Office of the Assistant Secretary of Defense: Research & Engineering (OASD(R&E))

TECHSIGHT SNAPSHOT REPORT

NOVEMBER 2017

Office of Net Technical Assessments (ONTA)

Hypersonics

[1]

Executive Summary

Hypersonics represents a set of technologies that enable vehicles to travel at speeds of Mach 5 or greater. This field enables missions such as "re-entry from orbit, hypersonic cruise, and hi-speed accelerator, which can be used as a reusable booster" (NASA, n.d.) *to provide economic access to space, point-to-point transportation, rapid-responsiveness, and increased survivability for strike capabilities. While hypersonic research has been occurring for decades, recent advances include novel lifting body vehicle design, heat-resistant materials, modeling and simulation and propulsion design. Hypersonics is primarily driven from military and space programs and focuses on: developing propulsion systems, understanding hypersonic aerothermodynamic properties, and developing structures such as thermal protection systems. Future technical progress is underpinned by the ability to collect data in a currently limited environment for improved understanding of thermochemical impacts, model development and validation. In general, the research field still remains relatively small, with a total of ~6,000 publications over the past 20 years, but has a high rate of research transition, as indicated by the high patent to publication ratio. Research trends over the past 20 years show two distinct growth regimes: a slow trend from 1997 to 2007 and a much more rapid trend from 2007 to 2016. This latter trend is almost entirely attributable to a rise in published research from China. While the U.S. and China are currently comparable in both publications and patents, China has only been a significant player within the last decade, and 70% of its research production growth has occurred within the last 4 years. Historically the U.S. has outperformed China in citation rates by a factor of 3. However, in the past five years China has surpassed the U.S. in both publication and patent counts and citations.*

[1] Graphic element is derived from (Schmisseur, 2015)

I. Introduction to Snapshot Reports

Snapshot reports provide a short overview of recent activity in emerging and potentially disruptive research areas using quantitative metrics generated from the statistical analysis of publication trends in the scientific and patent literature exclusively using ONTA's TechSight System. The aim of these reports is to generate questions for deeper investigations, and they are engineered to be produced monthly in a rapid, timely fashion with figures automatically generated by TechSight. Since these figures are inserted from a dynamic interface, readers are encouraged to access this data on TechSight for further exploration. TechSight is available to all DoD personnel and contractors (*see APPENDIX for access instructions*). Future snapshot reports will analyze top organizations and entities as system improvements to TechSight such as entity disambiguation is implemented.

II. What is Hypersonics?

- **Hypersonics describes a speed regime of Mach 5 and above obtained by integration of "propulsion, aerothermodynamics, and structures"** (Sziroczak & Smith, 2016). Essential to advancing the understanding of critical scientific phenomena and the integration of these systems is the collaborative use of flight research with **computational fluid dynamics (CFD)** and ground testing. "In the last decade the envisioned applications of hypersonic capabilities have focused primarily on the rapid response to time-critical targets and, to a lesser extent, on potential alternatives for economic access to space" and "the potential benefit of [hypersonics] can be realized in terms of rapid responsiveness, increased survivability in contested environments and efficient range coverage" (Schmisseur, 2015). **The current state-of-the-art in hypersonic propulsion is the scramjet** (supersonic combustion ramjet). These engines rely "on the combustion of fuel and an oxidizer to produce thrust" and have the added benefit of leveraging "the high kinetic energy of a hypersonic flow to compress the incoming air to operational conditions" (Wikipedia, n.d.). "Oxygen needed by the engine to combust is taken from the atmosphere passing through the vehicle, instead of from a tank onboard. The craft becomes smaller, lighter and faster" (NASA, n.d).
- **Aerothermodynamics accounts for aerodynamic lift, aerodynamic drag, aerodynamic heating, and stability and control in vehicle design**, which must meet an "extensive range of speeds… and fulfil several, often contradictory requirements" because of the variability of air flow in each speed regime. In terms of **lifting body vehicle** design, "a hypersonic vehicle can rely solely on thrust, provided the engines are powerful enough" or, as in the waverider configuration, use shockwaves to reduce drag and provide lift (Sziroczak & Smith, 2016). "Physical deformations, surface imperfections, or surface roughness on a hypersonic vehicle can promote early localized boundary-layer transition. If transition occurs asymmetrically, leading to drag asymmetry, it is essential that these effects be small enough to be compensated by the control system of the vehicle. If the effects are too great, the asymmetries can perturb the vehicle to a state that is uncontrollable, leading to vehicle loss" (Ryan, Lewis, & Yu, 2015).
- **Thermal protection systems (TPS) are integrated into hypersonic air vehicles' structure to compensate for surface heat loads experienced due to friction at high Mach speeds.** Convective heating dominates at low speed and altitude. As speed and altitude increase, other methods of heat transfer become dominant including "catalytic reactions on the vehicle surface, which can account for up to 40% of stagnation heat loads. In addition to this, depending on the atmosphere, radiation from the superheated plasma surround-

ing the aircraft could also transfer significant amount of heat into the vehicles." These forms of heating require novel materials and structural solutions to prevent vehicle degradation (Sziroczak & Smith, 2016).

