Technology & Innovation in China – A case Study of Single Crystal Superalloy Development for Aircraft Turbine Blades

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TECHNOLOGY & INNOVATION IN CHINA

A CASE STUDY OF SINGLE CRYSTAL SUPERALLOY DEVELOPMENT FOR AIRCRAFT TURBINE BLADES

International Strategic and Security Studies Programme
NATIONAL INSTITUTE OF ADVANCED STUDIES
Bangalore, India

Technology & Innovation in China

A Case Study of Single Crystal Superalloy Development for Aircraft Turbine Blades

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Contents

Overview and Major Findings

The rise of China as a global economic and military power has resulted in a lot of attention being paid to China's ability to innovate. Emerging Chinese capabilities in science and in technology are increasingly seen as a route for the transformation of China from a follower country to a global leader in innovation.

This study looks at one technology – single crystal technology for making aircraft turbine blades – that is critical for improving the performance of a modern jet engine that powers advanced aircraft. It tries to assess China's ability to use this knowledge in the production of aircraft engines that then fly on airplanes. In making this assessment we chose to compare the Chinese effort with what had happened in the US – the pioneer of this innovation.

From our analysis of the evolution of this technology in the US through patents and publications we surmise that outside experts tracking technology in the aircraft engine domain would have known about this technology in the 1985 to 1990 time frame. Chinese R&D engineers are known to be particularly good at tracking new developments in the western world. There is no reason to doubt that they had identified this technology as a key material for use in their aircraft engine programme fairly early in the evolution of this technology.

Our study also reveals that after a lot of problems with the reverse engineering of Soviet aircraft and a number of attempts to build up capabilities in both aircraft and aircraft engines via imports and technology transfer agreements, the Chinese had embarked on a major effort at revamping their R&D infrastructure to design, develop and produce aircraft engines by 1980. These activities culminated in the development of the WS10 engine by 1992. After a delay in flight testing lasting about a decade, the WS10 was finally qualified in 2005. However the WS10 engine that was qualified did not use single crystal technology. It used the earlier generation Directionally Solidified (DS) technology that had preceded it.

This non-use of single crystal technology appears particularly puzzling since our survey of the Chinese technical papers published in Chinese journals reveal that a number of Chinese R&D organisations, including several closely linked to aircraft development and production, had started work on this technology in the early 1980's. The papers suggest that these organisations had achieved considerable progress on all aspects of single crystal technology. An independent evaluation of Chinese capabilities by outside experts from the US seems to confirm that China could produce single crystal aircraft turbine blades during the timeframe of the development of the WS10 engine.

In contrast to what happened in China, both DS technology as well Single Crystal technology became operational in the US within six to seven years after invention. These technologies were developed by the US aircraft engine company Pratt & Whitney in their in-house Materials Research Laboratory. This development was a logical consequence of identifying certain bottlenecks that constrained the performance of the engine and then finding technical ways to overcome these constraints. Though both these path-breaking inventions gave Pratt & Whitney a major advantage for about a decade, our research reveals that by about 1985 most other aircraft engine manufacturers in the US, UK, France, Japan and Russia had caught up with the leader.

Figure A below provides an overview of the choices that China faced in trying to build a world class aircraft jet engine that used single crystal technology for the turbine blades of the engine. Even after more than twenty years of work, the Chinese do not have an indigenously produced engine that uses this technology. Their more recent advanced aircraft the J-10, J-11 and the J-20 all use imported Russian engines. If the Chinese had skipped the DS technology and gone directly to single crystal technology they might have been able to narrow the technology gap significantly. Such a riskier approach may be necessary for follower countries to catch up with the leaders. In spite of being competent in the technology the Chinese decision-making system was not able to act appropriately. This seems to suggest some structural weaknesses in the Chinese ecosystem for innovation at least in this area.

The study also examined the knowledge networks in China and the US by looking at collaborations between different entities in "single crystal" technology as seen through published papers in technical journals. The Chinese network is shown

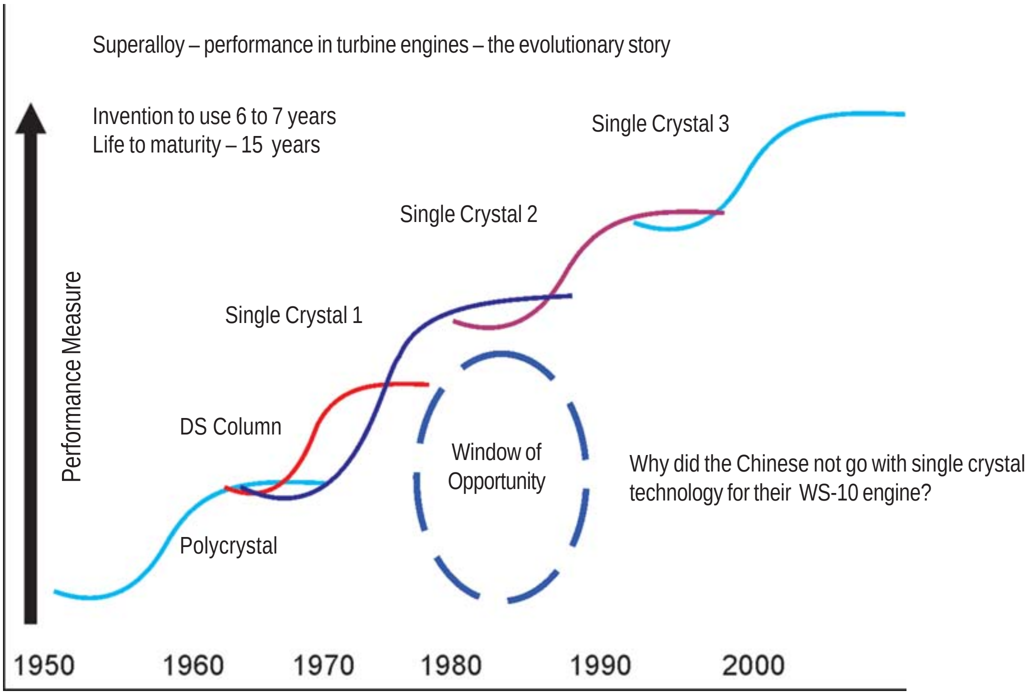

Figure A: Window of Opportunity for China

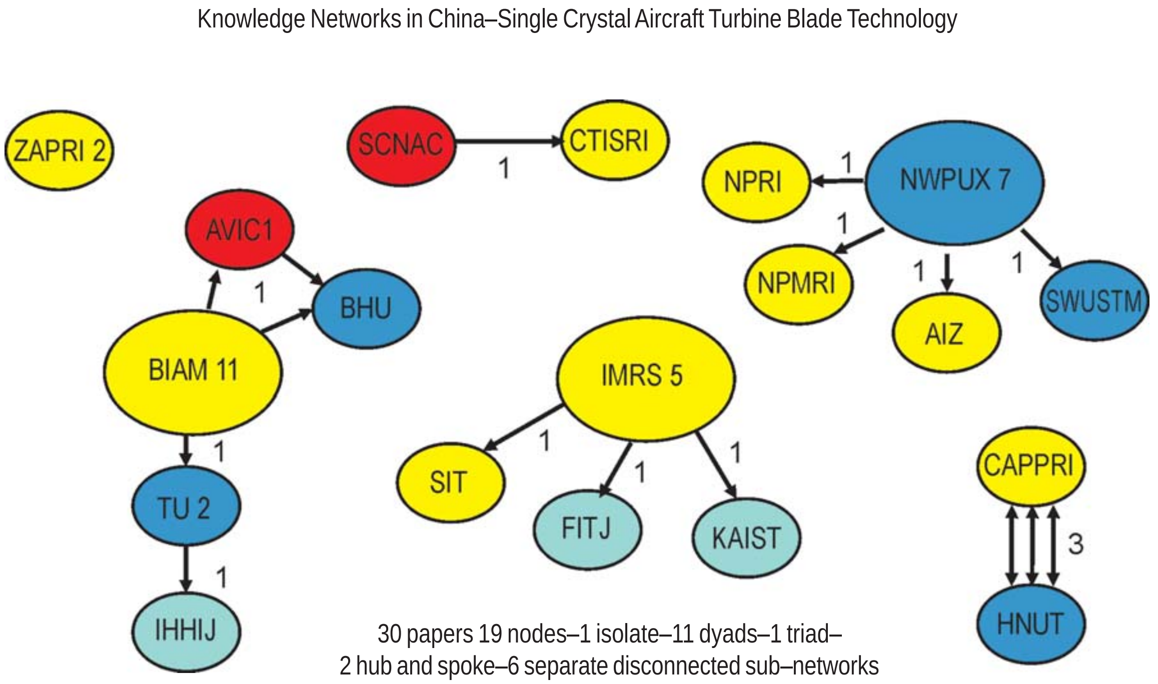

Figure B: Knowledge Networks in China – Single Crystal Technology

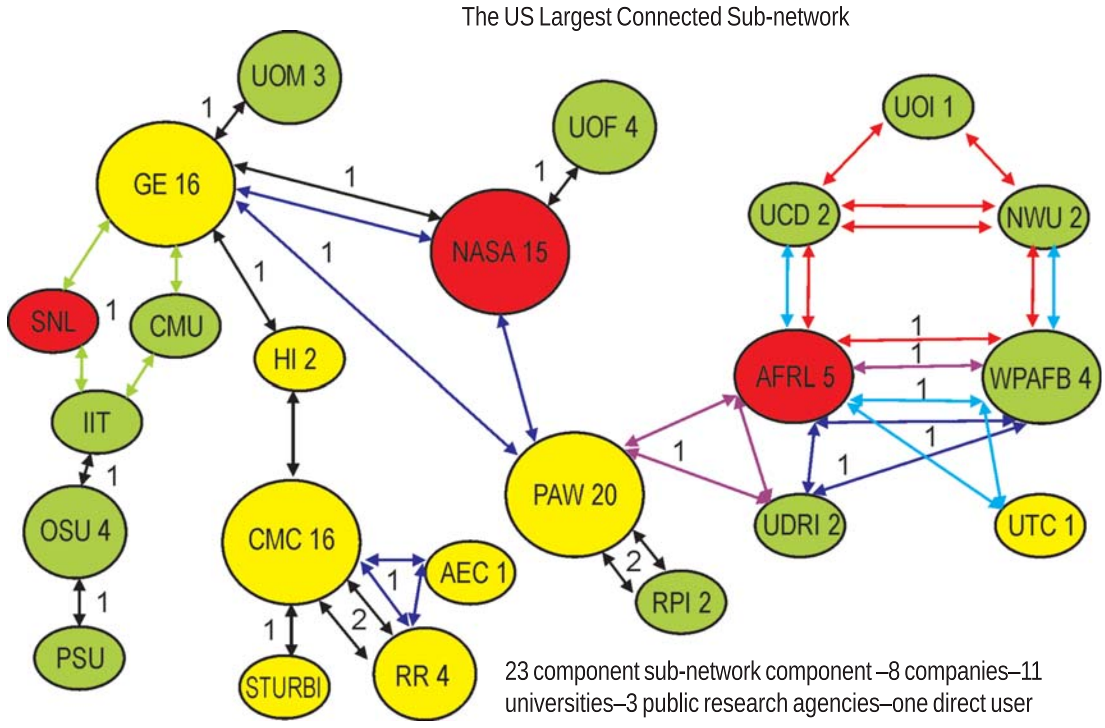

Figure C: Largest Component in the US Knowledge Network in Figure B whilst the largest connected component of the US network is shown in Figure C.

A closer look at the two networks reveals stark differences between the two countries that seem to be symptomatic of more deep-rooted fundamentally different approaches.

The US network as revealed through published papers is a 45 node network. The Chinese network is only a 19 node network. There is therefore a huge scale difference between these two networks. The number of papers published – 30 for China and 109 for the US – also reveals that the US enjoys a considerable scale advantage.

