaborator.

Collaboration Topics

BluePath Labs' previous report clustered publications from PRC institutions into six categories of hypersonic vehicle technology, which were described by authors Cai Guobiao [蔡国飙] and Xu Dajun [徐大军] in their 2012 book, *Hypersonic Vehicle Technology* [高超声速飞行器技术]:

- C1 - Overall Design Technology [总体技术]
- C2 - Propulsion Technology [推进技术]
- C3 - Materials / Processing / Manufacturing Technology [材料/工艺/制 造艺术]
- C4 - Testing and Verification Technology [试验验证技 术]
- C5 - Flight Navigation, Guidance, and Control Technology [飞行导航制 导与控制技术]
- C6 - Flight Demonstration and Validation Technology [飞 行演示验证技术]

Figure 4 displays the number of hypersonics articles by category for the period 2012 – 2020. Category 2 (Propulsion) proved the most frequent research topic, accounting for over 30% of articles. No articles were identified for category 6 (Flight Demonstration and Validation Technology) and only two were identified for category 4 (Testing and Verification Technology). These categories are therefore not addressed in the subsequent topical breakdown (see Appendix I for complete counts of articles between US and PRC researchers by category for all US institutions with 4+ collaborations). This pattern may indicate that US-PRC hypersonics collaborations are less likely to involve late-stage applications of hypersonics technology.

The remainder of this section provides information on each of the four categories that had publications involving US-PRC collaborations, including a brief description of the technology area and a set of AI-extracted keywords that summarize the specific nature of the work being done. Appendix II gives a sample of the articles from each of the four categories.

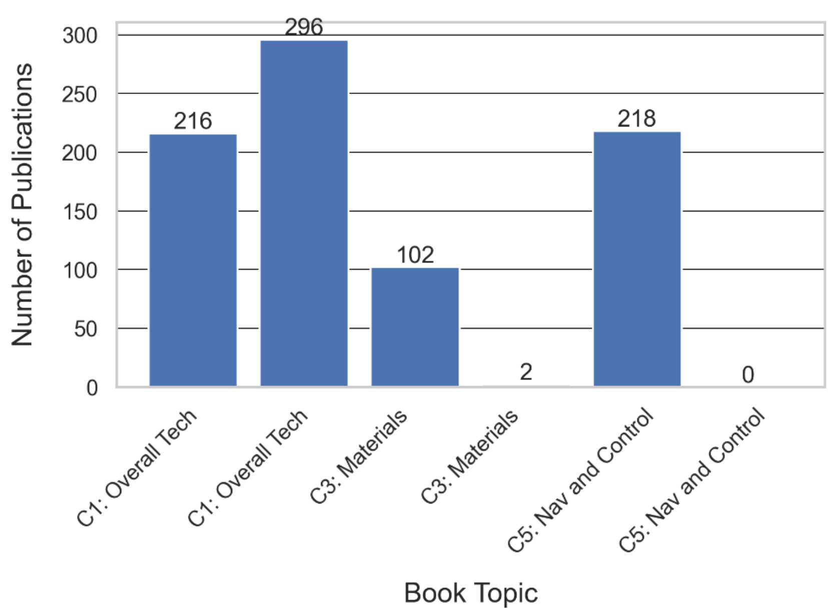

Figure 4. Number of collaborative publications from US and PRC researchers within the hypersonics categories mentioned above.

C1 - Overall Integrated Design Technology

This field integrates components of hypersonic vehicles such as propulsion systems, thermal protection, and aerodynamic structures, all of which must be tailored to endure the conditions of hypersonic flight. It emphasizes the use of advanced simulations and models for optimizing design and performance under high-temperature and high-pressure conditions. Additionally, this approach prioritizes the entire lifecycle of hypersonic systems. Rapid prototyping, innovative materials technology, and an iterative testing methodology are central to this approach.

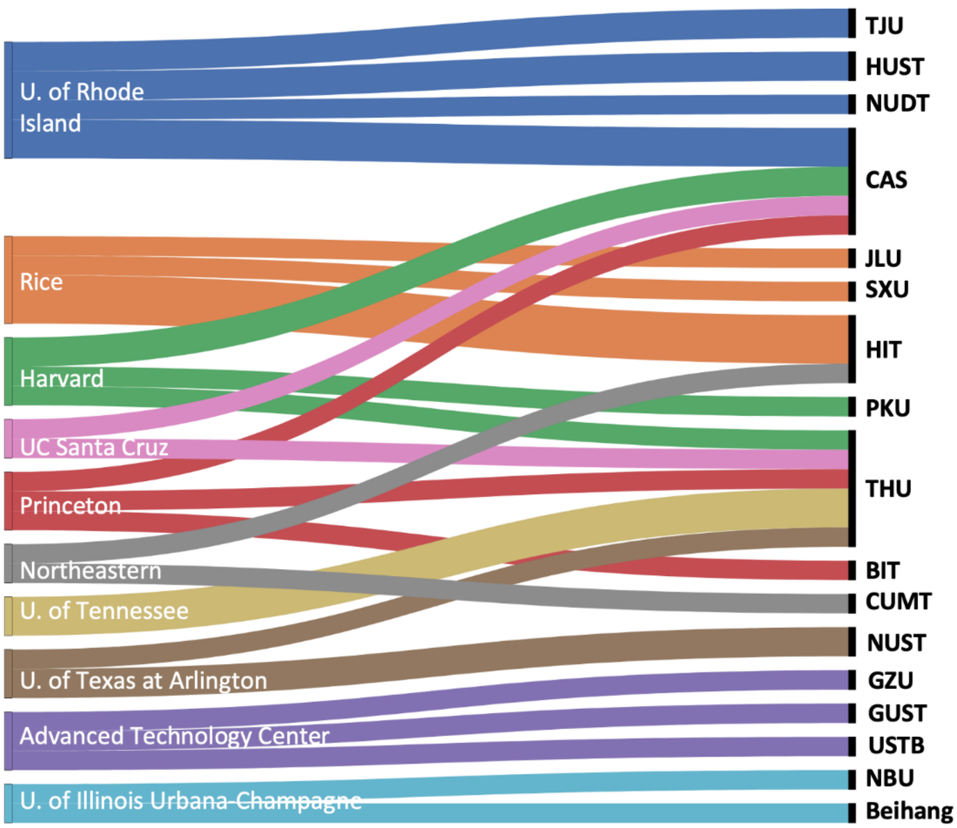

Figure 5. Top 10 US institutions by Overall Integrated Design Technology research and their PRC collaborators. For readability, US-PRC connections with only a single collaboration are dropped from this Sankey diagram.[iii]

Top five key topics in US-PRC collaboration in this category:

- **Computational Fluid Dynamics (CFD):** Essential for integrated design, as it provides comprehensive simulations of fluid flow, crucial for understanding and optimizing the aerodynamics of hypersonic vehicles.
- **Adaptive Dynamic Programming:** This method is important to the integrated design of optimizing control systems, allowing for effective management of the complex dynamics and control requirements of hypersonic flight.