While military and space hypersonic air vehicles have been successfully tested, with the longest test flight lasting a 140 seconds, commercial transport vehicles currently only exist in concept (Wikipedia, n.d.)**.** Examples of hypersonic flight programs "include the Hypersonic International Flight Research Experimentation (HIFiRE) program of the Australian Defense Science Technology Organization and the United States Air Force Research Laboratory, the Chinese DF-ZF Hypersonic Glide Vehicle (HGV), the Scramjet Powered Accelerator for Reusable Technology Advancement (SPARTAN) at the University of Queensland, the SHarp Edge Flight Experiment (SHEFEX) at the Deutsches Zentrum für Luft-und Raumfahrt (DLR), the HEXAFLY and HEXAFLYINT experimental flight test vehicles at the European Space Agency (ESA), and the United States Defense Advanced Research Projects Agency (DARPA) Falcon project" (Knight, et al., 2017). All of these prototypes are supported through national military or aeronautics programs.

To overcome current challenges, research focus is on engineering system integration and gaining fundamental knowledge of hypersonic thermophysical properties. Generally, there are two areas with distinct challenges (Schmisseur, 2015). The first is related to **aeropropulsion integration** including "understanding the behavior and impact of **laminar–turbulent transition** and **unsteady shock interactions**." The other area is related to **thermochemical non-equilibrium** resulting from high thermal loads significant enough to cause molecular vibrational excitation, dissociation and ionization. This causes an "interaction between the non-equilibrium gas environment and reactive material surfaces" leading to material degradation. Understanding of properties that drive this process is currently limited. To advance predictive capabilities integral to the test and evaluation process (e.g. **numerical simulations**), "accurate knowledge of the rates of fundamental thermochemical reactions that occur in the gas, at the gas–surface interface, and within the near-surface region of the material" must be established (Schmisseur, 2015). Research addressing these two challenge areas include:

- Airflow control by **plasma actuators** (Erfani, Zare-Behtash, Hale, & Kontis, 2015)
- Propulsion advances in **plasma jet engines** (Wikipedia, n.d.), **endothermic cracking fuel systems** (United States Patent No. 9150300, 2015), "**pre-cooled turbojets**, **scramjets** and combined **cycle/hybrid systems**" (Sziroczak & Smith, 2016)
- Materials advances in TPSs including **woven TPS** via **advanced manufacturing** (Owen, Merkel, Sansoz, & Fletcher, 2015); (NASA, 2015) and **polymeric ablative materials** (Natali, Kenny, & Torre, 2016)
- Improved methods and parameter validation for **numerical simulations** (e.g. CFD DSMC) (Knight, et al., 2017)

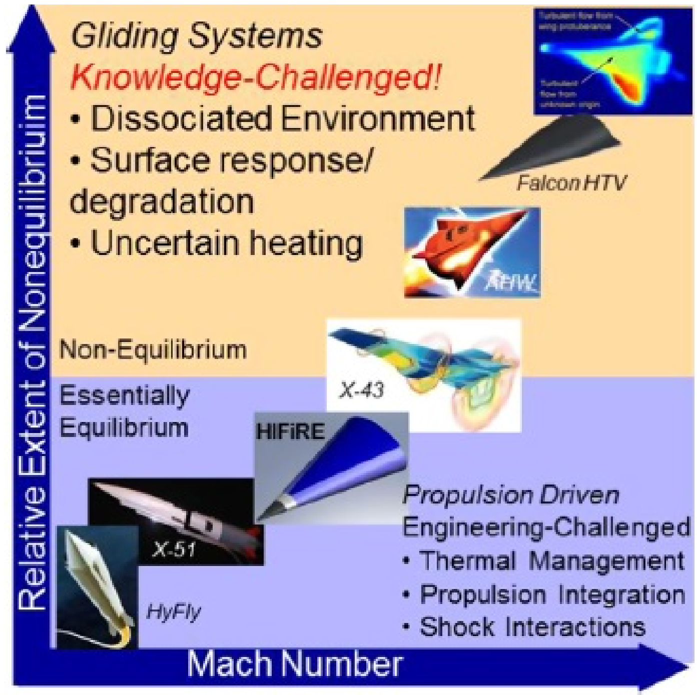

Figure 1: "Relative comparison of recent hypersonic technology development programs in a notional Mach number vs extent of non-equilibrium effects space." At equilibrium and lower Mach numbers, challenges are driven by system integration issues, while at non-equilibrium and high Mach numbers, progress is limited by a lack of fundamental knowledge in the hypersonic regime. Figure and description derived from **(Schmisseur, 2015).**

III. What is the Research Landscape?

Top Research Disciplines: Aerospace Engineering and Mechanics

- *Prevalence of engineering-related categories (**Aerospace, Mechanical and Electrical Engineering, Mechanics, Control Systems**) suggests that most of the innovations occur at the system level vice the device level.*
- *Fundamental work in this field is also strongly represented in:*
  - ***Thermodynamics** (#4) which is supported by the appearance of **aerodynamic heating** as a keyword in Web of Science and **heat** as a term in Derwent Patent Index.*
  - ***Physics** (#5 & #8)*
  - ***Materials Science** (#10) which is also supported by the presence of the Patent Classification area **(l) refractories, ceramics, cement**.*

Top Research Topics: Fluid Dynamics Modeling, Propulsion Design and Control Systems

- *Fluid dynamics modeling, in particular **Computational Fluid Dynamics (CFD), Numerical Simulations,** and **Direct Simulation Monte Carlo (DSMC)** are highly ranked terms, indicating novel fluid flow regimes while maintaining hypersonic speeds. This is supported through the high frequency of terms such as **Hypersonic flow, Aerodynamic Heating,** and **Shock Wave**.*
- *The high frequency of modeling techniques in publications indicates the majority of aircraft design and testing is focused on computer-based methods.*
- *Propulsion is a key focus area:*