47% of all papers produced in China in this area are collaborative papers as compared to 22% for the US.

Companies and Universities are the main generators of papers in the US. This technology was pioneered by companies and not universities. All the major aircraft engine manufacturers in the US are major nodes in the network. Publicly supported agencies like the Air Force laboratories and NASA are also big players. Companies also dominate the patent scene in the US with patents exceeding papers by a fairly big margin. By contrast in China the major nodes are all publicly supported research institutions with universities having a somewhat smaller role. There are only two companies represented in the Chinese knowledge network related to single crystal development.

From Figure B we can also see that the Beijing Institute of Aeronautical Materials (BIAM), North Western Polytechnical University Xian (NWPUX) and the Institute of Metals Research Shenyang (IMRS) are the major nodes in the Chinese network. They are linked to other nodes in a hub and spoke configuration. They however function as separate components of the network and are not connected to each other.

From Figure C we see that all the major companies, Air Force Research Laboratories, NASA are dominant players in the US network. This 23 node connected component of the larger US network is significantly more powerful than the largest 5 node BIAM dominated component of the Chinese network.

Of the 19 nodes in the China network only one node (5.3 %) is not connected to at least one other entity. 18 out of the 45 nodes in the US network (33.3 %) are not connected. The percentage of two and more party collaborations within the Chinese network is 6.5%. This percentage is only 1.7% within the US network. The Chinese network is more collaborative, indicative of a top down approach. The US network is more individualistic that suggests a more company driven bottom-up approach to knowledge.

The density of the Chinese network is 0.09 which is much higher than the 0.05 density of the US network. This reinforces the point that the US network is more individualistic or company driven whereas the Chinese network is more collaborative and research institute driven.

Even though the US is individualistic in approach all nodes including the dominant ones are weakly connected to each other in a 23 node configuration. This would suggest that diffusion of knowledge and technology will happen fairly quickly. In contrast the Chinese network is clustered into dominant groups with no connection between them. Such dominant unconnected clusters suggest structural rigidities within the Chinese network. This could come in the way of new knowledge being easily accommodated within a complex project or undertaking.

Since there is a major time lag between the development of these technologies in the US and China, we also investigated the possibility that the US network might have been more like the current Chinese network earlier in its history. Our investigation of papers published between 1970 and 1990 in the US reveals that there are no connections at all between any of the major nodes in the network. This means that the US network was even more individualistic in the past before it has evolved into its current loosely interconnected structure.

These comparisons between the US and China suggest that the problems that follower countries face are quite different from the problems faced by leader countries. Leaders are always at the cutting edge of new knowledge. Even if they are a bit late in identifying and responding to a new development they have the inherent strength to play catch up. Though General Electric was behind in single crystal technology they were able to catch up and even surpass the pioneer Pratt & Whitney over a period of about ten years. Follower countries on the other hand have to resolve the dilemma between immediate needs and long term interests. Imports of technology and products create interest groups within the ecosystem that could make decision-making involving indigenous, emerging technologies more difficult. These factors compounded by the complex nature of the technology and its associated organizational arrangements create rigidities within the ecosystem of the follower country. This often precludes them from taking riskier decisions involving new technologies that are so necessary for them to catch up. This would suggest that whenever countries face constraints such as embargos and denial of technologies from the more advanced countries they may be able to take greater risks and advance more speedily along an emerging technology cycle. China's advances in the nuclear and missile areas seem to suggest that this is so. More recently their creative approach to dealing with the threat posed by US aircraft carriers by developing an Anti-Ship Ballistic Missile (ASBM) lends additional credence to this line of thought.

Figure D and Figure E capture the innovation ecosystems of the US and China as seen through our study. The US – as stated earlier – has an enormous advantage that it enjoys because of its scale. We can see clearly that in every part of the value chain - from idea generation to the procurement of the final product - there is competition in the US system. Our analyses of patents in the US reveal that a lot of the early risk reducing funding for companies came from NASA or from one of the research supporting arms of the various armed services. Since the US is already at the cutting edge, ideas compete for value at this stage. Independent multiple sources of funding are available for the pursuit of these ideas. If ideas are promising then companies motivated by profit try to sell it to different buyers. The US is fortunate to have the scale of being a global power. There are therefore multiple possible buyers for new advances that promise to push the envelope of performance of a product. This ensures a fairly robust selection mode for new ideas. Good ideas that come through this selection process see further development either in other national security establishments or move into the civilian domain as in the case of single crystal technology. Companies pursuing profit are the crucial nodes in this network.

The Chinese have tried to mimic the US on the supply side of technology. Over the years they have created multiple sources of funding for the pursuit of new ideas. They have also put in place a competitive selection process for the selection and pursuit of ideas. In our case study we can see that Chinese engineers had identified single crystal technology quite early in its life cycle and had developed the capability to make it. However on the demand side the Chinese system is quite different. The PLAAF is a complex entity that makes crucial decisions including the ones on imports and indigenous development. It has to deal with immediate threats as well as with the long-term creation of strategic capabilities. These trade-offs may also be subject to the play of various political and power equations within the system. Unlike the US there are no multiple independent users that could buy a product or support a riskier new technology. China has tried to create competition at the company level by splitting its integrated Aviation Industry of China (AVIC) into two entities AVIC 1 and AVIC 2 ostensibly to promote competition. However if we carefully examine this division we see that this restructuring did not really promote competition but only changes a single monopoly into two monopolies that operate in different market segments. More recently the Chinese have gone back once again into a single company mode. Political factors more than other efficiency or innovation consideration seem to dominate the decision making system. The long delay between the development of the WS10 engine and its flight testing also suggest differences in approach arising from the distribution of power within the ecosystem.

As China becomes richer and starts projecting its power on a larger scale it may be able to move towards a more competitive ecosystem that is closer to the US. However such a transformation may require a fundamental ideological shift in the role of the State and the power exercised by the PLAAF. Whether China can affect such a radical transformation of its political system is a moot point.In the interim however, China is still a considerable distance away from catching up and overtaking the US at least in this technology and product domain.

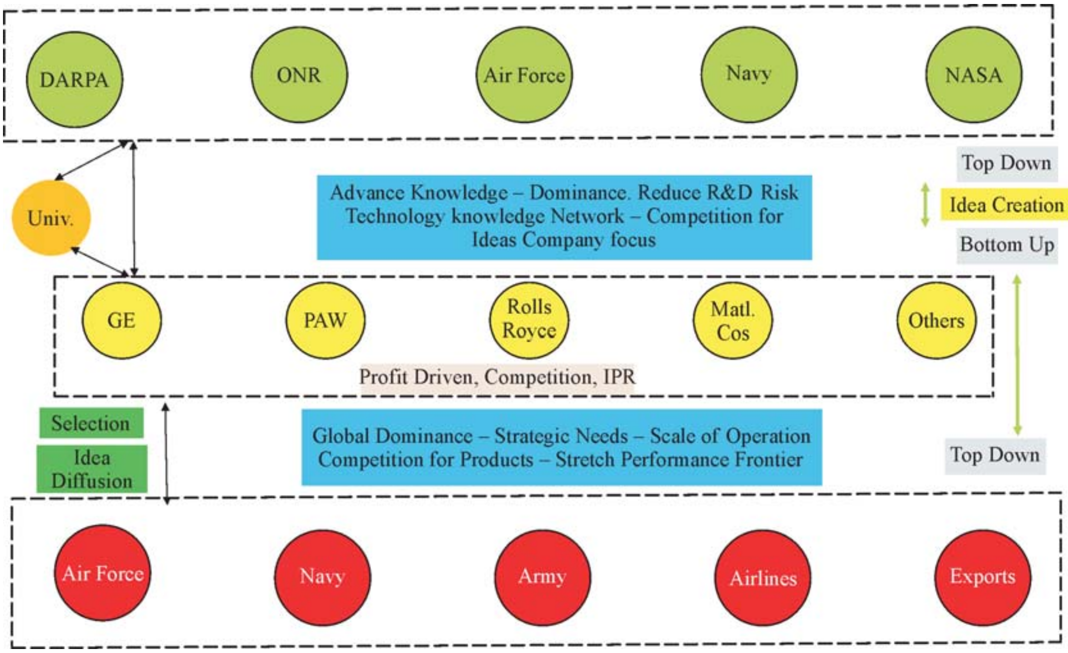

Figure D: The US Eco-System for Knowledge Generation & Use - Single Crystal Technology for Aircraft Turbine Blade

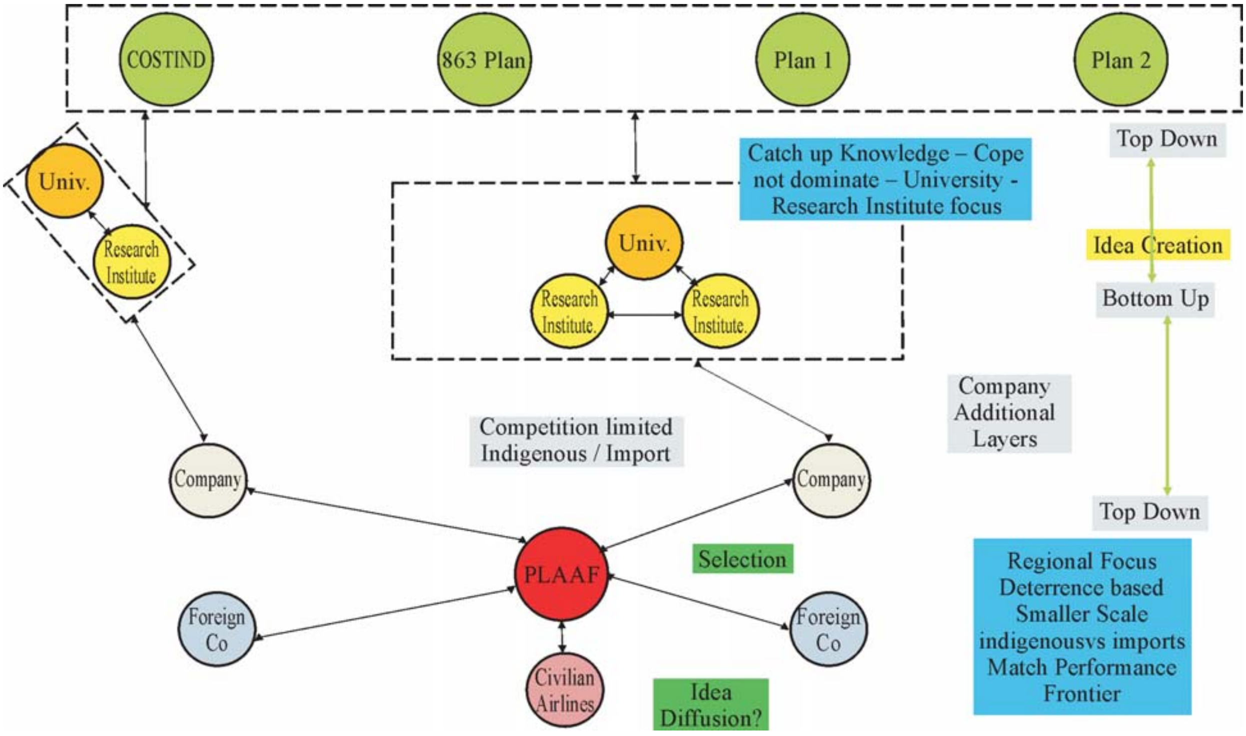

Figure E: China's Ecosystem for Knowledge Generation & Use - Single Crystal Technology for Aircraft Turbine Blade

1. Background

As a part of its mandate the International Strategic & Security Studies Programme at the National Institute of Advanced Studies (NIAS) had identified “China’s Capabilities in Science & Technology (S&T)” as a major area of interest. A review of the Programme in October 2009 had identified “Chinese Aeronautics, Materials and Electronics” as potential areas of work for NIAS in trying to address the larger issues of Chinese capabilities in Science & Technology.