[iii] See Appendix III for a list of PRC institution acronyms and abbreviations.

- **Closed-Loop Systems:** Integral for maintaining stability and control in an integrated design framework, especially at hypersonic speeds where feedback systems are crucial for real-time adjustments.
- **Direct Numerical Simulation:** Offers detailed insights for an integrated design, especially for understanding complex fluid dynamics and thermal effects at hypersonic speeds.
- **Supersonic Flows:** Understanding supersonic flow is foundational for integrated design technology in hypersonics, as it forms the basis for advancing into higher-speed regimes and affects various aspects of vehicle design, from aerodynamics to material selection.

C2 – Propulsion Technology

Hypersonic propulsion refers to the technology used to propel vehicles at hypersonic speeds. This area of aerospace engineering involves the development of jet engines capable of operating efficiently and stably at these extreme speeds, where traditional jet engine designs encounter significant challenges due to intense aerodynamic heating, air friction, and changes in air density. Technologies in hypersonic propulsion include scramjet (supersonic combustion ramjet) engines, which use the high vehicle speed to forcibly compress incoming air before combustion, and hybrid systems that combine features of rockets and traditional jet engines. Research in this field often focuses on improving fuel efficiency, reducing engine weight, and enhancing the ability to withstand high temperatures and pressures.

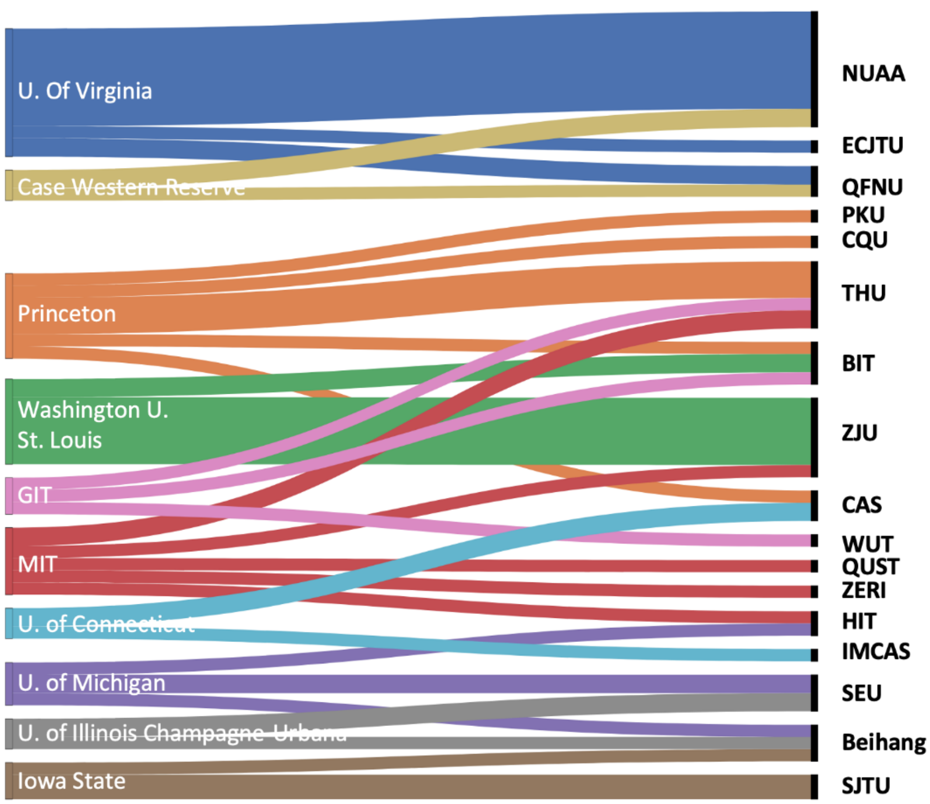

Figure 6. Top 10 US institutions by Propulsion Technology research and their PRC collaborators. For readability, US-PRC connections with only a single collaboration are dropped from this Sankey diagram.

Top five key topics in US-PRC collaboration in this category:

- **Scramjet Combustors:** Scramjets utilize high vehicle speeds to compress air before combustion, enabling efficient operation at hypersonic speeds.
- **Mach 6 Wind Tunnels:** Critical for testing propulsion systems at hypersonic speeds, these wind tunnels allow for the simulation and study of the effects of air flow and other factors on propulsion technology at speeds around Mach 6.
- **Closed-Loop Stability:** In the context of propulsion, this refers to the ability to maintain stable operation of propulsion systems under varying conditions. Stability is particularly challenging and crucial at hypersonic speeds.
- **Flow Heat Transfer:** Flow heat transfer involves the study of how heat is transferred within the air flow around a vehicle. This is critical for designing propulsion systems that can withstand the extreme temperatures of hypersonic flight.
- **Binary Gas Mixtures:** This relates to the behavior of gas mixtures in propulsion systems, crucial in the design and optimization of hypersonic engines, where different gas dynamics come into play compared to lower-speed flight regimes.

C3 - Materials / Processing / Manufacturing Technology

Materials / Processing / Manufacturing Technology refers to the development and innovation of materials, processing methods, and manufacturing technologies specifically engineered to meet the extreme demands of hypersonic environments. This includes creating materials that can withstand the intense thermal stress, aerodynamic heating, and high-speed friction characteristic of hypersonic flight. Advanced composite materials, ceramics, and metal alloys are often explored for their heat-resistant properties and structural integrity at high velocities. Additionally, processing techniques such as additive manufacturing, precision machining, and advanced coating methods are crucial for producing components with the necessary tolerance and durability.