- *Supersonic combusting ramjet (scramjet)* is present in high frequency in part because of query seeding. However, scramjet engines are also the enabling technology for aircraft to reach hypersonic speeds
- *The patent classification **(q) reaction engines: external combustion; gas turbines; rockets)** appears at #3*
- *Propulsion through combustion is further suppoered by #10: **(q) combustion equipment/processes**.*

- *While **Automation & Control Systems** do not explicitly appear as keywords, it is a major research area for both publications and patents (**digital computer, engineering instrumentation, process and machine control**).*

Top Application Areas: Hypersonic Air Vehicles & Weapons

- *Hypersonic aircrafts:*
  - ***Aircraft** is listed as a top-ranked subject category*
  - ***Hypersonic vehicle** is a popular keyword that is becoming more popular in recent years.*
  - ***(q) aircraft, aviation, cosmonautics** is the #2 patent classification*
- *Hypersonic weapons could also be a potential application since **(q) weapons, ammunition, blasting** appear at #6 in patent classifications.*

Research fields are comprised of different thrust categories. Self-organization of articles often occurs around these thrust categories, key questions and drivers in the field. The semantic content of the technical language, namely the technical terms, is typically a good indicator for tracking this activity. Similarly, how this research populates curated hierarchical subject categories can indicate what disciplines influence and dominate the field as well as other fields where this research has been influential. To extract the research field of interest, the following Boolean query was used:

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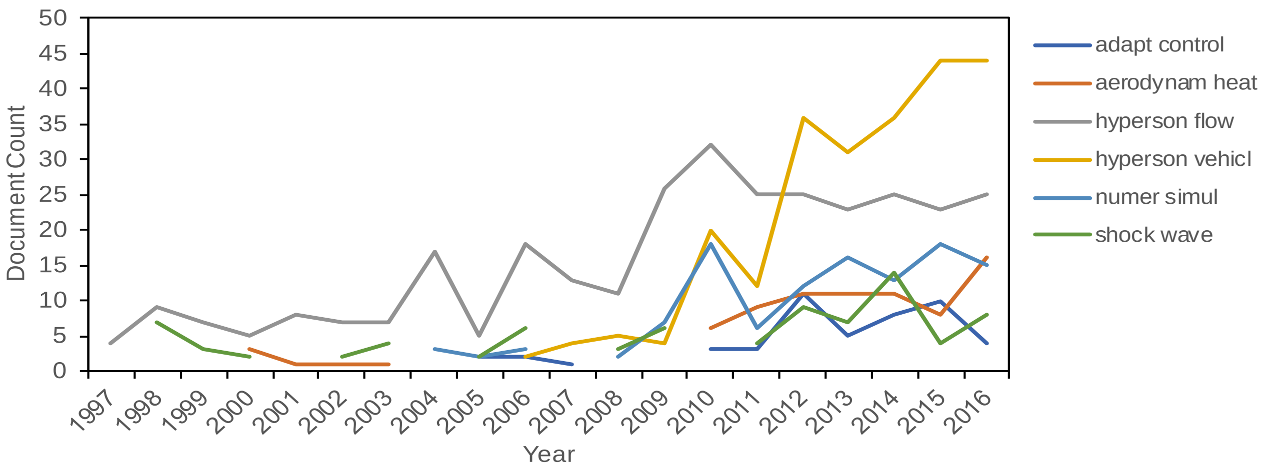
hypersonic OR scramjet OR "supersonic combustion ramjet" OR ("aerodynamic heating") OR (aerothermodynamics AND vehicle) OR ("cfd" AND "high-altitude" AND "high speed") OR (airbreathing AND engine AND mach) NOT "hypersonic band gap" NOT "hypersonic crystal" NOT "hypersonic phononic" NOT "hypersonic plasma" NOT brillouin NOT “hypersonic sound”



Top Publication Keywords

Rank	Keywords	Counts	Citations
1	hyperson flow	316	1,398
2	hyperson	270	951
3	hyperson vehicl	250	785
4	scramjet	212	1,197
5	numer simul	124	397
6	shock wave	99	490
7	superson combust	90	675
8	aerodynam heat	87	157
9	cfd	77	297
10	superson flow	75	409

Top Patent Terms

Rank	Term	Counts	Citations
1	hypersonic	484	1,121
2	method	385	1,093
3	aircraft	341	1,288
4	engine	306	1,100
5	system	266	1,203
6	air	216	607
7	device	206	520
8	heat	193	598
9	connect	184	401
10	vehicle	181	824

Top Publication Subjects

Rank	Subject	Counts	Citations
1	engineering, aerospace	2,496	15,467
2	mechanics	1,185	5,749
3	engineering, mechanical	974	4,096
4	thermodynamics	678	3,036
5	physics, fluids &	499	3,889
6	engineering, electrical & electronic	477	1,506
7	automation & control systems	440	1,834
8	physics, applied	440	1,693
9	engineering, multidisciplinary	312	1,634
10	materials science, multidisciplinary	271	1,693

Top Patent Classifications

Rank	Classification	Counts	Citations
1	(w) aviation, marine and radar systems	246	940
2	(q) aircraft; aviation; cosmonautics	230	1,131
3	(q) reaction engines: external combustion; gas	229	949
4	(t) digital computers	209	848
5	(s) engineering	160	305
6	(q) weapons, ammunition, blasting	77	272
7	(t) process and machine control	77	326
8	(s) scientific instrumentation	70	238
9	(l) refractories, ceramics, cement	65	322
10	(q) combustion equipment/processes	49	145

Figure 2 These figures are derived from a search query performed to define the hypersonics field. **(Top)** Shows popular keywords used in Web of Science over time. **(Middle, Left)** Shows the popular keywords used in Web of Science. **(Middle, Right)** Shows the popular terms used in the title section of patents in the Derwent Patent Index. **(Bottom, Left)** Shows the subject categories used in Web of Science. **(Bottom, Right)** Shows the patent classification keywords used in the Derwent Patent Index.