An Internet based literature survey of China’s national capabilities in S&T revealed a very large number of reports on assessing S&T Capabilities at a national level. Some of the best reports were from the Rand Corporation. These reports not only addressed S&T competitiveness of the United States[1] but also included very comprehensive assessments of Chinese capabilities in different areas of science and technology such as Biotechnology, Information Technology and Nanotechnology.[2] Some of these publications not only looked at the technology or science side but also addressed institutional, organisational and political problems that could act as a barrier to the diffusion of science or technology based innovation into broader society. Still other studies were exclusively focused on China including certain specific regions of China.[3]

In January 2006 China unveiled a 15 year “Medium- to Long-Term Plan for the Development of Science and Technology”. This Plan[4] called for China to become “An Innovation Oriented Society by 2020 and a world leader in S&T by 2050”.The preparation of this plan was a major effort within China. The Plan talks about the different approaches needed to realise the innovation goals outlined as necessary for the transformation of China.[5]

Many studies on S&T and its links with innovation are focused on the macro or broad picture. Studies that look at specific technologies by contrast do not address the larger social, political, economic and institutional aspects of how specific technologies diffuse through societies in the form of new products and how the consequent changes that they bring about affect the larger national system. One area for original contribution would be case studies on specific technologies. If such studies could not only cover the hard core supply side of technology but also address the softer part of how developments in S&T diffuse into society and become a major force of economic and social change, they might help us get a different but useful

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[1] Titus Galema and James Hosek (Editors), “Perspectives on US Competitiveness in Science and Technology”, Rand National Defence Research Institute, Rand Corporation, 2008.

[2] For a comparative overview of 29 countries including China see Richard Silberglitt, Philip S.Anton, David R.Howell, Anny Wong et al, “The Global Technology Revolution 2020, In-Depth Analyses – Bio / Nano / Materials / Information – Trends, Barriers, and Social Implications”, Rand National Security Research Division, Rand Corporation, 2006.

[3] Richard Silberglitt, Anny Wong et al “The Global Technology Revolution – In-Depth Analyses, - Emerging Technology opportunities for the Tianjin Binhai New Area (TBNA) and the Tianjin Economic Technological Development Area (TEDA) Rand Transportation, Space & Technology Programme, Rand Corporation, 2009.

[4] For an overview of how this transformation is to be achieved please see Cong Cao, Richard P. Suttmeier, and Denis Fred Simon, “China’s 15-year science and technology plan“, Physics Today, December 2006, pp 38-43 available at http://www.levin.suny.edu/pdf/Physics%20Today-2006.pdf

[5] 11 key areas, 8 frontier technologies, 13 Mega technology products and two mega science projects are the specific routes through which this transformation will be brought about.

perspective on how innovation happens within different countries.

Keeping this very broad mandate in mind, one area of dual use interest - the development of aircraft in China - appeared to be a particularly promising line of research.[6] During the course of conducting this research a number of references to Chinese capabilities in "Single Crystal Superalloy Aircraft Turbine Blades" came up. Available public domain information seemed to suggest that the Chinese had mastered this technology and had developed "indigenous aircraft engines and aircraft" that used this state-of-art technology.

After extensive discussions we thought it worthwhile to look at this technology as a typical case study on how China manages a critical and strategic dual use technology. Such a micro level study would complement other more macro studies on Chinese capabilities in Science & Technology.

In order to get some kind of an idea of the Chinese Science & Technology system and its links to deliverable products and services, there is a need to compare it with some other system. We choose to compare it with the US system simply because of the availability of a lot of public domain information and research literature. We also decided that we would use patent information as well as research papers to look at the development history as well as the pattern of linkages between different players in the Science, Technology and Innovation eco-systems of China and the US. We hoped through this process to get a micro-level view of the working of the Chinese S & T system and its connections with the delivery of hi tech products and services.

2. Approach

The methodology we adopted was a comparative case study approach. We decided to use the emergence and evolution of the single crystal technology in the US as a benchmark or template for comparing China's efforts at developing and using "single crystal" technology for aircraft turbine blades.

Through search of the published literature and information available in the public domain we built up a timeline of developments related to the emergence of this technology in the US and linked it to its use in a product – the aircraft turbofan jet engine. We also used the US patent data base to look at the history of patenting in this area of technology with an emphasis on the link between patents and competing technologies and approaches.

We then looked at the number and type of papers published in the various journals dealing with this domain of knowledge. We also used these papers as well as papers presented at Conferences to understand collaborative efforts between different players in this area.

Through a combination of patents, journal papers and conference papers we built up a comprehensive picture of how the technology emerged and evolved in the US and how it was incorporated into an aircraft engine flying on an aircraft.

In parallel we also studied the competition between different companies within the US and how the different players operating in this industry responded to the emergence of this new capability.

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[6] R. Arun Kumar, "An Assessment of Chinese Airplane J-10 and WS-10A Engine", REP – ISSP 1 -09, NIAS Working Report, 2009.

The understanding that we achieved through the above process was used to create a reference template for looking at Chinese efforts in this domain of technology.

Using public domain information we then studied in some detail the evolution of the aircraft industry in China. We particularly focused our interest on the Chinese efforts to build a globally competitive aircraft industry that catered to both military and civilian needs. We studied two advanced military aircraft – the J-10 and the J-11- that the Chinese developed and their underlying technologies to look for the incorporation of single crystal technology or the related Directionally Solidified Columnar Grain and Equiaxed Grain turbine blade technologies into their aircraft engines.

We also studied developments in this domain through a search of the patenting history in China. We looked at the published papers in China for identifying collaborations between different players in the Chinese system (super alloys, turbine blades, single crystal) and tried to link these up with product timelines and patenting history.

Using this data we built up a comprehensive timeline for the development of this technology in China and linked S&T developments with its use in a specific product or service.

We used the data on collaborations and competition to compare the two knowledge networks as seen through papers and other publications in the US and in China. The role of universities, mission organizations, companies and government supported R&D entities were assessed through both the paper links and patent information.

From this comprehensive understanding of the evolution of these two trajectories in these two countries we then drew some inferences about the capabilities of the S&T system as seen through this case study. We also tried to look at the links between the S&T system and other parts of the Chinese establishment that helped or hindered the diffusion of technology.

Finally at the end we raise a set of issues related to the approach and the findings from this research.

3. Single Crystal Technology & Other Complementary Technologies for Aircraft Engines

The turbofan engines that power modern military as well as civilian aircraft are complex hi tech products. Their development, production, deployment and continued operation require a large infrastructure as well as a cadre of experts and specialists in various domains of knowledge. These various elements or components have to be put together and managed efficiently. Continuous dynamic changes and periodic radical changes both from the user side of this value chain as well as from the technology or supply side of the chain are an essential feature of this complex ecosystem.[7]

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[7] There is a lot of work done on characterising technological changes. They can be viewed as incremental, modular, architectural and radical change. The ability of organisations especially companies to cope with different modes of change has also been covered extensively in the literature on management. For one detailed assessment based on the study of the photolithography industry in the US see Rebecca M. Henderson, Kim B. Clark, "Architectural Innovation: The Reconfiguration of Existing Product Technologies and The Failure of Established Firms", Administrative Science Quarterly, 35 1990, pp 9-30.

The efficiency of the engine depends greatly on the temperature at which the turbine operates. The higher the temperature the more efficient is the conversion of the chemical energy into thrust.

An engine consists of many critical parts. However we can understand the key elements of the current aircraft engine architecture[8] in the following simple way.

The fuel that powers the aircraft is mixed with compressed air and ignited in a combustor that is made up of materials that can withstand high temperature. The combustion product which are hot gases are expanded through high pressure and low pressure turbines to provide the required thrust. The turbines comprise a number of geometrically shaped blades made of superalloys.

Superalloys are nickel based alloys to which a large number of alloying elements are added. The alloying elements are carefully chosen depending upon the nature of the use and involve a fairly sophisticated understanding of the phases available in the alloy and how they respond to different fabrication and heat treatment conditions.[9]

By providing some ways of cooling the elements that go into these hot parts the temperature of operation can be raised.

There are also fairly complex fabrication and heat treatment processes involved in order to realize the optimum performance from each part.

When jet engines were first introduced the temperature of operation was limited by the melting point of the material. Through proper choice of alloying elements and through improvements in casting fabrication and heat treatment techniques obvious performance improvements occurred.[10]

In addition to the above approaches engineers also tried to raise the temperature of these components by cooling the blades. Improvements in various cooling techniques can also raise the temperature of operation.

Another way to raise the temperature of the aircraft component is to coat it with some heat resistant refractory material. This once again raises the temperature of operation of the engine and improves its efficiency.

In spite of these improvements inherent technical problems to further improvements soon become a bottleneck. This is because of the way the products are made. For aircraft turbine blades casting techniques have remained the mainstay for the various improvements achieved during the first two decades of development.

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[8] The term architecture is specifically used to look at how various subsystems, components, parts are linked together. The replacement of the piston engine that powered aircraft prior to the advent of jet engines not only changes the underlying subsystems, components and parts but also changes in the way these are put together and linked. Such changes are both modular, architectural as well as radical.

[9] For a typical list of various alloying elements used in three generations of single crystal alloys see G.A. Kool, “Current and Future Materials in Advanced Gas Turbine Engines”, Paper prepared for presentation at the 39th ASME International Gas Turbine and Aero-engine Congress and Exposition June 13-16 1994, The Hague, The Netherlands, National Aerospace Laboratory NLR, NLR TP 94059, 31 January 1994. Though a very traditional domain as the number of alloying elements increase the complexity of understanding the phase diagrams as well as the experimental facilities for research become significantly more complicated.

[10] For people familiar with the technology S curve this is typically seen in a plateauing of the S curve of technology development.

The casting approach that is traditionally used results in a polycrystalline structure. This meant that the strength in a particular direction (important during operations) was lower than the inherent strength of the material. With a large number of grains the boundary areas between grains increase appreciably. These boundaries are the major sources of corrosion and reduced life during the temperature and stress cycling that a typical turbine blade goes through during its duty cycle of operation.

This limitation suggests two logical approaches to improving performance. If the grain boundary area can be reduced in the transverse direction, performance can be improved. By orienting these grains in a preferred direction that coincides with the direction of maximum stress the performance can be further improved.

Alternatively the grain boundary problem can be completely eliminated if the entire part can be cast as a single crystal aligned in the appropriate direction.

These technology trajectories – equiaxed multiple crystal turbine blades, columnar directionally solidified turbine blades and single crystal turbine blades[11] will be the major focus of our study. How these technologies were embedded in products in two different contexts – the USA and China–will be the main focus of this report.

However we must keep in mind that when we look at the trajectory of development of the final products – the aircraft engine and the aircraft itself there are many other technologies that can affect performance – in our specific case the fuel efficiency.

For the engine itself the designer could play around with:
The material and the alloying compositions;

The heat treatment and other fabrication processes associated with manufacture;

Combustion efficiency:
The design of the aerofoils (systems of vanes and turbine blades) and the way in which they are arranged;

The cooling system for the turbine blades;

The thermal barrier coating on the blades;

The nature of the grains – equiaxed grains, directionally solidified columnar grains or single crystal products.[12]

At the level of the aircraft there could be other parameters – for e.g. engine performance can be traded off for lighter weights or superior aerodynamics.

There are therefore many technology choices or degrees of freedom available for meeting a performance requirement at any given time. The choices that one makes for use in any specific product would depend upon other factors like the development status of the technology, the user

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[11] Though this is so, we cannot ignore other related component technologies of the product – alloy composition, cooling arrangements, casting and heat treatment methods as well as thermal barrier coatings. Changes in all of these happen simultaneously – but even with all of them the final bottleneck will be the nature and type of grains that are formed. While not ignoring the other component technologies this is the part we want to highlight in this study

[12] For a good overview of all the related technologies see Robert Schafrik and Robert Sprague "Saga of Gas Turbine Materials Part III", Advanced Materials & Processes, May 2004 pp 29-33.

preferences, perceptions of risk for the different routes especially with respect to time schedules fixed by leaders and managers, as well as organizational, marketing and other social or political factors. These aspects have to be kept in mind in looking at the Chinese development of capabilities in this area and in comparing it with the American system. Figure 1 shows the blades made by the three approaches. Figure 2 shows the typical production line for a turbofan aircraft engine.