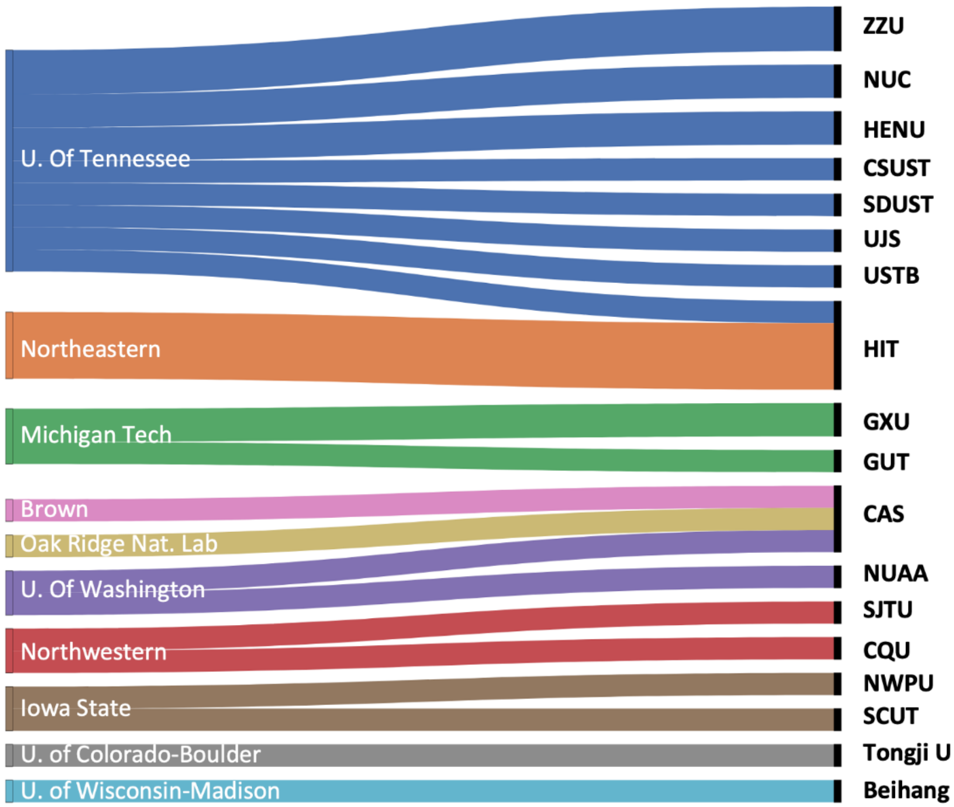

Figure 7. Top 10 US institutions involved in collaborations with PRC institutions in the Materials / Processing / Manufacturing Technology category of research. For readability, US-PRC connections with only a single collaboration are dropped from this Sankey diagram.

Top five key topics in US-PRC collaboration in this category:

- **High-Entropy Alloys**: These alloys are notable for their strength at high temperatures and resistance to wear and oxidation, making them suitable for use in hypersonic applications where materials are subjected to extreme thermal and mechanical stresses.
- **Thermal Conductivity**: This research ensures materials efficiently manage the heat generated at hypersonic speeds, protecting the vehicle's structure and internal systems.
- **Carbon Fiber**: Known for its high strength-to-weight ratio and thermal properties, carbon fiber is often used in hypersonic applications to reduce weight while maintaining structural integrity under high stress and temperature conditions.
- **Spark Plasma Sintering**: This manufacturing process is used to create high-strength materials by applying electric current and pressure to powders. It is particularly relevant for producing components that can withstand the harsh conditions of hypersonic flight.
- **Ti-6Al-4V Alloys**: This titanium alloy is known for its high strength, light weight, and corrosion resistance, making it an excellent choice for components in hypersonic vehicles where strength and weight reduction are critical.

C5 - Flight Navigation, Guidance, and Control Technology

This subject encompasses the development and application of technologies and algorithms designed to improve the accuracy and reliability of navigation, the precision of guidance systems, and the efficacy of control mechanisms. It covers topics like GPS technology, autopilot systems, flight management systems, inertial navigation, and advanced control algorithms.

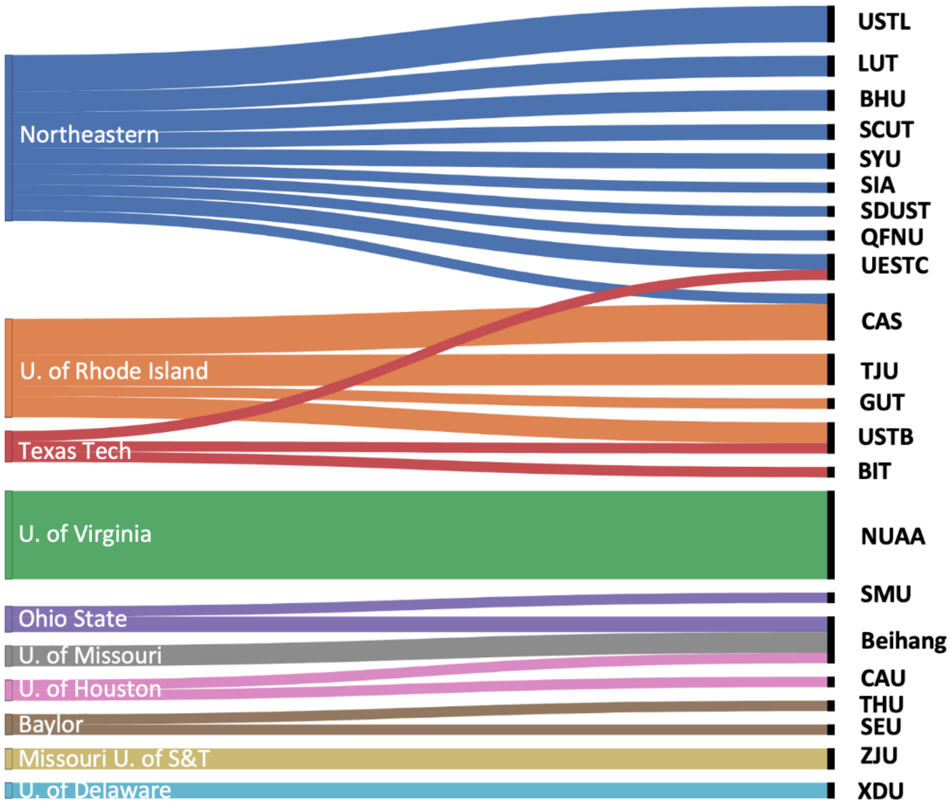

Figure 8. Top 10 US institutions by Flight Navigation, Guidance, and Control Technology research and their PRC collaborators. For readability, US-PRC connections with only a single collaboration are dropped from this Sankey diagram.

Top five key topics in US-PRC collaboration in this category:

- **Active Disturbance Rejection Control**: Critical for managing the disturbances and instabilities of hypersonic flight, enabling more stable and controlled navigation.
- **Controller Design**: Essential for designing control systems that can handle the unique challenges of hypersonic speeds, such as rapid changes in airflow and high thermal stresses.
- **Lyapunov Stability Theory**: A mathematical approach to ensuring the stability of control systems, particularly important in the highly dynamic environment of hypersonic flight.
- **Actuator Faults**: Actuators are critical components in controlling hypersonic vehicle flight. Identifying and managing faults is crucial for maintaining control and stability.
- **Nonlinear Systems**: Hypersonic vehicles operate in regimes where nonlinearities in aerodynamics and control dynamics are significant. Understanding and managing these nonlinear systems is key to effective navigation and control at hypersonic speeds.

US AND PRC COLLABORATING INSTITUTIONS

The following table presents the US institutions with the highest number of joint research works with PRC military-affiliated institutions. We also provide a Sankey diagram of the breakdown of collaborations with military-affiliated institutions.

Table 3. Top US institutions by hypersonics research collaboration with PRC military-affiliated institutions.