IV. How Mature is the Field?

ONTA estimates that Hypersonics are rapidly maturing with a moderate footprint in both research and innovation. It bases this judgment on the factors below.

Size: Medium

- *The field is moderately sized with ~6,000 publications and ~1,000 patents.*

Growth: Rapid

- *While hypersonics grew slightly from 1997 to 2007, the field has been experiencing exponential growth in the last 10 years.*
- *The amount of articles published in 2016 is nearly triple that published in 2017 (~200 vs. ~600).*
- *Patents also experienced high growth through 2013, doubling from 2007 to 2016.*

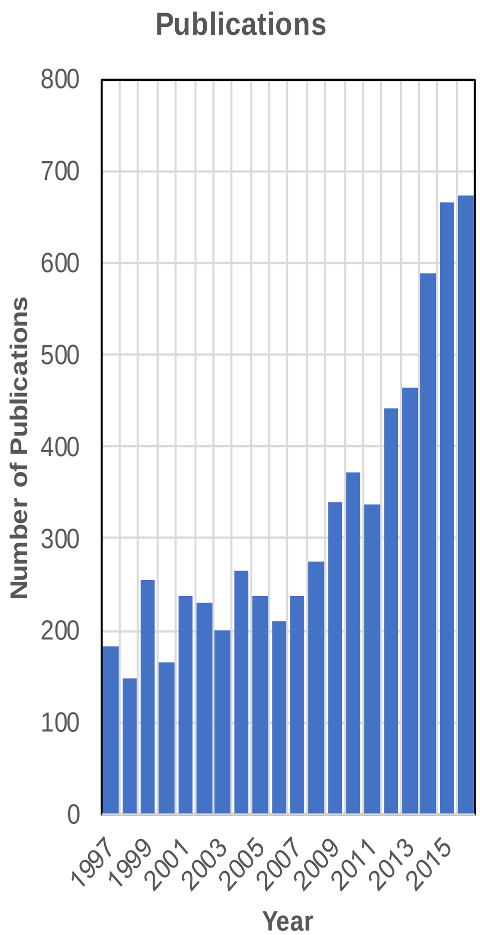
Influence: Moderate

- *Publications in this field average about 5 citations per paper.*
- *Patents average about 5 citations per filing.*

Maturity: Developing

- *The ratio of patents to publications is ~1:6, indicating a high level of transition from basic research to real-world applications.*
- *However, because the field is moderately sized and both publications and patents are experiencing strong growth, the field and associated technologies are still developing.*
- *No literature review articles appear in the top cited articles ranking, indicating the field requires additional maturation.*

	Publications	Patents
Document Counts	6,530	1,403
Citations	39,313	5,280
Authors/Inventors	10,516	2,540



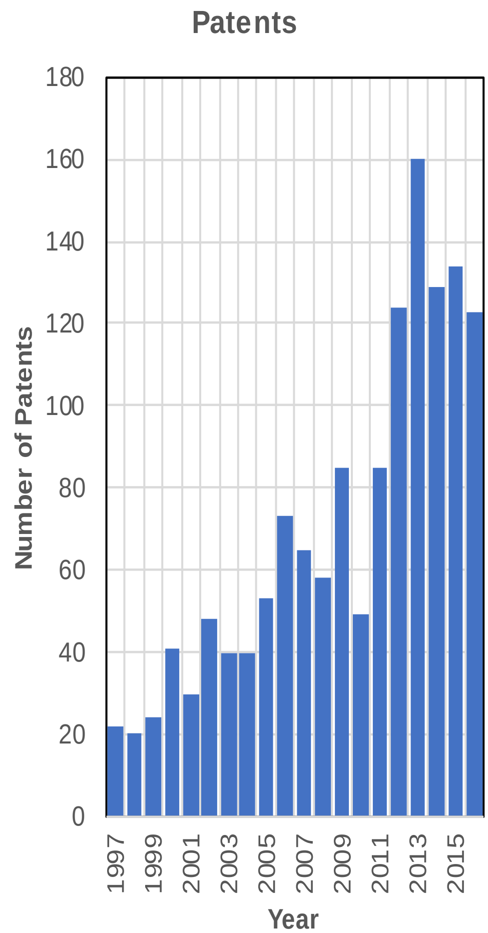


Figure 3 (Top, Left) Shows the *document counts, author counts and citation counts* for Hypersonics in the Web of Science. These fields correlate to *accumulated knowledge, workforce size and influence/quality*, respectively. **(Top Right)** Shows the *patent counts and citation counts* for the field of Hypersonics in the Derwent Patent Index. **(Bottom Left)** Shows the number of articles and conference proceedings mentioning Hypersonics in the title or abstract per year of publication. **(Bottom Right)** Shows the number of patents mentioning Hypersonics in the title or abstract per year of publication. The current year has been omitted since not all the publications for this year have been indexed.

V. What are the Leading Countries?

Top Researcher: China & U.S.