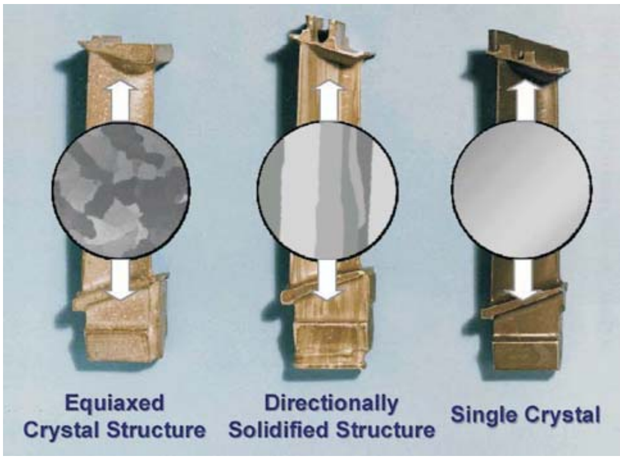

Figure 1: Turbine Blades Made by Three Different Methods *(Source: Man Hoi Wong, 2003[13])*

G.A. Kool in his review paper cited earlier provides a simple overview of the developments in the three technologies of interest – equi-axed poly crystal grain, directionally solidified columnar grain and directionally solidified single crystal – for making aircraft turbine blades. This paper provides information on alloy compositions as well as cooling and coating of the turbine blades to improve performance.[14] Data on the performance improvements arising from various developments taken from Kool's paper are presented below. Figure 3 shows the improvements brought in operating temperature through use of one of several underlying technologies – cooling of the blades.

Figure 2: A Typical Production Line for Turbofan Aircraft Engines *(Source: Flight International, 16 February 1980, p 474)*

Figure 4 shows details of the percentage improvements in specific fuel consumption over different engines over time.

Figure 5 shows the improvements achieved through the use of single crystal technology for aircraft turbine blades as compared to equiaxed and

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[13] Man Hoi Wong, "Case Study: Single Crystalline Turbine Blades", 2003, at http://my.ece.ucsb.edu/mhwong/documents/turbine_blades.pdf

[14] See Reference 9

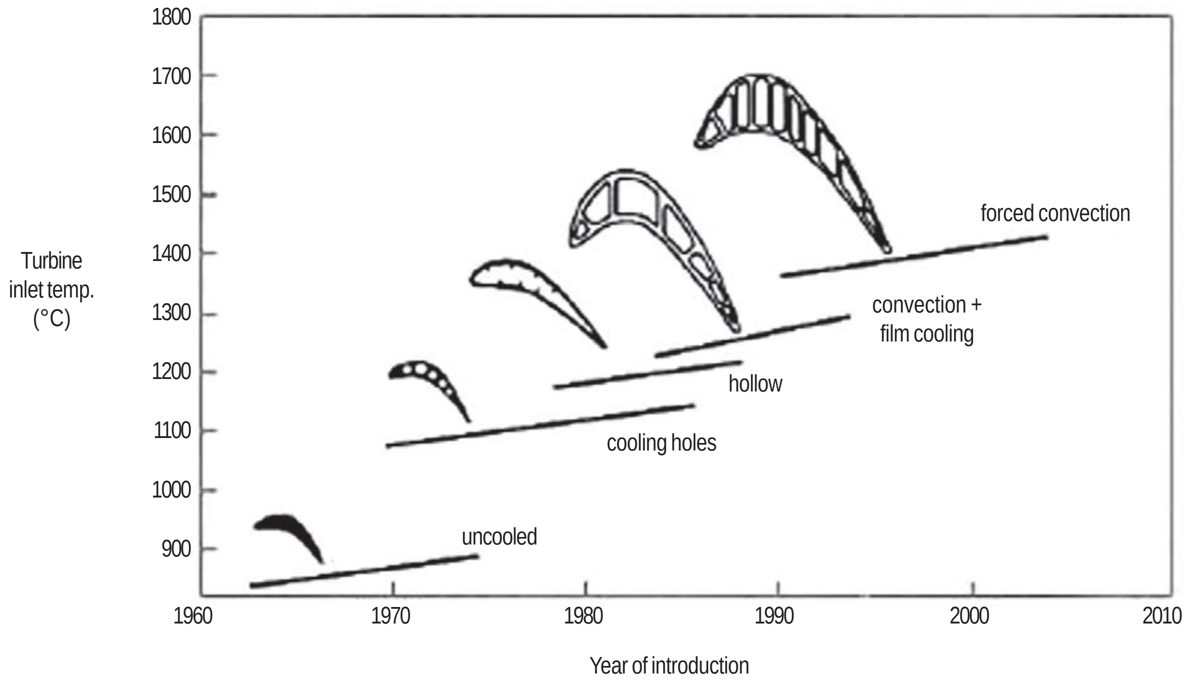

Figure 3: Improvements in Operating Temperature by Cooling of the blades
(Source: G.A. Kool,1994)

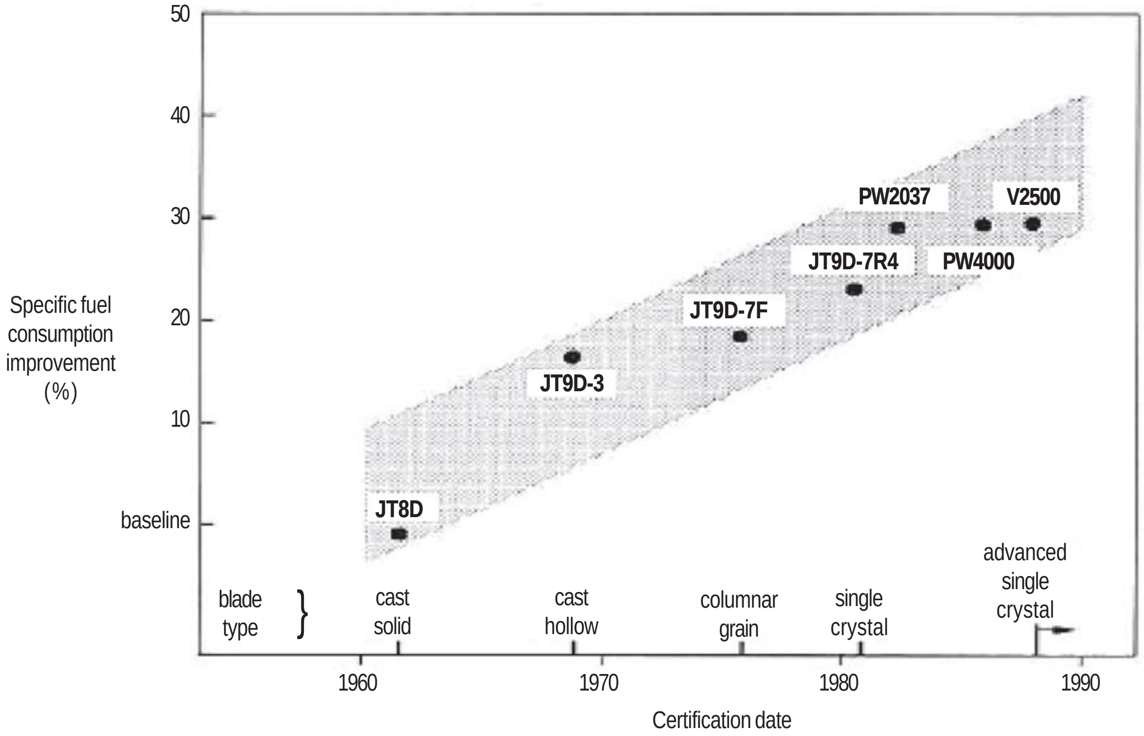

Figure 4: Improvements in Specific Fuel Consumption
(Source: G.A. Kool,1994)

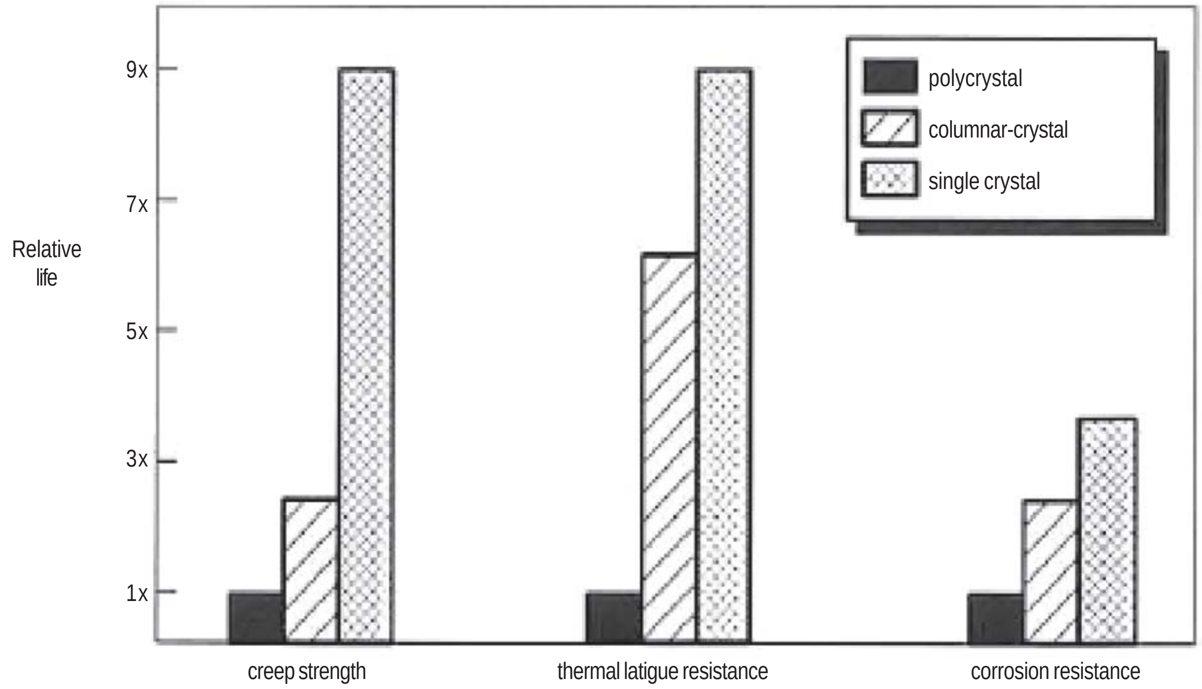

Figure 5: Improvements Achieved in Key Properties
(Source: G.A. Kool,1994)

directional solidified columnar grain technologies in three key areas – creep strength, thermal fatigue resistance and corrosion resistance.

Figure 6 provides a conceptual overview of the trajectories of development of the three technologies

We can look at the development of various key technologies as we move from the polycrystal to the directionally solidified columnar grain to the single crystal technology. Even in the single crystal technology Generation 1 technology has given way to Generation 2 and Generation 3 technologies brought about by adding a new alloying element Rhenium.