Rank	Institution	Total Military-Affiliated Collaborations	PRC Military and Defense Company Collaborations	Seven-Sons Collaborations	Other Collaborative Publications
1	Northeastern University	13	1	12	69
2	University of Illinois	10	3	7	22
3	University of Tennessee	9	1	8	15
4	Iowa State University	8	0	8	12
5	University of Michigan–Ann Arbor	7	3	4	9
6	University of California, Irvine	7	1	6	10
7	University of Rhode Island	5	3	2	26
8	Purdue University	5	0	5	12
9	University of Missouri	5	0	5	13
10	Washington University in St. Louis	5	0	5	17
11	Georgia Institute of Technology	5	0	5	17
12	Princeton University	5	0	5	24
13	Clarkson University	5	0	5	5
14	Rice University	5	0	5	10
15	University of New Orleans	4	1	3	6
16	Ohio State University	4	0	4	11
17	University of Central Florida	4	0	4	6
18	University of Houston	4	0	4	11
19	University of Connecticut	3	1	2	9
20	Alabama A&M	3	1	2	2
21	Texas A&M University	3	0	3	9
22	North Carolina State University	3	0	3	5
23	University of Texas at Arlington	3	0	3	12
24	Massachusetts Institute of Technology	3	0	3	13
25	University of Kentucky	3	0	3	9
26	Wayne State University	3	0	3	3
27	Duke University	3	0	3	5

Next, we provide a table of the PRC military and military-affiliated institutions with collaborations with US institutions. The top of the list is dominated by Seven Sons research institutions, with PLA institutions and defense enterprises appearing less frequently.

Table 4. Top PRC military and military-affiliated organizations by number of collaborative publications.

Rank	Institution	Collaborating Researchers at Institution	Collaborating Institutions from US	Collaborative Publications	Organization Type
1	Beihang University	124	49	72	Seven Sons
2	Harbin Institute of Technology	112	37	48	Seven Sons
3	Northwestern Polytechnical University	58	24	34	Seven Sons
4	Beijing Institute of Technology	57	24	33	Seven Sons
5	Nanjing University of Science and Technology	17	12	14	Seven Sons
6	National University of Defense Technology	16	9	10	Military
7	China Aerodynamics Research and Development Center	17	7	7	Military
8	CASC Aerospace Research Institute of Materials and Processing Technology	7	4	3	Defense Enterprise
9	Space Engineering University	3	4	7	Military
10	Harbin Engineering University	11	3	3	Seven Sons
11	China Academy of Engineering Physics	1	3	1	Gov. Research Institute
12	CASC China Academy of Space Technology	1	1	1	Defense Enterprise
13	Aero Engine Corporation of China	1	1	1	Defense Enterprise
14	Aviation Industry Corporation of China	1	1	1	Defense Enterprise

The low number of collaborations with military institutions and defense enterprises leaves little overlap in the Sankey diagram. In the majority of cases presented above, institutions had only one military collaboration.

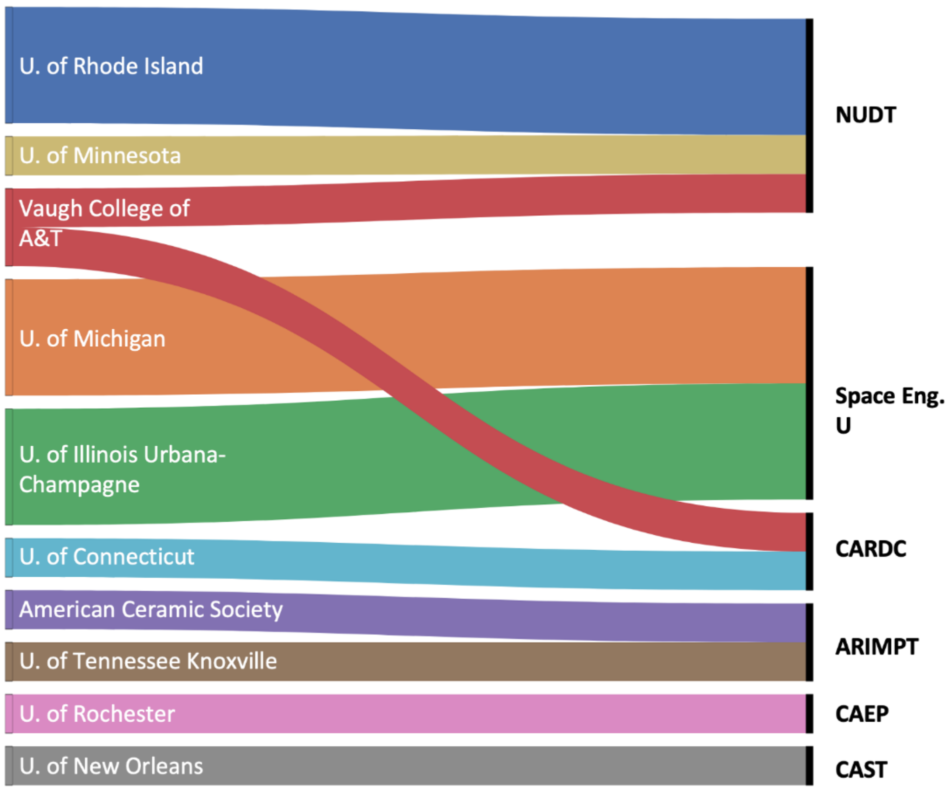

Figure 9. Sankey diagram displaying the breakdown of collaborations between the top 10 US institutions with the most PRC military-affiliated collaborations. The width of the lines between US institutions on the left and military institutions on the right captures the quantity of collaborations. The black vertical lines on the right indicate single PRC military entities.

US institutions participated in far more research collaborations with members of the Seven Sons, with numerous US institutions collaborating with multiple PRC institutions.