- ***China*** *is the top producer of academic research, with the US lagging by just less than 5% of its competitor.*
- *While China and the US have near equal publications,* ***China*** *has produced almost all of its publications in the last 10 years and nearly 70% within the last 4 years.*
- *The* ***U.S.*** *has the most research citations, with just under triple its closest competitor, China.*
- *Recent spike in total growth in the field (last 10 years) is attributable to* ***China*** *which accounts for about half of the articles produced annually in recent years (last 3 years).*

Top Innovator: China & U.S.

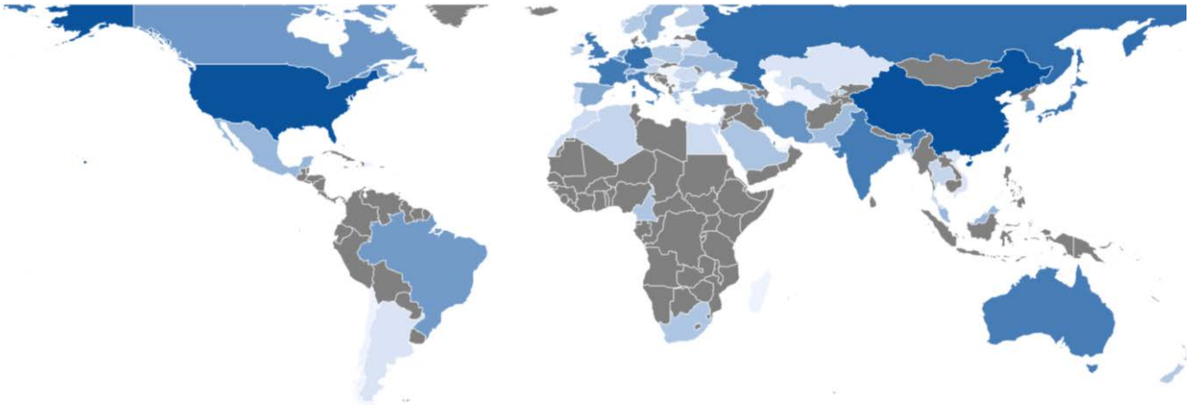
- ***China*** *produces the most patents of any country, with the U.S. awarded 20% less patents than China.*
- *The* ***U.S.*** *has the most number of patent citations, tripling its closest competitor, China.*

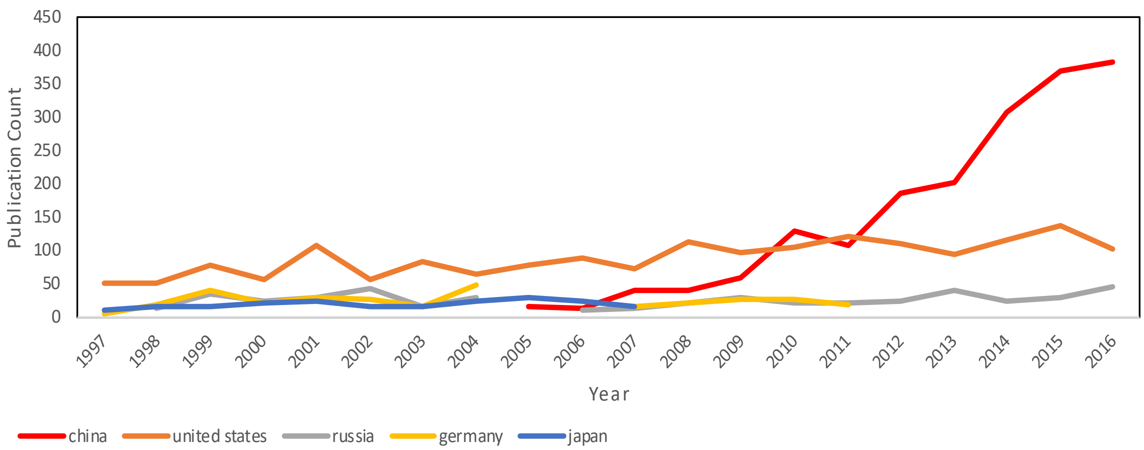
Top Market for Innovation: China & U.S.

- ***China*** *files 15% more patents than the U.S. However, the most patents cited were filed with the* ***U.S.*** *Patent Office, outperforming its closest competitor, China, by a factor of 2.*
- *The high ratio of patents to publications indicates a high level of transition from basic research to real-world applications. However this is considered to be an artifact of the nature of funded work rather than field maturity.*

China currently has a slight lead over the U.S. in the total volume of research produced, but China's high growth rate in this area could significantly increase their lead in the near future. In addition, it appears China's entry into the field has vastly changed the research landscape in the last 10 years. While China is prolific in both publication and patent spaces, they are not as highly cited as those from the U.S, indicating lower impact research and innovation. The U.S. remains highly competitive, but does not lead in any particular area, securing 2nd place across the board. Other strong countries include Russia (#3 in articles, #3 in patents) and Japan (#5 in articles, #4 in patents).

The country affiliation of articles and patents are inferred through the mailing address. These broadly indicate a country's contribution and expertise. Additionally, we can also analyze the patent-granting authority, which is often associated with a country and indicates where an innovation area has the most protection and coverage.