In the book "The World is Flat", Thomas Friedman talks about one of the world's foremost aircraft engine manufacturers Rolls Royce. Rolls Royce outsources and offshores 75 % of the components that goes into its engines. It however makes the remaining 25% in-house. According to Friedman this 25% is responsible for the critical difference between Rolls Royce and other similar companies. Friedman quotes the Chairman of Rolls Royce, "The 25 percent that we make are differentiating elements. These are the hot end of the engine, the turbines, the compressors and fans and the alloys, and the aerodynamics of how they are made. A turbine blade is grown from a single crystal in a vacuum furnace from a proprietary alloy, with a very complex cooling system. This very high-value-

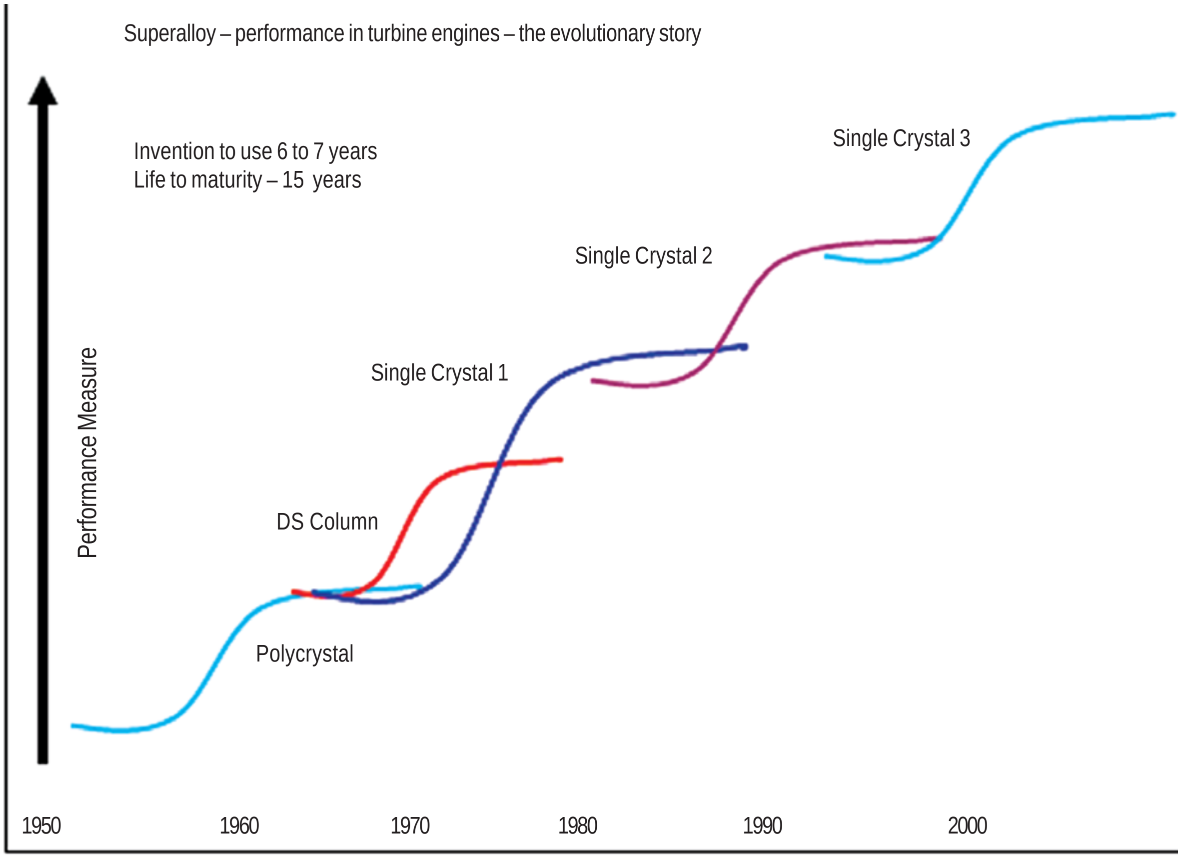

Figure 6: Trajectories of Development

added manufacturing is one of our core competencies."[15]

It is clear from the above that the technology associated with making turbine blades using single crystals is considered to be a key capability area for a company making jet engines. Countries too may view technologies associated with certain dual use products like aircraft or rockets as strategic and look to support and grow capabilities both within the commercial sector as well as in national laboratories or other national security establishments.

The choice of dual use single crystal technology as a case study to illustrate the evolution of the technology and its incorporation into a product in the contexts of China and the US should therefore enable us to compare and contrast two systems that follow different approaches. Through such an understanding we may be able to get a handle on the Chinese Science & Technology System and its link with other larger political and economic systems. Hopefully at the end of such an exercise we would be better able to judge China's mastery over critical technologies needed for its future emergence as a global power.

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[15] http://www.memagazine.org/backissues/membersonly/feb06/features/crjewels/crjewels.html Lee S. Langston, in his article "Crown Jewels" describes the development of the three technologies – polycrystal turbine blades, columnar turbine blades and single crystal turbine blades in a simple easy to understand way.

4. The Emergence and Evolution of Single Crystal Technology in the US

4.1 Overview

According to Langston the single crystal technology was pioneered by researchers at the Advanced Materials Research & Development Laboratory of United Technologies (Pratt & Whitney) in the early 1960s under the direction of Bud Shank. He states "the first important development was the directionally solidified columnar-grained turbine blade, invented by Frank VerSnyder and patented in 1966." Langston provides a simple technical explanation of the process of growing these columnar grains and talks of the superior ductility, thermal aging and greater tolerance to local strain areas of the blades grown in this way. He then goes on to talk about the first patent of a single crystal turbine blade, a patent on an improved blade by Bernard Kear, mentions Maurice Gell's patent on single crystal alloy composition improvements and links these developments to a major increase in the operating temperature of the aircraft engine by 150 to 200 degrees. The account also talks of Pratt & Whitney's efforts at producing these blades in the early 1970's. According to him "Yields greater than 95 percent are now commonly achieved in the casting of single-crystal turbine airfoils for aviation gas turbines, which minimizes the higher cost of SX[16] casting compared to equiaxed casting."

Langston's article goes on to describe the movement of the technology into the aircraft engine and its first flight in an aircraft. The first time a single crystal was actually used in an engine was in the Pratt & Whitney JT9D-7R4 in 1982. This first single-crystal blade engine powers the Boeing 767 and the Airbus A310.The J58 engine which powered the famous Lockheed SR-71 Blackbird also used turbine blades made of single crystals.

Langston's account also mentions more recent developments in the diffusion of this technology from the military into the civilian electricity sector. He states "General Electric's 9H, a 50 Hz combined-cycle gas turbine, is the world's largest. The first model went into service in 2003 at Baglan Bay on the south coast of Wales, feeding as much as 530 MW into the United Kingdom's electric grid at a combined-cycle thermal efficiency just under 60 percent. The 9H, at 367,900 kg, has a first-stage single-crystal turbine vane with a characteristic length of 30 cm and first-stage single-crystal blade of 45 cm (the blade lengths in the PW JT9D-7R4 are about 8 cm). Both vane and blade are cooled by steam (from the unit's combined-cycle operation) rather than by air. Each finished casting weighs about 15 kg and each is a single crystal airfoil". This implies that the diffusion of single crystal super alloy technology from the higher value and relatively smaller jet engine and aircraft market to the larger and lower price power turbine engine market is currently underway.

4.2 The US Patent Story - The Early Patents

Using the Langston account we looked at the US patent data base to study how the technology emerged and developed in its early phases. Starting with the patents cited by Langston we tried to look for links between these and earlier patents. Table 1 provides a tabulation of all these related

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[16] SX stands for single crystal

patents. A study of these patents gives us some kind of a timeline of technological changes in this domain from the end of the second world war to 1975.

The review of sample patents that we studied makes it clear that nickel based super alloy compositions that helped raise the temperature of operation of the engine was the major driver of technology development during the early years after the war. The first patent to exclusively talk about single crystal in a metal or alloy application was a US government patent, Patent No 3060065 entitled “Method for the growth of preferentially oriented single crystals of metals” taken out in 1962. A scrutiny of this patent reveals that it is a general purpose patent that looks at equipment and methods for producing single crystals of metals. It does not specifically address the question of using such a method for casting a super alloy or a turbine blade.

The first patent for a single crystal application for a turbine blade to be used for an aircraft engine was US Patent 3519063 “Single crystal metallic part” issued to United Technologies in 1970. United Technologies was a major manufacturer of aircraft engines in the US. This patent covers the product which is an airfoil for a turbine application as well as the method for producing the product. The application is filed on February 16 1966 and the patent is granted on February 10, 1970. So obviously most of the work on this development must have taken place in the company prior to 1966.

Going back in time, the first patent to talk about Directionally Solidified columnar grain (also termed Directionally Solidified or DS) was another United Technologies Patent US Patent 3124452 “Unidirectional solidification of lamellar eutectic alloys”, that was filed in September 1960 and granted in March 1964. However the major patent filed by United Technologies that specifically addresses the problem of making a gas turbine blade using the DS technology is US patent 3260505 entitled “Gas Turbine element” filed in April 1964 and granted in July 1966.

From the patent record it is clear that both the DS columnar grain as well as the single crystal technology was pioneered at United Technologies, the parent company of the jet engine manufacturer Pratt & Whitney.[17] The record also suggests that though other companies were also working on super alloys and aircraft turbine blades it was only United Technologies that was pushing the R&D in the direction of DS columnar and single crystal technology. Companies such as Rolls Royce, TRW and General Motors were looking at other ways of improving performance.

The DS columnar grain technology emerged out of R&D at United Technologies in the period 1964 to 1966. Work on the next generation single crystal technology would have been in a reasonably advanced stage by 1966, the date of filing the single crystal patent. Thus work on these two technologies was going on nearly simultaneously though the patents on DS were filed about two or three years earlier.

The string of patents taken out by United Technologies during this period also shows that having come up with an original innovation they

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[17] Some patents refer to the United Aircraft Corporation. For our purpose United Technologies, Pratt & Whitney as well as United Aircraft Corporation represent the same business entity.

Table 1: Key US Patents Related to Super alloy Turbine Blades

Year	US Patent No	Company	Patent Title
1955	2712498	Rolls Royce	Nickel Chromium alloys having high creep strength at high temperatures
1961	3008855	General Motors	Turbine blade and method of making same
1962	3060065	US Government	Method for the growth of preferentially oriented single crystals of metals
1964	3124452	United Technologies	Unidirectional solidification of lamellar eutectic alloys
1966	3248764	TRW	Alloys having improved stress rupture properties
1966	3254994	TRW	Methods for improving grain structure & soundness in castings
1966	3260505	United Technologies	Gas Turbine element
1970	3526499	TRW	Nickel base alloy having improved stress rupture properties
1970	3494709	United Technologies	Single crystal metallic part
1970***	3519063	United Technologies	Shell mould construction with chill plate having uniform roughness
1971	3554817	United Technologies	Cast Nickel columbium aluminium alloy
1971	3572419	United Technologies	Doubly-oriented single crystal castings
1971	3567526	United Technologies	Limitation of carbon in single crystal or columnar grained Nickel base super alloys
1973	3738416	United Technologies	Method of making double-oriented single crystal castings
1973	3763926	United Technologies	Apparatus for casting of directionally solidified articles
1974	3793010	United Technologies	Directionally solidified eutectic type alloy with aligned delta phase
1975	3915761	United Technologies	Unidirectional solidified alloy articles

were quick to capitalise on it and protect it through a string of process, product and combination patents.

A study of these patents for the period from 1955 to 1975 also reveals that most of the patents did not cite references to any published articles as prior art. Most of them only refer to other patents that were filed. Some patents that we examined in this domain also referred to the interests of the US government especially the US Navy. One can surmise that there was US government support to companies for carrying out R&D in this area.

From the patent record it appears that innovation was largely company driven and application focused. Universities and academia do not seem to have played a major role..

4.3 The Early Publications - The First Paper

In parallel with the patent search we also tried to look at the technical literature.The earliest reference to single crystal development that we could locate was a Review Paper for Materials Science & Engineering, Volume 6, No. 4, 1970, p 231 entitled “Columnar Grain and Single Crystal

High Temperature Materials" by Ver Snyder and Shank. Shank headed the R&D Group at United Technologies and Ver Snyder is the person who filed the first DS patent for a gas turbine element in 1966. Both of them held important positions at United Technologies.