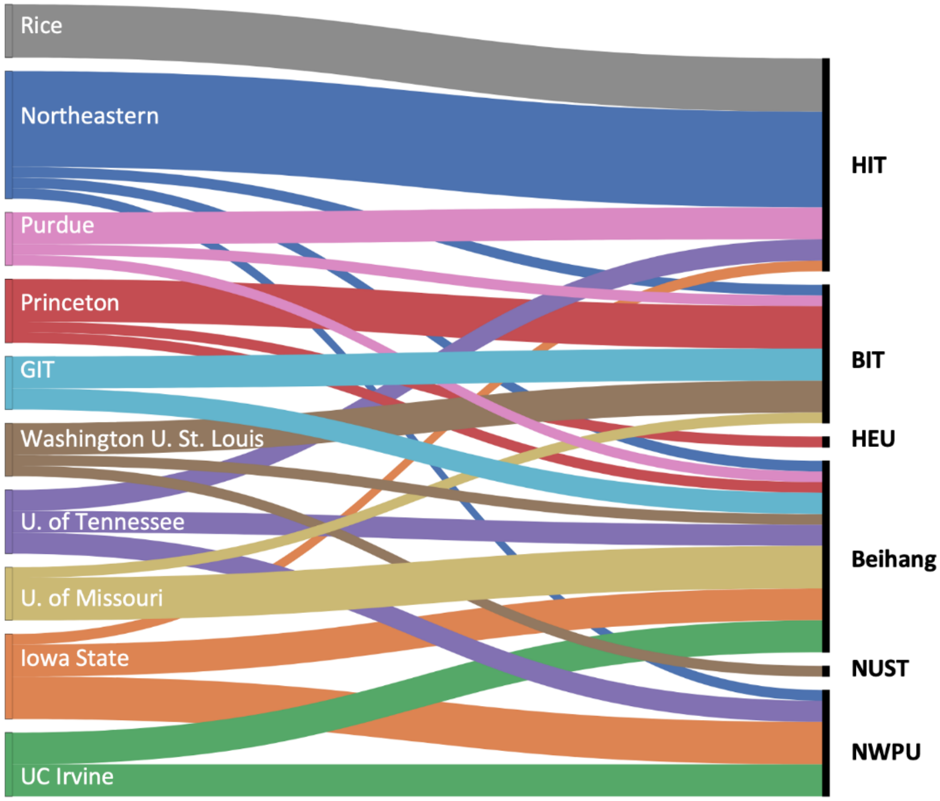

Figure 10. Sankey diagram displaying the breakdown of collaborations between the top 10 US institutions with the most Seven Sons collaborations. The width of the lines between US institutions on the left and PRC research institutions on the right captures the quantity of collaborations. The black vertical lines on the right indicate a single PRC research institution.

Finally, Figure 11 displays the changing rates of US collaboration with military institutions and Seven Sons institutions over time. While military collaborations do not show an evident trend across the period, the number of collaborations with Seven Sons increased in frequency beginning in 2017.

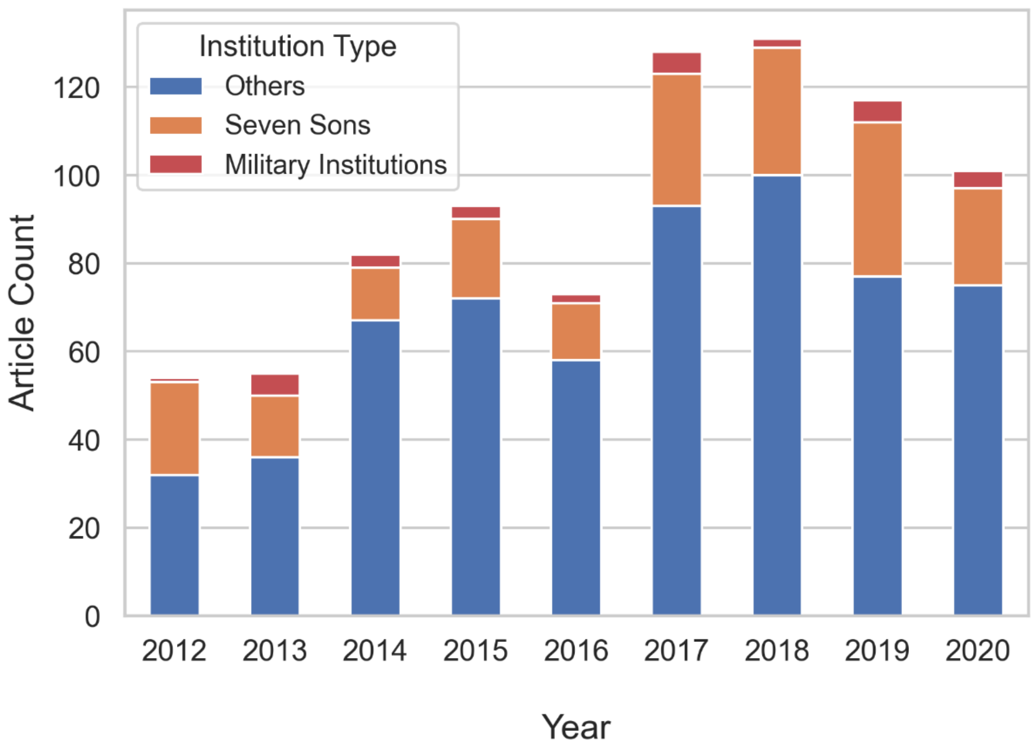

Figure 11. Number of US-PRC collaborations broken down by PRC institution type.

COMPARING RELATIVE RESEARCHER INFLUENCE: PRC VS. PARTNERS

In this analysis, we examine the average H-index of researchers in the field of hypersonics across various nations. The H-index is a commonly used metric for research impact that measures the total number of publications assigned to a researcher and the number of citations those publications receive. We applied H-indices to assess the relative contribution of international partners. Specifically, we computed the mean H-index across all researchers from the PRC and each of the other leading hypersonics researcher countries, then compared the related mean H-index for China with each of its collaborating nations. This provides a "power ratio" for understanding net flows of innovation potential. For example, if the average impact of PRC research partners is lower relative to another country, it may indicate that China is seeking to leverage external expertise.

In the field of hypersonics research, researchers from the PRC generally possess higher H-index scores than their counterparts in the US, according to our analysis of the hypersonics corpus. However, this trend does not persist in collaborative research between the US and PRC. In these collaborations, PRC researchers have an H-index of 33.05, exceeding the overall average H-index of 22 for all PRC researchers in the field of hypersonics. This suggests that PRC researchers engaging in collaboration with the US are more prominent in their field. Conversely, US researchers involved in collaborations with PRC counterparts have an H-index of 37.6, compared to an average H-index of 18 for all US researchers in hypersonics. This difference in H-index scores indicates a disparity in influence and prestige, with United States researchers appearing more dominant within these collaborative projects. In Figure 12 the comparative strength of US researchers in these collaborations is captured by the US's distance from the red parity line; anything above that line indicates that PRC researchers in the collaborations with the listed country have, on average, higher H-indices than their foreign counterparts.