Top Countries by Publication

Rank	Country	Articles	Citations
1	china	1,880	6,997
2	united states	1,809	19,257
3	russia	500	2,074
4	germany	435	2,489
5	japan	365	2,060
6	france	286	2,334
7	united kingdom	272	2,422
8	india	263	886
9	italy	254	1,972
10	australia	245	1,527

Top Countries by Patents

Country	Patents	Citations
china	527	1,111
united states	437	3,451
russia	142	162
japan	67	490
south korea	51	35
germany	39	130
france	26	90
united kingdom	25	59
taiwan	18	22
canada	9	58

Top Patent-Granting Offices

Office	Patents	Citations
china	578	1,568
united states	504	3,983
russia	187	444
world intellectual property organization	180	1,679
european patent office	147	1,512
japan	134	976
south korea	80	329
germany	64	549
australia	43	792
canada	38	463

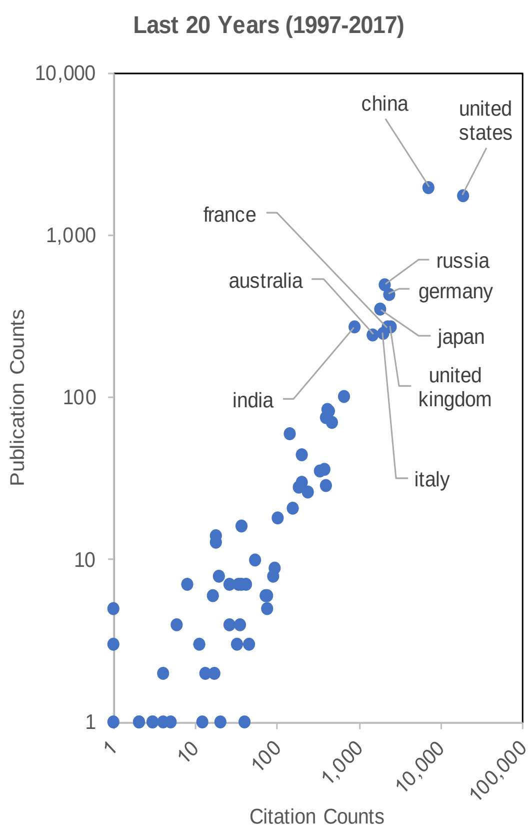
Figure 4 Shows the top countries in Hypersonics based on: **(Left)** the country affiliation of the authors in the Web of Science, **(Middle)** the country affiliation of the assignee from the Derwent Patent Index, **(Right)** the patent granting authority (typically a country) from the Derwent Patent Index.

VI. Featured Advanced Analytics

Every month, TechSight Snapshot Reports highlight a different advanced analytic method or visualization available to all users on the TechSight platform and illustrate how it can be useful for analysts in the course of their investigations.

This month's highlight will focus on a custom Kibana plug-in developed by NSWC-DD called "Scatter." In this example, we have chosen to plot the document counts versus the citation counts from Web of Science for the field of Hypersonics. This visualization is useful because it allows users to review both metrics at a glance.

- *The United States has an apparent advantage in the cumulative comparison in citation counts. However, when filtering by the last 5 years (2012-2017), we observe that China surpassed the U.S. in citations by more than double: (3588 citations for China vs. 1448 for U.S.)*
- *There is a cluster of "second tier" countries that appears distantly behind the U.S. and China consisting of the UK, Germany, Japan, France, Australia, Italy, India and Russia. The remaining countries produced less than ~100 articles and received less than ~1000 citations.*



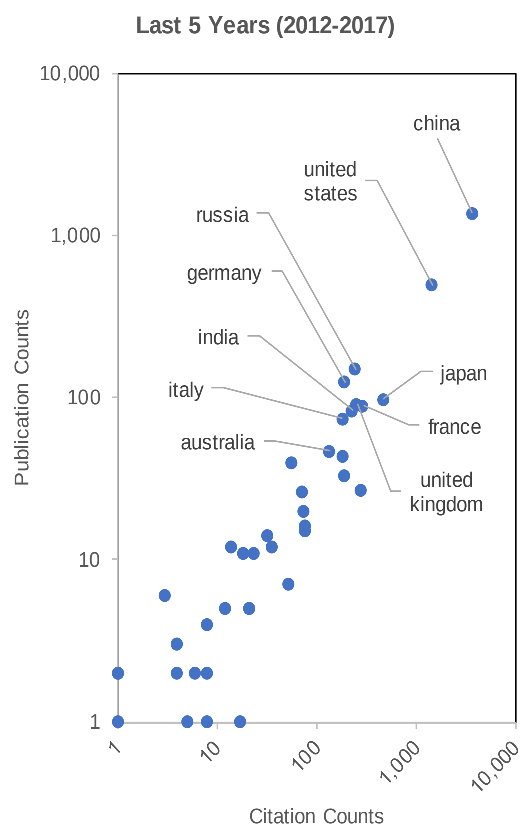


Figure 5 Shows the top countries in Hypersonics based on the country affiliation of the authors in the Web of Science, by plotting the publication counts versus the citation counts on a log-log scale. **(Left)** Cumulative counts over the last 20 years (1997-2017), **(Right)** Filtered for only the last 5 years (2012-2017).

VII. Questions for Further Study

Snapshot reports are meant to be quick scans of S&T and to ultimately stimulate interesting questions using only statistical data from the S&T literature. Answering these questions requires other methods, including interviewing stakeholders and experts.