The paper written by them is 35 pages long and provides a fairly detailed description of both directional solidification as well as single crystal developments at United Technologies. Any person with a reasonable background in materials would be able to understand the implications of these developments on the production of turbine blades and the consequent economic benefits.

The paper refers to other papers and some patents. Most if not all the references are to work carried out at the Pratt & Whitney Division of United Technologies. This finding reiterates the point we made earlier that the hub of innovation in this area are companies and not universities or other academic centres.

Interestingly the paper is received for publication on March 15, 1970 which is about a month after the granting of the single crystal patent to Piarcey of United Technologies on February 11, 1970. The DS columnar grain turbine blade had also become a commercial product in the military domain in 1969 and had entered the civilian domain by 1972. In the case of DS columnar grain technology, the publication of the paper is a little over three years after the granting of the patent for a DS turbine blade in 1966.

Patent protection seems to precede publication especially in the US.

Maurice Gell, one of the patent holders described in the early patent part of our report, along with two other colleagues describes the development of single crystal turbine blade development at United Technologies in a paper presented at the 1980 Super alloys Conference.[18] According to this account, unidirectional columnar crystal or DS technology and single crystal technology were discovered and developed almost at the same time in the 1963 to 1970 period.

Gell in his paper states clearly that the early single crystal alloys did offer superior transverse strength and ductility but did not at least initially offer major improvements in the other parameters of interest – creep strength, thermal fatigue resistance or oxidation resistance.

By adding hafnium,[19] direction solidified columnar crystals matched even the potentially superior properties of transverse strength and ductility offered by single crystal technology. The company therefore decided to push the DS columnar technology and go slow on the single crystal approach.

From Gell's narrative DS columnar grain technology based turbine blades entered service in military engines in 1969 and in civil aircraft engines in 1974. This means that in the case of DS technology it took about 5 years from invention to product in the United States in the 1960's.

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[18] M. Gel & D. N. Duhl and A. F. Giamei, "The Development of Single Crystal Superalloy Turbine Blades", Paper presented at Super alloys 1980, pp 205 -214

[19] The paper mentions 1969 as the year when hafnium addition was first tried out for the DS route. By this time an engine with a DS blade had already entered service.

Gell goes on to state that heat treatment studies on the Directionally Solidified (DS) columnar alloy shed new light on how single crystal properties could be improved. This gave a new approach to alloy design. This happened in 1975 and provided a fillip to the technology. The single crystal technology entered service in an engine in 1982 according to Gell.[20]

From Gell's account of the development, though both single crystal and DS columnar grain technologies emerged at the same time, it was the DS technology that was commercialised first. Within about 6 years from invention it enters service in a military engine. Though single crystal technology was identified as a promising route almost at the same time, the greater potential of DS technology in matching the single crystal performance at least initially comes in the way of further commercialisation of the single crystal technology. It is only after work on DS provided new inputs around 1975 that United Technologies goes ahead with the commercialisation of the single crystal technology.

Though the first patent on single crystal was in 1970, it is only after 1975 that the technological bottlenecks for commercialisation of the single crystal approach are finally removed. An engine with a single crystal turbine blade is approved for flight in 1982. The period from discovery to use in this case is about 16 years if we assume that the invention coincided with the filing of the patent in 1966. However in 1966 the competing DS columnar technology and subsequent improvements to it are responsible for delays in using the single crystal technology. There seem to be additional bottlenecks to be overcome before the single crystal becomes a viable route to engine performance improvements. These bottlenecks to further improvements were only removed in 1975. If 1975 is taken as the date when the invention process has been completed, it took about 7 years from the date of the practical invention to commercial use in the US in the 1970's.

It is also clear from this analysis that improvements to already developed technologies may come in the way of the development of new technology and that cost as well as market considerations are also important factors for companies making strategic R&D choices.

4.4 The US Patent Story Continued

A search of the US patent data base from 1976 till date[21] with the search word "super alloy" threw up 3855 patents.[22]

A more refined search with the terms – super alloy – turbine– single crystal turned up 775 patents.[23] If we consider the patents only up to the end of 2009 there are 757 patents in our domain of interest. We also identified patents awarded to major manufacturers of aircraft engines.

General Electric leads the patent list with 276 patents followed by United Technologies (Pratt & Whitney) with 126 patents. Other companies with

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[20] As mentioned earlier single crystal technology entered service in the Pratt & Whitney JT9D-7R4 engine in 1982. This engine was used both in the Boeing 767 as well as the Airbus 310 commercial aircraft.

[21] Our analyses covers the period 1976 to August 24 2010.

[22] As of August 24, 2010

[23] Most of the patents are taken out by the turbine engine manufacturers or by companies supplying super alloy materials and components. The companies who have taken out the 775 patents are amongst the biggest in these areas in the US.

a fairly large number of patents are Rolls Royce (31 patents), Allison Engine Company (16 patents), Howmet Corporation (66 patents), Allied Signal Aerospace (11 patents), Westinghouse (19 patents) and TRW Inc. with 4 patents.

From the above data it is obvious that major aero-engine manufacturers are big players in this technology space. A number of companies who specialise in the production of super alloy materials and components like Howmet are also significant players. General Electric appears to be ahead of the others in terms of numbers though United Technologies also has a large number of patents. Smaller turbine engine manufacturers like Allison and Allied Signal are also important players.

A more detailed scrutiny of some of the patents showed that the US government had an interest in several of the patents. It is obvious from this that many of the companies involved in the development of these materials and components were supported by the Government. The various Defence, Space and Aviation Research Funding Organisations may be the sources of funding for the early R&D.[24]

Since the focus of our interest in this study was China we also tried to find out whether there were any patents in this domain of technology assigned to any entities or persons in China. A patent search on this did not throw up any patents. Chinese research organisations and China based researchers working in this area of technology have apparently not filed for any patents in the US. We also searched for references to China in all US patents dealing with super alloys. There were 13 patents that referred to China amongst patents that had super alloy somewhere in the text. A closer scrutiny of these patents revealed that only 10 of them related to our field of study.Most of these cited work that had been carried out in China. Many of these references to Chinese work and Chinese publications seem to emanate from ethnic Chinese researchers located in the US. Though we did not investigate this aspect in greater detail, there seem to be links between US based researchers of Chinese origin and their counterparts in China. This is indicative of an official Chinese policy to leverage Chinese talent in the US and the western world for achieving national goals.

Figure 7 below shows the number of patents taken out every year from 1976 to 2009.

Figure 8 provides the cumulative patents which may indicate in a better way the diffusion of technology into products and services.

From the above trends we can see that the technology of using single crystals for the production of aircraft turbine blades had become fairly widespread by about 1985. The number of patents taken out every year shows an increase and the cumulative total starts moving upwards though a takeoff of sorts happens only around 1990. These curves make itclear that within the US and by implication the western world, single crystal technology for turbine blade production had become established by at least 1985. It had become pretty well recognized definitely by about 1990. Table 2 below provides details of the patents taken out by the major players in the “super alloy”, “turbine” “single crystal” domain.

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[24] In many of the patents the interest of the Air Force, the Navy and of NASA are mentioned.