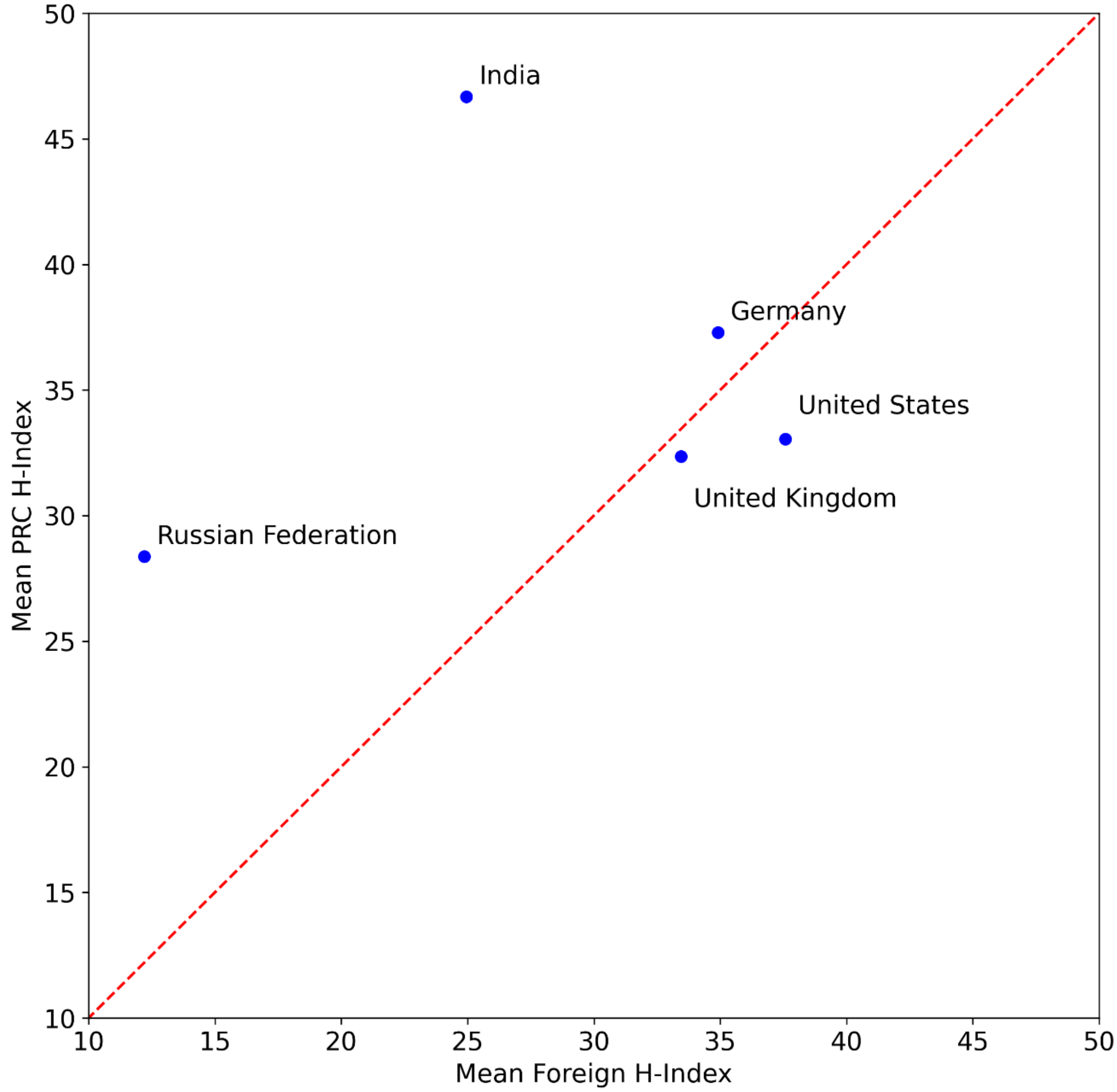

Figure 12. The mean H-indices for hypersonics researchers in countries who have collaborated with PRC researchers. The y-axis represents the average PRC researcher H-index in collaborations with the listed country, and the x-axis represents the average foreign researcher H-index from each country. The labeled points represent the average PRC researcher H-index and average foreign researcher index from their collaborations.

CONCLUSION

Overall, the level of collaboration between the US and the PRC on hypersonic technologies trails that of other top researching nations. Despite this, US institutions conducting research on hypersonic technologies have, on multiple occasions, pursued collaborations with PRC institutions with military affiliations, potentially raising security concerns. After reviewing US-PRC collaborations for the 2012 – 2020 time period, we identify three key takeaways:

1. US collaboration with the PRC on hypersonics often involves PRC military and military-affiliated institutions, which could present security risks.

   In recent years, US institutions have collaborated on hypersonics research with military institutions such as NUDT and CARDC, defense enterprises such as CASC, and civilian universities with close connections to the military, including but not limited to the Seven Sons. Any research conducted with these institutions is at high risk of being put to military use, where applicable. While some of these institutions are clearly military in nature, others may appear innocuous at first glance, often as a result of deliberate obfuscation. These findings illustrate the importance of adequate due diligence and screening mechanisms for US institutions wishing to collaborate on dual-use research with PRC entities.

2. US collaboration with PRC institutions on research into hypersonic technologies is significant in volume, but it is also a relatively low proportion of US hypersonics research overall.

   The US ranks second in the global hypersonics research arena, with contributions to 6,523 publications. It was found to have collaborated with PRC researchers on 834 publications, accounting for 12.8% of the US's total hypersonics research output. This proportion, while noteworthy, is relatively low compared to other top hypersonics research-producing nations. This contrasts with other leading nations in hypersonics research, such as the United Kingdom and Australia, where a larger percentage of hypersonics research involves collaboration with the PRC.

3. US-PRC collaboration in hypersonics research tends to focus on propulsion technology, with secondary foci on overall design technology, materials processing and manufacturing, and flight navigation, guidance, and control.

   US-PRC collaborative research on hypersonic technologies was limited in testing, verification, demonstration, and validation, potentially indicating that such collaborations focus on basic, rather than applied, hypersonics research.

4. US hypersonics researchers who collaborate with PRC researchers tend to have higher scores of research impact than their PRC partners, indicating that the PRC may benefit more from those collaborations.

   In our analysis using H-indices to gauge research impact within the hypersonics domain, overall we discovered that hypersonics researchers from the PRC, on average, have higher individual H-index scores than hypersonics researchers from the United States. However, this disparity reverses in US-PRC collaborative hypersonics research. In those collaborations, PRC researchers have an average H-index of 33.05, while US researchers have a higher average H-index of 37.6, well above the US national average of 18. This disparity indicates that US researchers collaborating with the PRC are more accomplished than their PRC counterparts, indicating that the PRC may disproportionately benefit from these collaborations.

Taken together, these findings indicate that while US collaborations with the PRC on hypersonics research are relatively limited, there are still a number of collaborative connections that could benefit the PRC military. While our analysis cannot speak directly to how risky such connections are, it nonetheless highlights areas of collaboration that may merit additional scrutiny.

APPENDIX I: BREAKDOWN OF INSTITUTION ARTICLE COUNTS BY TYPE

Here we provide a table listing the number of hypersonics research outputs from all US institutions with more than four collaborations on hypersonics topics with PRC organizations. These article counts are also broken down into the four hypersonics categories discussed above.