International Competition

- *Is China's heavy interest in hypersonics driven by their military and/or space program expansion? What specific hypersonics research areas are of interest to China?*
- *The U.S. has a stable publishing rate over the reviewed period despite a large rise in China's publications. Are the major causes for the U.S. not expanding research in this area due to technology or policy or both?*
- *Which countries lead research in the three major areas that compose hypersonics (e.g. propulsion, aerothermodynamics and structures)?*

Technology Advancements

- *Current major challenges exist in hypersonics for sensing and control.* (Peck, 2016) *What tangential research fields will be impacted by this need, specifically considering the current rate of sensor development?*
- *Scramjets are considered the propulsion system of choice for atmospheric hypersonic flight, while rockets are required for space flight.* (Peck, 2016) *As we push towards hypersonic space travel, what hybrid propulsion and control systems will need to be developed?*
- *Numerical simulations in conjunction with ground and flight testing is required for test and evaluation of hypersonic vehicles* (Schmisseur, 2015)*. Will computational modeling of these systems ever be capable of eliminating the need for conventional flight testing? What are the key parameters required to make this possible?*

Impacts

- *What additional opportunities are there to leverage research and innovation conducted by the closest runner-ups, United Kingdom, Germany and Japan?*
- *What are defensive technologies that will require development with the use of hypersonic flight?*
- *How might hypersonic flight change:*
    - *Globalization and global economics with point-to-point transportation and delivery?*
    - *Speed of decision making?*
    - *Planetary colonization?*
    - *Space dominance?*

VIII. Further Reading (Most Cited Work)

Rank	Citations	Article Title	Source	Year
1	745	Refractory diborides of zirconium and hafnium	JOURNAL OF THE AMERICAN CERAMIC SOCIETY	2007
2	450	Oxidation-based materials selection for 2000 degrees C plus hypersonic aerosurfaces: Theoretical considerations and historical experience	JOURNAL OF MATERIALS SCIENCE	2004
3	357	Pluto: A numerical code for computational astrophysics	ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES	2007
4	317	Adaptive sliding mode control design for a hypersonic flight vehicle	JOURNAL OF GUIDANCE CONTROL AND DYNAMICS	2004
5	291	Verification and validation in computational fluid dynamics	PROGRESS IN AEROSPACE SCIENCES	2002
6	228	Nonlinear longitudinal dynamical model of an air-breathing hypersonic vehicle	JOURNAL OF SPACECRAFT AND ROCKETS	2007
7	224	Robust nonlinear control of a hypersonic aircraft	JOURNAL OF GUIDANCE CONTROL AND DYNAMICS	2000
8	216	Control-oriented modeling of an air-breathing hypersonic vehicle	JOURNAL OF GUIDANCE CONTROL AND DYNAMICS	2007
9	212	Advanced ceramic matrix composite materials for current and future propulsion technology applications	ACTA ASTRONAUTICA	2004
10	150	Velocity boundary condition at solid walls in rarefied gas calculations	PHYSICAL REVIEW E	2004

Rank	Citations	Patent Title	Assignee	Year
1	85	Acoustic generator of speaker apparatus, has resin layer that is filled within frame of frame element, so as to cover laminated piezoelectric element	KYOCERA CORP	2011
2	55	Payload carry and launch system for a hypersonic reusable spacecraft that incorporates three stages	SPACE ACCESS LLC	1998
3	48	Supersonic lean fuel combustion plasma arc turbine used with motor generator, high bypass fan, or propeller, includes compressor exit connected to tangential entry of cyclone combustor	FORET PLASMA LABS LLC	2008
4	47	Three-dimensional heat exchanger, useful in thermal control devices for microelectronic of photonic systems e.g. lasers, diodes or infrared detector devices, comprises open cell foam having hollow ligaments	UNIV VIRGINIA PATENT FOUND	2000
5	46	Method for enhancing atomization of fuel injected into internal combustion engine of vehicle, involves radiating ultrasonic energy beam to fuel spray injected in combustion chamber through injector	BONUTTI IP LLC	2002
6	46	Flow control apparatus for a nozzle exhaust plane consists of pulsed jets of fluid directed into the plume from diametrically opposite locations spaced circumferentially around the plume. The jets are pulsed out of phase with one another	BOEING CO	1999
7	43	Fuselage shaping and inclusion of spike on supersonic aircraft for controlling and reducing sonic boom, by creating linear lower profile	GULFSTREAM AEROSPACE CORP	2002
8	42	Vertically aligned nanotubes array composite composition for use in e.g. hypersonic aircraft, has nanotube array with carbon nanotubes, where thermal diffusivity of nanotubes increases as function of distance from substrate	UNIV TENNESSEE RES FOUND, UT-BATTELLE LLC	2005
9	41	Hybrid seal for gas turbine, has flexible seal that pressure biases against outer shroud and interface seal by purge gas relatively colder than hot gas in communication with inner shroud	GENERAL ELECTRIC CO	2004
10	41	Continuous rotary engine powered by shockwave induced combustion	UNIV SHERBROOKE	2002

Figure 5 The following list shows **(Top)** the most cited articles in the hypersonics field from the Web of Science and **(Bottom)** most cited patents from the Derwent Patent Index.

IX. About this Publication

Referenced work in this publication does not constitute endorsement by the United States Department of Defense (DoD) of the linked web sites, nor the information, products or services contained therein. In addition, the content featured does not necessarily reflect DoD's views or priorities. To provide feedback or ask questions, contact us at asdre-st-bulletin-reply@sainc.com. This publication is authored and distributed by:

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XI. APPENDIX

A. Scientometric Methodology

TechSight is an open-resource, cloud-based ecosystem developed and maintained by ONTA. As of this writing, it consists of an ElasticSearch database infrastructure with a Kibana front-end and some commercial and custom-written plugins. The databases used for this analysis were global scientific publications using the Web of Science and global patent applications using the Derwent Patent Index, both provided by Clarivate, Inc. All of the figures generated in this report come from visualizations generated by Techsight.