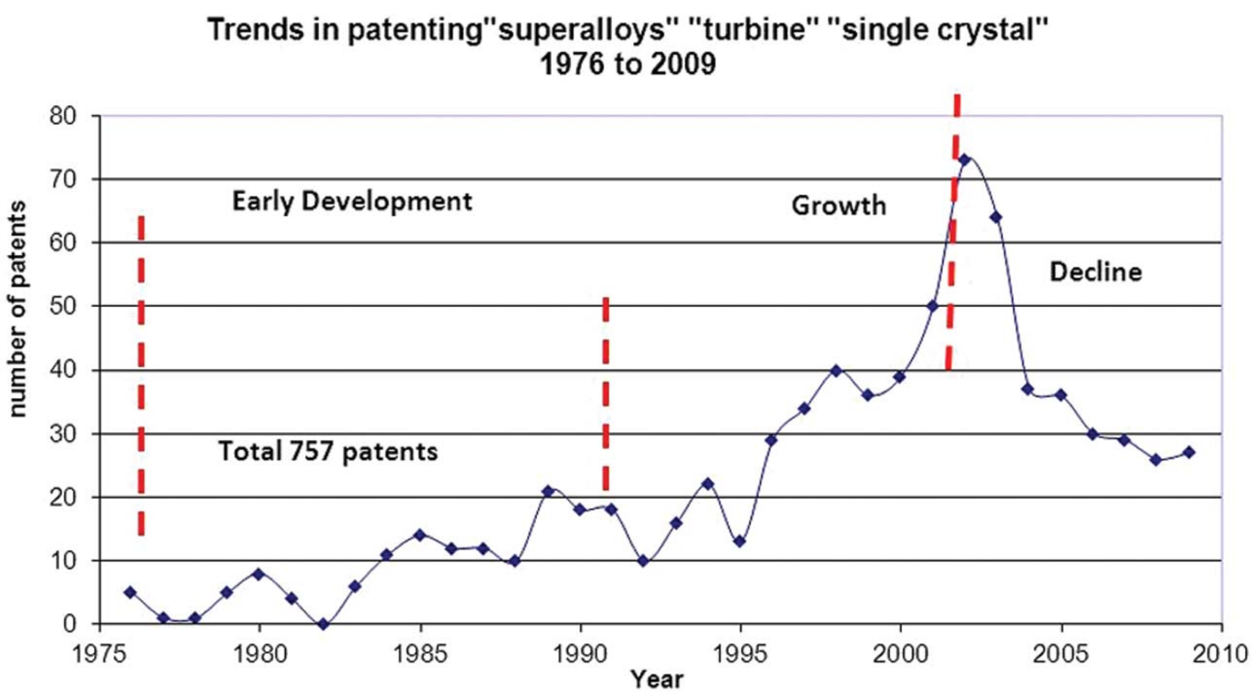

Figure 7: Trends in Patenting 1976 - 2009

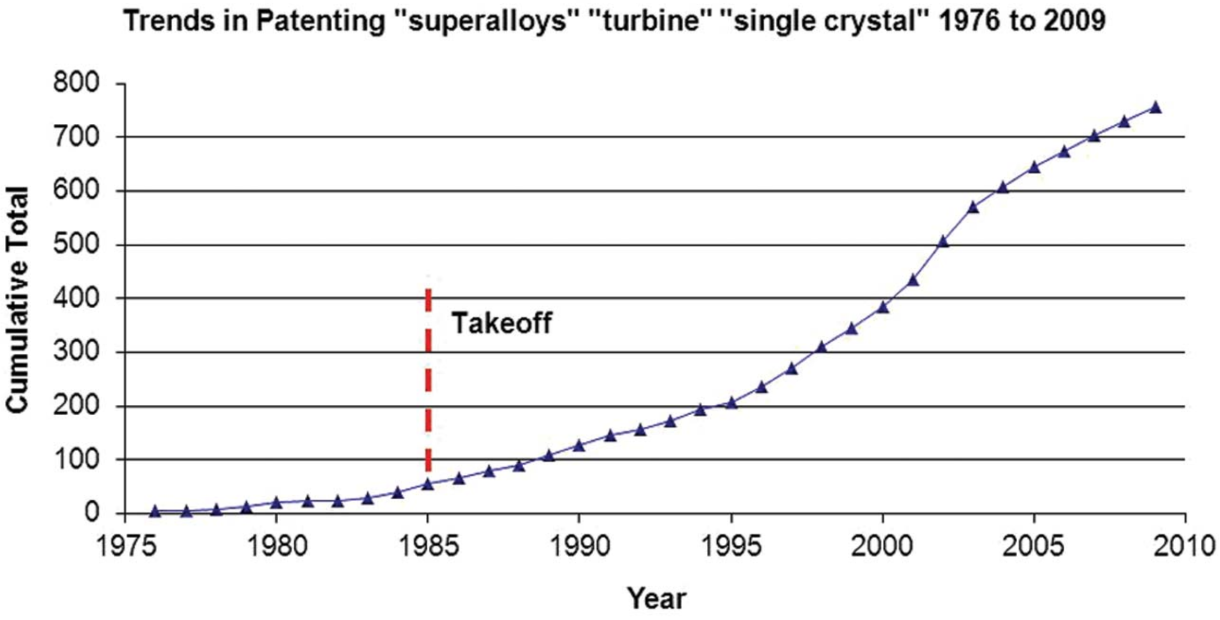

Figure 8: Trends in patenting – A cumulative graph

Table 2 Company Patents in the US – Trends

Year	GE	United Technologies	Howmet	Rolls Royce	Others	Total	Cumulative Total
1976	3	1	0	0	1	5	5
1977	1	0	0	0	0	1	6
1978	0	1	0	0	0	1	7
1979	4	1	0	0	0	5	12
1980	5	3	0	0	0	8	20
1981	1	2	0	1	0	4	24
1982	0	0	0	0	0	0	24
1983	0	5	0	0	1	6	30
1984	0	5	1	3	2	11	41
1985	0	9	0	1	4	14	55
1986	0	7	1	1	3	12	67
1987	0	5	0	1	6	12	79
1988	0	4	2	0	4	10	89
1989	1	9	1	2	8	21	110
1990	0	6	0	0	12	18	128
1991	2	2	1	0	13	18	146
1992	4	1	1	0	4	10	156
1993	6	2	3	0	5	16	172
1994	8	4	6	0	4	22	194
1995	5	2	1	1	4	13	207
1996	10	3	3	1	12	29	236
1997	15	8	4	1	6	34	270
1998	21	5	4	1	9	40	310
1999	11	5	7	0	13	36	346
2000	12	8	3	2	14	39	385
2001	19	5	6	1	19	50	435
2002	32	7	8	4	22	73	508
2003	38	2	6	2	16	64	572
2004	11	1	1	3	21	37	609
2005	23	2	1	1	9	36	645
2006	14	1	1	0	14	30	675
2007	10	5	2	1	11	29	704
2008	10	3	1	3	9	26	730
2009	10	2	2	1	12	27	757
2010	4	6	0	2	6	18	775
Total	280	132	66	33	264	775	

Figure 9 provides the patent information in the form of a trend curve for the three major players – GE, United Technologies and Howmet -so as to enable us to look at the actions of these players. We can also see that in the early period of the evolution of this technology from about 1976 to about 1984 GE is ahead of United Technologies. Starting from around 1984 United Technologies overtakes GE which remains somewhat static till about 1991 when it starts becoming important in

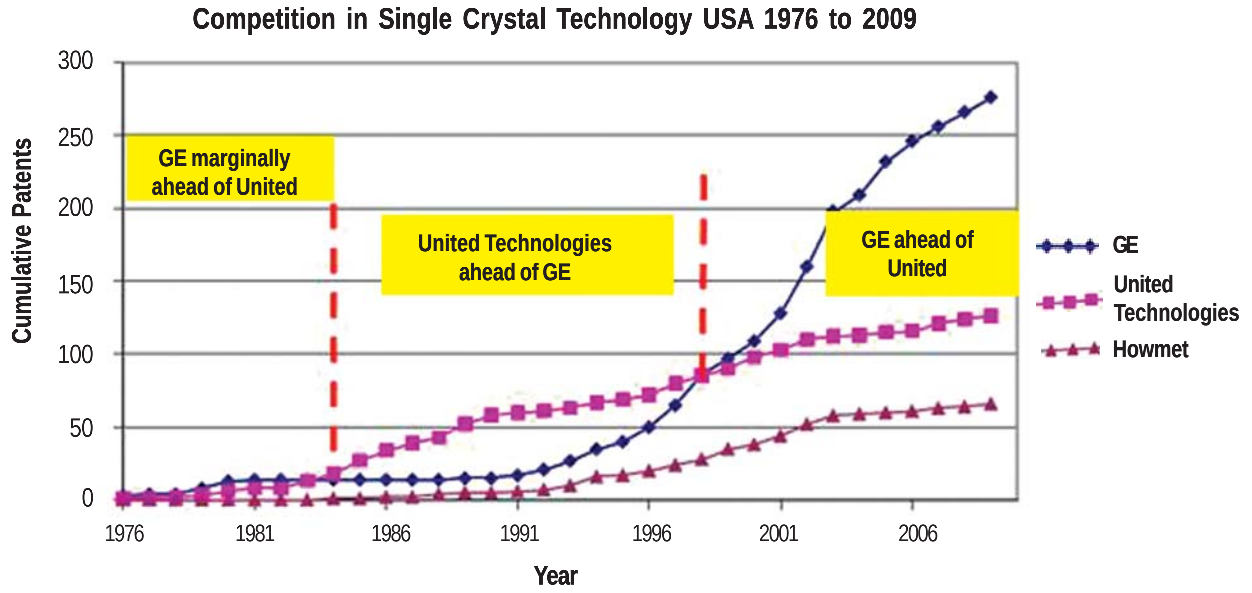

Figure 9: Competition in Single Crystal Technology in the USA

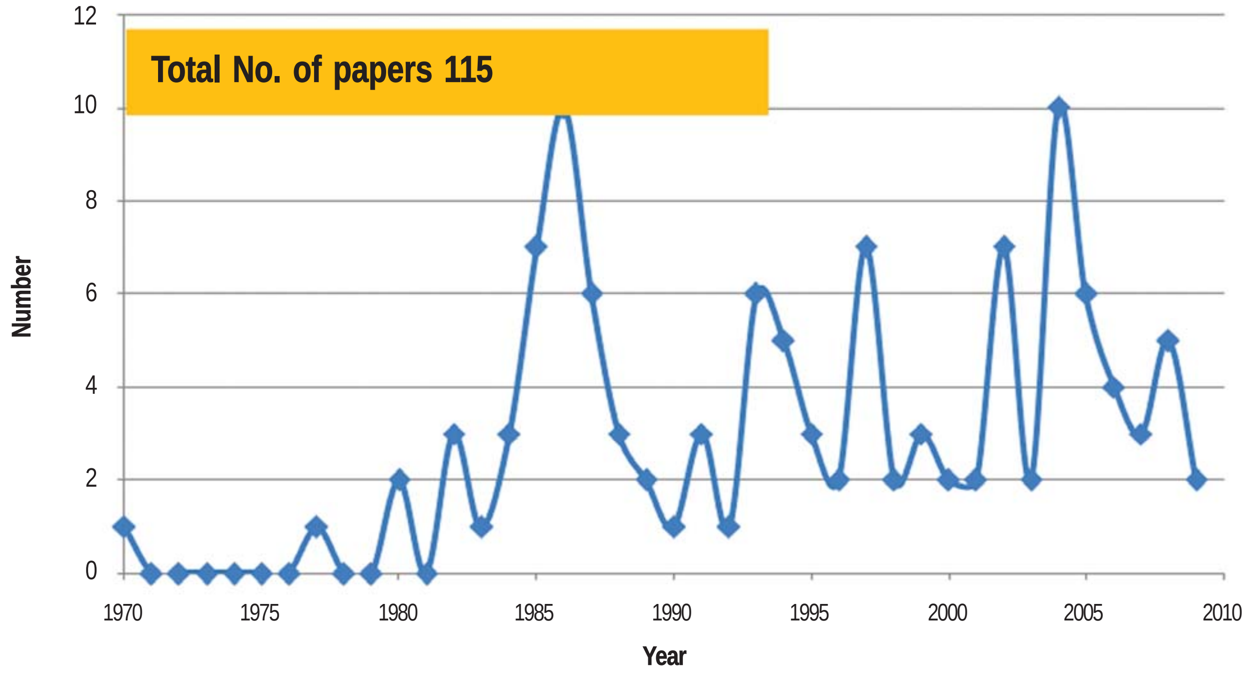

Figure 10: No. of papers on Single Crystal Super alloys in USA (1970 – 2009)

the patent domain once again. From about 1998 GE once again takes over the lead and becomes the dominant player in terms of patents.

4.5 What do Publications tell us about Single Crystal Development in the US?

Figure10 provides the number of papers published in US from 1970 to 2009 that include the terms “super alloys” and “single crystal”.

Figure 11 provides the same data but in cumulative terms.

Figure 12 provides a comparison between annual patents and annual publications in the US for the period of our study.

Figure 13 provides the same data but in a cumulative form.

From figures 12 and 13 we can clearly see an increasing trend in both patents and publications that becomes quite obvious and evident by 1985. Any analyst tracking either the patents or the publications would be able to make the assessment that single crystal technology for aircraft turbine blade manufacture had become a clear and visible trend. In the US the number of patents always exceeds the number of publications. We can also see from the Figure 12 that after 1990 the trends in patenting and publishing seem to follow similar paths with publications lagging patents by about a year.

The trends we saw become a little clearer in the cumulative curve plot. The transition point when the technology trend of growth and diffusion as seen through patents and papers is between 1985 and 1990. Patents seem to reflect the emergence of single crystal technology more clearly and easily than publications at least in the US. It is also fairly clear that the major drivers of this innovation at least in the US are companies who make these complex products. This goes against the standard theory of universities or other academic establishment as being the critical nodes for either the idea generation or for its transformation into a working technology.

The conclusion we can draw from this review of patents and publications in the domain of ‘super alloys”, “single crystal” and “turbine” is that by about 1985 its potential would be clear to any researcher tracking publications. It would also be obvious to any technology or R&D manager tracking patents. Extending this logic a bit one would expect any aircraft engine development programme that started after 1985 to take note of these developments in single crystal technology and incorporate this knowledge into their development plan or agenda for R&D.

In the USA the technology had become commercial by 1982. We can see from the above that this knowledge was available commonly by 1985. Before we turn to China and what they did let us look at what the other major players in the aircraft engine business did.

4.6 Competitive Responses

From the patent record and from a review of some of the published papers there is little doubt that both the DS columnar grain route as well as the single crystal route for the production of aircraft turbine blades was pioneered by the Pratt & Whitney Division of United Technologies. The DS columnar grain route had become operational in 1969 whilst the single crystal route was incorporated into an engine in 1982. One would expect that with these

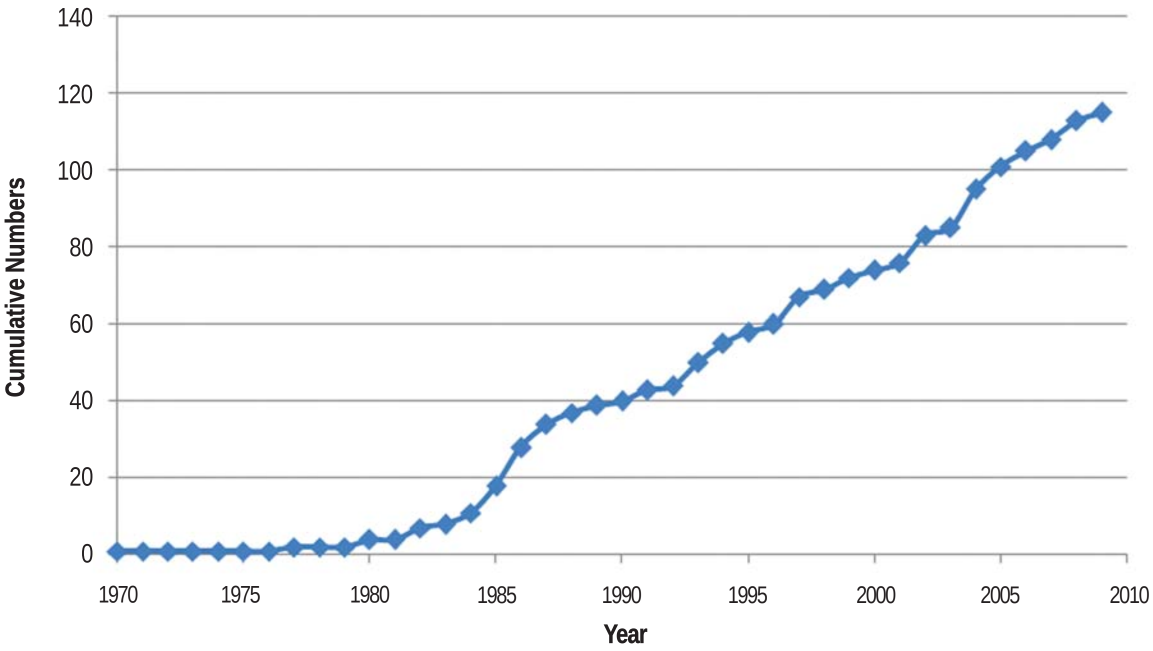

Figure 11: Cumulated No. of papers on Single Crystal Super alloys in USA (1970 – 2009)