Institution	Collaborative Publications	C1: Overall Tech	C2: Propulsion	C3: Materials	C5: Nav and Control
Northeastern University	69	5	3	11	49
University of Virginia	41	1	19	1	20
University of Rhode Island	26	10	4	0	12
Princeton University	24	7	14	1	2
Texas Tech University	19	8	6	0	5
Georgia Institute of Technology	17	2	9	2	4
Washington University in St. Louis	17	1	15	0	1
University of Tennessee	15	4	1	9	1
Massachusetts Institute of Technology	13	3	7	2	1
University of Missouri	13	4	3	1	5
Purdue University	12	3	0	4	5
Iowa State University	12	2	6	2	2
Missouri University of Science and Technology	12	1	6	0	5
Brown University	12	1	2	3	6
University of Texas at Arlington	12	7	0	0	5
University of Michigan	11	3	4	2	2
University of Illinois at Urbana–Champaign	11	6	1	2	2
Virginia Tech	11	3	5	0	3
Harvard University	11	5	2	3	1
Ohio State University	11	4	0	2	5
University of Southern California	11	3	6	1	1
University of Houston	11	6	3	0	2
Northwestern University	11	2	1	7	1
University of California, Irvine	10	4	3	1	2
University of Pittsburgh	10	2	4	3	1
Rice University	10	10	0	0	0
University of Connecticut	9	4	5	0	0
University of Michigan–Ann Arbor	9	0	8	0	1
University of Kentucky	9	1	4	3	1
University of California, San Diego	9	2	2	0	5

California Institute of Technology	9	2	3	2	2
Texas A&M University	9	3	5	1	0
University of Illinois Urbana-Champaign	8	0	6	0	2
University of Washington	8	1	2	5	0
Louisiana State University	8	3	5	0	0
University of South Carolina	7	3	1	1	2
University of Delaware	7	2	1	1	3
Michigan State University	7	2	1	4	0
Old Dominion University	7	5	0	0	1
Los Alamos National Laboratory	7	3	3	1	0
University of Texas at Austin	7	1	1	3	2
University of Maryland, College Park	7	4	2	1	0
University of Minnesota	6	1	2	0	3
University of Wisconsin-Madison	6	1	1	4	0
University of California, Berkeley	6	3	0	2	1
Argonne National Laboratory	6	1	3	2	0
University of Nebraska–Lincoln	6	3	0	1	2
University of New Orleans	6	2	1	3	0
University of North Texas	6	4	2	0	0
Arizona State University	6	4	1	0	1
University of Central Florida	6	0	4	1	1
Carnegie Institution for Science	5	1	2	2	0
Stanford University	5	2	3	0	0
New York University	5	1	1	1	2
Pennsylvania State University	5	1	2	1	1
University of Colorado Boulder	5	2	1	2	0
Duke University	5	2	2	0	1
University of New Mexico	5	1	3	1	0
Baylor University	5	0	1	1	3
Lawrence Berkeley National Laboratory	5	2	3	0	0
North Carolina State University	5	0	0	1	4
Western Michigan University	5	1	4	0	0
Clarkson University	5	1	4	0	0
Cleveland State University	5	1	0	0	4
Cornell University	5	2	1	0	2

University of Florida	5	3	1	0	1
San Diego State University	5	1	4	0	0
University of California, Davis	5	1	1	2	1
National Taipei University of Technology	5	3	1	0	1
University of Miami	5	1	4	0	0
Electric Power Research Institute	5	1	0	0	4
Virginia Commonwealth University	5	0	5	0	0
Case Western Reserve University	5	0	3	0	2
Johns Hopkins University	5	1	4	0	0
University of Arizona	4	1	2	0	1
University of California, Merced	4	0	2	0	2
Rensselaer Polytechnic Institute	4	0	2	1	1
California State University, Long Beach	4	0	3	0	1
University of Maryland, Baltimore County	4	2	1	0	1
Oak Ridge National Laboratory	4	1	0	2	1
University of Iowa	4	2	1	1	0
University of Kansas	4	3	0	1	0
University of California, Los Angeles	4	2	1	1	0
National Research Council	4	1	2	1	0
Columbia University	4	4	0	0	0
State University of New York System	4	2	0	1	1
Florida Atlantic University	4	0	2	0	2
Goddard Space Flight Center	4	2	1	1	0
Purdue University West Lafayette	4	0	3	0	1
Advanced Technology Center	4	3	0	0	1
Michigan Technological University	4	1	0	3	0
Rutgers University	4	4	0	0	0
University of Texas at San Antonio	4	1	0	0	3
University of Pennsylvania	4	3	1	0	0
Indiana University – Purdue University Fort Wayne	4	1	1	0	1

Appendix II: Example article titles and explanations

Here we provide example titles from each of the four categories described above. These titles, along with explanations, provide the reader with a better grasp of the four categories.

C1: Overall Design Technology

1. "**Numerical Simulation of Energy Deposition in a Supersonic Flow Past a Hemisphere**"

   The study focuses on simulating the energy deposition in supersonic flows, a key factor in understanding the thermal and aerodynamic stresses that hypersonic vehicles endure. This knowledge is essential for designing vehicles that can withstand extreme conditions at hypersonic speeds.

2. "**New Scaling for Compressible Wall Turbulence**"

   This research provides insights into the behavior of turbulent flows over surfaces in compressible conditions, which is a common challenge in hypersonic travel. Understanding these turbulent dynamics is critical for the aerodynamic design of hypersonic vehicles.

3. "**Transient Thermal Behavior of a Microchannel Heat Sink with Multiple Impinging Jets**"

   The study addresses thermal management, a crucial aspect in hypersonic design due to the extreme heat generated at high speeds. Effective cooling techniques like microchannel heat sinks are essential for protecting hypersonic vehicles and their payloads.

4. "**Direct Numerical Simulation of Supersonic Turbulent Flows around a Tandem Expansion-Compression Corner**"

   This paper deals with the behavior of turbulent flows in supersonic conditions, a fundamental aspect of hypersonic flight dynamics. Understanding these flow dynamics is crucial for the aerodynamic design of hypersonic vehicles.

5. "**Numerical Study of Micro-Ramp Vortex Generators for Supersonic Ramp Flow Control at Mach 2.5**"

   This article explores the use of micro-ramp vortex generators for controlling supersonic airflow, a crucial aspect of hypersonic aerodynamics. Understanding and managing airflow at these high speeds is vital for the overall design and efficiency of hypersonic vehicles.

C2: Propulsion Technology

1. "**A Novel Method for Flame Stabilization in a Strut-Based Scramjet Combustor**"

   This paper introduces a new strut design for flame stabilization in scramjet combustors, crucial for the operation of hypersonic aircraft propulsion systems. The design is evaluated through simulations using multi-species Navier-Stokes equations and a hydrogen-air reaction model, demonstrating its effectiveness in creating a high-temperature and high-pressure region for efficient combustion.

2. "**Effect of Film Cooling Injection on the Aerodynamic Performances of Scramjet Isolators**"

   This study investigates the application of film cooling in scramjet isolators to address the issue of increased aerodynamic heating at higher flight Mach numbers. Numerical analysis evaluates various cooling flow conditions, showing that appropriate film cooling can reduce friction drag and enhance backpressure resistance, benefiting scramjet engine performance.

3. "**Inverse Identification of Boundary Conditions in a Scramjet Combustor with a Regenerative Cooling System**"

   The paper proposes a methodology for determining boundary conditions in scramjet combustors with regenerative cooling systems, essential for accurately modeling fuel burning, fluid flow, and heat transfer. The approach involves solving a transient inverse heat conduction problem, highlighting its potential for optimizing scramjet combustor design and cooling system efficiency.