More dashboards for this specific report are available on the ONTA TechSight system and contain additional visualization elements not included in this report since their dynamic nature is not compatible with static reporting. These include network visualizations that allow for a finer-grained analysis and allow the user to delve into specific information on top performing universities, companies, authors and inventors. To access it, sign up for a free account at:

https://registration.761link.net/accountRequest-ZoneB/accountRequest/techsight.

You must be either a DoD employee, or a contractor supporting DoD, and register using your .mil e-mail address.

A search query is manually developed by an analyst to capture best capture the field of this report. Development of this query is directed at improving precision (by eliminating non-relevant documents from the results) and recall (by collecting as many relevant documents as possible) through the use of Boolean operators and unique terms. Since ElasticSearch is being used, differences in term suffixes are automatically accounted for and require no additional specification.

B. How large is a research field or area of innovation? (Frequency Analysis)

The size of a research field can be estimated in terms of total aggregated knowledge, for which the metric cumulative document counts (x) is a suitable proxy. Under the assumption that every article is unique and therefore constitutes a single unit of knowledge, the sum of all the articles in a research field approximates the total knowledge accumulated in the field. Another suitable metric is total community size, for which the number of unique authors is a suitable metric since these are the workers that generate knowledge. A larger workforce tends to correlate to a greater capacity to produce knowledge and therefore grows proportionately with aggregated knowledge. Some fields exhibit differing productivity (i.e. documents per unique worker) depending on ease of publishing, difficulty in carrying out experiments and field-dependent variables. Fields like particle physics and clinical medicine tend to have articles with a large number of authors due to the difficulty of the experiments. Fields such as nanoscience and nanotechnology tend to have higher productivity due to the ease of publishing new results. Fields like mathematics tend to have only a single author due to the nature of the work, and fields in computer science tend to have generally low publication rates relative to their research production. Similar factors affect patent indicators and are notably shaped by key differences between the two corpora, such as motivations for publishing versus patenting, the differences between peer review and patent examination, and the choice of technical terminology. Field sizes and influence are based on analyst observations and experience in a semi-quantitative rough order of magnitude sense: very small fields $0 \leq x < 100$ articles, small fields $100 \leq x < 1{,}000$ articles, medium fields $1{,}000 \leq x < 10{,}000$ articles, large fields $10{,}000 \leq x < 100{,}000$ articles, very large fields $x > 100{,}000$ articles. For influence: poorly cited <1 citation/article, medium citation rate ~1 citation/article, high citation rate >10 citations/article.

C. How influential is a research field? (Citation Analysis)

Scientific articles contain a list of references that cite previously published articles. The number of times an article has been referenced by other articles is called its citation count. Over time, an article's citation count tends to increase as subsequently published articles cite that article. Citation count tends to correlate with an article's influence, indicating the article's content has influenced other articles. Citation is also a suitable proxy for quality, as more articles describing the first reports of original work tend to have higher citations. An exception to this rule are review articles which tend to have very large citation counts and contain no original work but are cited typically to point new readers to a compact source for their further education in the field. Despite this exception, it is not inappropriate to include review articles in a citation analysis because the articles tend to be more widely read, and are a demand signal that a field has aggregated enough knowledge that a convenient repository for that knowledge is desirable. Since citation counts provide a usable proxy for "quality", this analysis provides a counterbalance to the "quantity" metric of document counts.

D. How fast is the research field or area of innovation growing? (Trend Analysis)

Scientific fields grow over time as researchers publish related articles, building on early seminal works. Emerging and potentially disruptive research areas typically display rapid, exponential-like growth early in their lifecycle.

E. What are the key areas of research, development and innovation? (Semantic Analysis)

The content of a research field can be understood from a hierarchical framework. Understanding the parentage of the field creates awareness of the nature and character of the field relative to the context of current scientific organization. As a proxy, we use the Web of Science's Subject Categories field, which are inspired by OECD's Field of Science (FOS) categories (OECD Cateogry Scheme, n.d.). While a field tends to localize around a specific section of this hierarchy, outliers sometimes exist arising from relevant articles in unrelated research fields indicating this field has influenced work or been adopted by these other fields. Similarly, patents in the Derwent Patent Index (DWPI Classification System, n.d.) are inspired by the WIPO classification and section scheme and lend themselves to similar visualization schemes. Research topics can often be conceptually subdivided into sub-topics. These sub-topics are often differentiated by specific keywords which are indicative of the content of these subtopics and represent segments of research focusing on research drivers such as key questions or specific innovations. Quantitatively tracking these keywords indicates the relative popularity of these sub-topics.

F. What are the leading countries? (Country Cross-Analysis)

Authors and inventors are affiliated with organizations whose addresses are in specific countries. By subdividing the data according to country, we can produce analyses at the national level that broadly indicate a country's participation level in a research field. Top 10 Countries by Publications are determined by the address of the affiliation of the author in the Web of Science. Note that an author can have multiple affiliations, thus belong to multiple countries. Top 10 Countries by Patent Application are determined by the address of the affiliation of the assignee in the Derwent Patent Index. An alternative approach is to use the inventor affiliation, which results in larger country counts since a patent can have multiple inventors, but only one assignee. Patent protection can be granted by applying to nation-specific authorities (i.e. U.S. Patent and Trademark Office), regional authorities (i.e. European Patent Office) or international authorities (World Intellectual Property Organization). It is often useful to compare which countries patents in a specific technology are granted and comparing that to where those companies are affiliated as it indicates whether one country is seeking IP protection in another country, or worldwide, for its products.