4. "**Turbocharged Solid Propellant Ramjet for Tactical Missiles**"

   This paper discusses the development and performance analysis of a Turbocharged Solid Propellant Ramjet (TSPR), which combines an air turbo ramjet with a solid ramjet for tactical missiles. The study explores the effects of various design parameters and demonstrates that TSPR offers a wide operational envelope and high performance, suitable for tactical missile applications.

5. "**Rapid Supersonic Performance Prediction for 2D Ramjet Inlets**"

   A computational tool for rapidly estimating mass-averaged throat performance of 2D ramjet inlets is presented. This tool, based on the method of characteristics and unique corrections for viscous flow and shock interactions, offers accurate predictions with less computational effort compared to more complex simulations, highlighting its utility in ramjet inlet design and optimization.

C3 - Materials / Processing / Manufacturing Technology

1. "**Manipulating the Temperature Dependence of the Thermal Conductivity of Graphene Phononic Crystal**"

   This study is significant for hypersonic materials due to its focus on controlling thermal conductivity in graphene. Effective thermal management is crucial in hypersonic vehicles because of the intense heat generated at high speeds, and graphene's unique properties make it a promising candidate for such applications.

2. "**Compression and Impact Testing of Two-Layer Composite Pyramidal-Core Sandwich Panels**"

   The research on carbon-fiber composite sandwich panels with pyramidal truss cores is relevant to hypersonic materials. These materials need to withstand extreme mechanical stresses and impacts, and the study's focus on their strength and energy absorption under such conditions is directly applicable to hypersonic flight.

3. "**Compression Behavior and Energy Absorption of Carbon Fiber-Reinforced Composite Sandwich Panels Made of Three-Dimensional Honeycomb Grid Cores**"

   This paper's focus on the properties of carbon fiber reinforced composites, particularly regarding their energy absorption and behavior under compression, is relevant to hypersonics. Such materials are essential for hypersonic applications due to their potential to offer high strength while maintaining light weight.

4. "**Effect of Temperature on Strength and Elastic Modulus of High-Strength Steel**"

   Although not explicitly mentioned as hypersonic, this study is indirectly relevant. Understanding how high-strength materials like alloy steel behave at elevated temperatures is crucial for hypersonic applications, where materials are subjected to extreme thermal environments.

5. "**Microstructure Evolution in a Single-Crystal Nickel-Based Superalloy Joint by Linear Friction Welding**"

The focus on the microstructural changes in a nickel-based superalloy, commonly used in high-temperature aerospace applications, is indirectly relevant to hypersonic materials. The welding and joining techniques of such alloys are critical in fabricating components that can withstand the harsh conditions of hypersonic flight.

C5 - Flight Navigation, Guidance, and Control Technology

1. "**A Comparison of Classical Runge-Kutta and Henon Methods for Capturing Chaos and Chaotic Transients in an Aeroelastic System with Freeplay Nonlinearity**"

   This study focuses on numerical methods to analyze aeroelastic responses, which can be relevant for hypersonic vehicles due to their high-speed flight dynamics and the associated aeroelastic effects.

2. "**Field Theory and Weak Euler-Lagrange Equations for Classical Particle-Field Systems**"

   While this research is more fundamental in nature, the principles of field theory and Euler-Lagrange equations can be applicable in formulating the dynamics and control laws of hypersonic vehicles.

3. "**Robust High-Order Discontinuous Galerkin Schemes for Two-Dimensional Gaseous Detonations**"

   This research is relevant for understanding fluid dynamics at high speeds, particularly for propulsion systems like scramjets used in hypersonic vehicles.

4. "**An Improved Direct Adaptive Fuzzy Controller of an Uncertain PMSM for Web-Based E-Service Systems**"

   Adaptive control systems, such as the one studied here, are crucial for managing the highly dynamic and uncertain environment of hypersonic flight.

5. "**Adaptive Backstepping Stabilization of Nonlinear Uncertain Systems with Quantized Input Signals**"

   This study deals with adaptive control in the presence of nonlinearities and uncertainties, which are common challenges in the control of hypersonic vehicles.

APPENDIX III: PRC RESEARCH INSTITUTION ACRONYMS AND ABBREVIATIONS

Aerospace Research Institute of Materials and Processing Technology	ARIMPT
Chinese Academy of Engineering Physics	CAEP
China Aerodynamics Research and Development Center	CARDC
China Academy of Space Technology	CAST
Beijing Institute of Technology	BIT
Beihang University	Beihang
Bohai University	BHU
Changsha University of Science and Technology	CSUST
China Agricultural University	CAU
China University of Mining and Technology	CUMT
Chinese Academy of Sciences	CAS
Chongqing University	CQU
East China Jiaotong University	ECJTU
Guangdong University of Technology	GDUT
Guangxi University	GXU
Guangzhou University	GZU
Guilin University of Technology	GUT
Guangdong University of Science and Technology	GUST
Harbin Institute of Technology	HIT
Henan University	HENU
Harbin Engineering University	HEU
Huazhong University of Science and Technology	HUST
Institute of Mechanics, CAS	IMCAS
Jiangsu University	UJS
Jilin University	JLU
Liaoning University of Technology	LUT
Nanjing University of Aeronautics and Astronautics	NUAA
Nanjing University of Science and Technology	NUST
National University of Defense Technology	NUDT
Ningbo University	NBU
North University of China	NUC
Northwestern Polytechnical University	NWPU
Peking University	PKU
Qingdao University of Science and Technology	QUST
Qufu Normal University	QFNU

Shanxi University	SXU
Shanghai Jiao Tong University	SJTU
Shanghai Maritime University	SMU
Shandong University of Science and Technology	SDUST
Shenyang Institute of Automation	SIA
Shenyang University	SYU
South China University of Technology	SCUT
Southeast University	SEU
Space Engineering University	Space Eng. U.
Tianjin University	TJU
Tongji University	Tongji U.
Tsinghua University	THU
University of Electronic Science and Technology of China	UESTC
University of Science and Technology Beijing	USTB
University of Science and Technology Liaoning	USTL
Wuhan University of Technology	WUT
Xidian University	XDU
Zhejiang Energy Research Institute	ZERI
Zhejiang University	ZJU
Zhengzhou University	ZZU

Endnotes

[1] See, for example: Jiang Yonggang [姜勇刚] et al., "Development of Microwave Transparent Materials for Hypersonic Missile Radomes" [高超音速导弹天线罩透波材料研究进展], 硅酸盐通报,2007,26(3):500-505. http://www.alljournals.cn/view_abstract.aspx?pcid=5B3AB970F71A803DEACDC0559115BFCF0A068CD97DD29835&cid=3FCF8B1A330466D5&jid=CD0AE7464AC1DB25E3B503085456C422&aid=FF0B78F0290FA792&yid=A732AF04DDA03BB3.

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