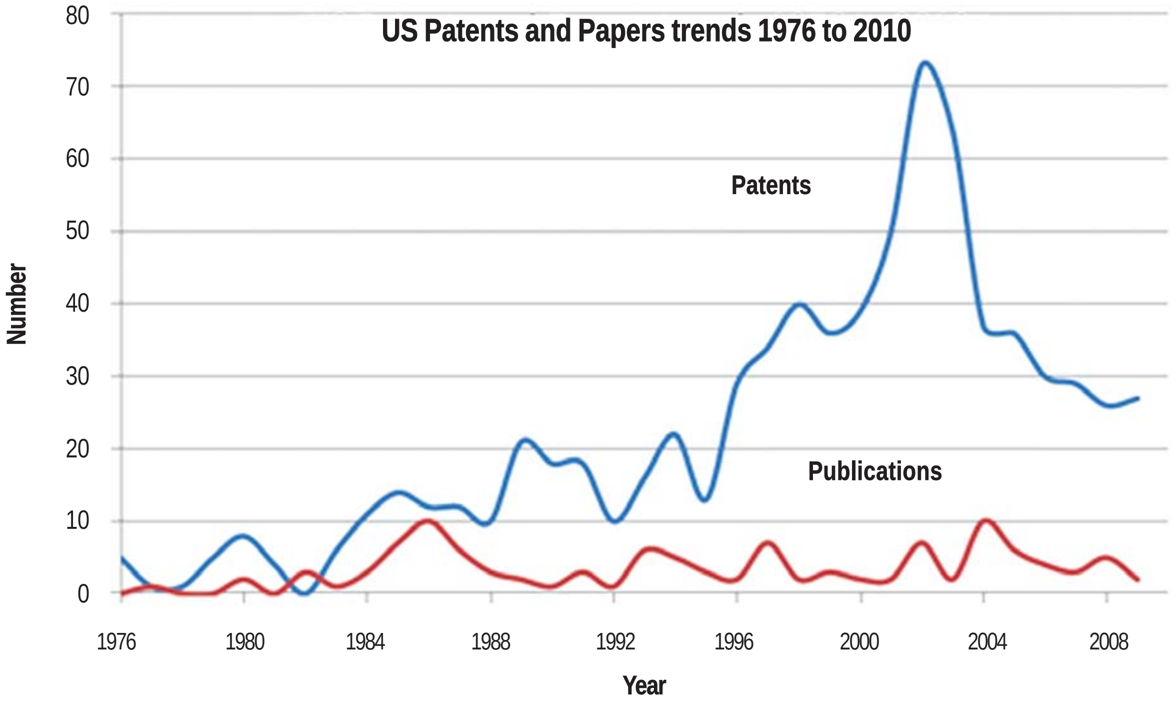

Figure 12: Trends in US Patents and Papers 1976 -2010

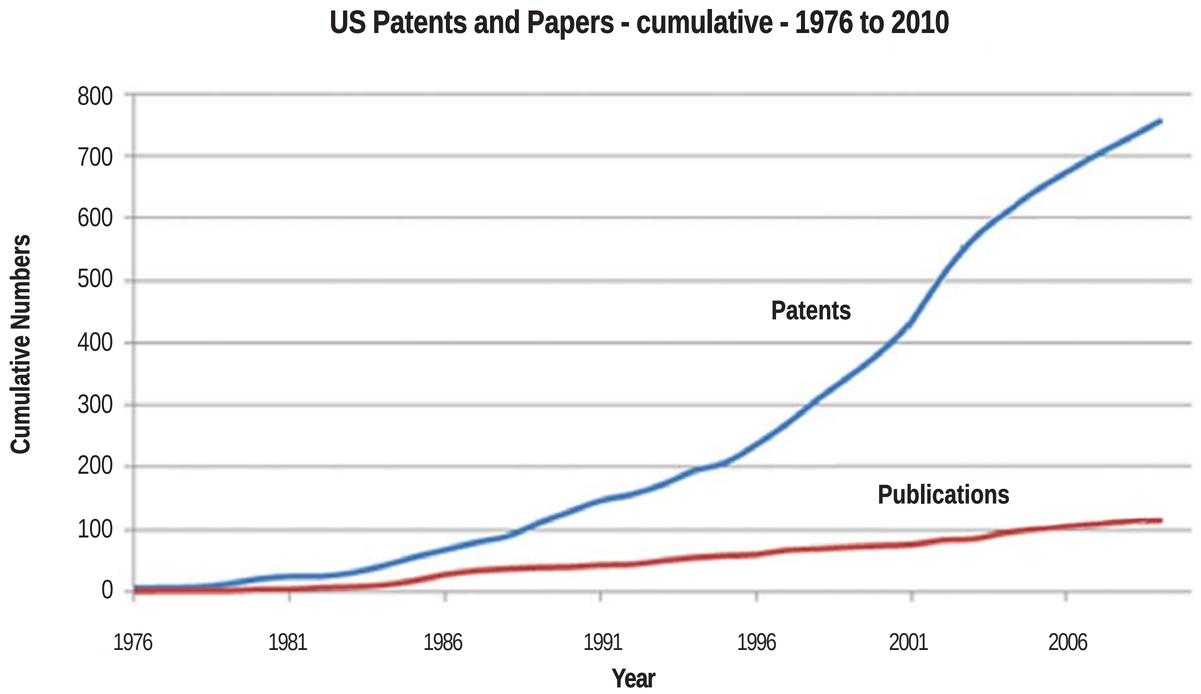

Figure 13: US Patents and Papers – Cumulative – 1976 - 2010

successes or even as soon as the patents are granted or filed, competitors who are in the similar lines of business would have become aware of the potential of this new technology and would try to benefit from this new knowledge. Their responses could take several forms. If they believed that it would be difficult for them to match United Technologies in the single crystal domain, they would try to improve some other parameters of the product. This could take the form of improved alloys, improved fabrication or heat treatment processes, better thermal coatings or even better cooling of the turbine blades. Companies may also try to look for other novel routes to compete with United Technologies in the domain of both DS as well as single crystal approaches so that they could improve their product offerings.

It is fairly clear from the patent and publications record that the potential of single crystal technology at least to the US and the western world had become clear by the period 1978 to 1980. What kind of responses did this evoke among the competitors to United Technologies?

By early 1980 everybody in the turbine and aircraft industry in the western world knew that single crystal blades were about to enter service. The Airbus 300, the Airbus 310, the Boeing 757, the Boeing 767 and the Boeing 747 are all mentioned as aircraft that would use the JT9D-7R4 engine with single crystal blades.[25]

The response of one of the major competitors to Pratt & Whitney, Rolls Royce is captured in the 18th April 1981 issue of Flight International.[26] Under the heading “Rolls to develop 60,000 lb.

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[25] Flight International, 16 February 1980, p 474. Pratt & Whitney engines were in high demand at that time.

[26] Flight International, 18 April 1981, p 1105

RB211" the Programme Director Ferrie of the RB211 engine outlines the response of Rolls Royce to the Pratt & Whitney engine. Ferrie states that the most powerful version of the RB211 the 524D had a 12% better fuel efficiency than the Pratt & Whitney JT9D engines that powered the early Boeing 747s. Rolls Royce had achieved this not by focusing on exotic materials but through paying detailed attention to improved component design. Ferrie goes on to admit that the RB211 does not use DS technology but that improved engines that Rolls Royce has under development may use single crystal technology and would be available in about 5 years time. He admits that "Pratt & Whitney has SC (Single Crystal) Technology sown up till the mid 1980's" but in spite of these developments, the products of Rolls Royce would remain competitive.[27]

It is clear from the above that even in early 1981, one of the big names in turbine engines, Rolls Royce, has not carried out any serious work on DS or on single crystal technology. Their response to the threat posed by the Pratt & Whitney single crystal engine is to try and improve performance through other component technologies.[28] It is also clear that Pratt & Whitney (United Technologies) has a clear four to five year lead over Rolls Royce. The remarks by the spokesman of Rolls Royce also suggest that the United Technologies lead in single crystal technology is not only with respect to Rolls Royce but could also include other competitors like General Electric.

From the patent record we can also see that there is a flurry of activity around the time of the expiry of the first United Technologies single crystal patent in 1998. A number of patents are filed on different aspects of the technology including alloy compositions, casting, heat treatment, thermal coatings, and different modes of making single crystal castings. It is around this time that GE takes over the leadership and becomes dominant once again both in the patent and business arenas.

For the USA, DS columnar grain technology takes about 6 years to progress from invention into a working product. In the single crystal domain too about seven years are needed from the invention of "single crystal" to the commercial use of the technology in an aircraft engine.

During the period of our study the leadership position changes from GE to United Technologies and then reverts back to GE after the expiry of the patents and the knowledge created by United Technologies becoming accessible and replicable.

Companies are the hub of both invention and innovation in the USA. Publicly supported R&D carried out in companies appears to be critical. Patent references are mainly to other company patents. Even in publications many of the key publications are from company personnel. Publications describing some of the key technology developments take place only after the patents are granted. This seems to suggest that commercial considerations and IPR issues are important considerations in the diffusion of knowledge. The role of the Universities at least in this technology area appears to be peripheral.

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[27] Incidentally the first patent in the super alloy single crystal domain of technology granted to Rolls Royce was also in 1981. From the patent record the United Technologies dominance continues till about 1998.

[28] The management literature talks extensively on why many successful companies are not able to respond to major shifts in technology. See Reference 7.

In this realm of technology most of the innovation appears to originate from companies.

5. China's Quest for Self-Reliance in Aircraft Technology

5.1 Historical Setting

Unlike the United States which created the modern aircraft industry, China was a latecomer into the aircraft development and production business.[29] Very early in its history China needed to fight the Korean War for which it needed aeroplanes. China turned to the Former Soviet Union (FSU) for help in creating an aircraft industry in China. Outright purchase of different kinds of aircraft, licensed production and technology transfer all happened fairly early on.[30] After the souring of relations with the FSU the Chinese had no alternative but to go ahead and start doing things on their own.[31] But this association with the Soviet Union did leave a legacy of sorts that still affects the way complex tasks in strategic areas are carried out in China.

Along with the indigenous development of key technologies and products, the Chinese have also gone ahead with licensed production of both aircraft as well as key subsystems like aircraft engines. China has been no stranger to the dilemmas faced by latecomer countries between indigenous development, imports and licensed production. China has bought as well as manufactured under licence a large variety of aircraft from other countries including the FSU and now increasingly Russia.[32]

Though China makes many kinds of aircraft to get an idea of their approach we took a look at the evolution of fighter aircraft in China. China has been in the business of making fighter aircraft for about fifty years. The early fighter aircraft that the Chinese produced were the F-5 and the F-6 which were Chinese produced MIG 17 and MIG 19 Soviet aircraft, the technology of which was transferred to them by the Soviet Union. Their mainstay fighter for many years has been the J-7 - a reverse engineered Soviet MIG 21.[33] Unlike the earlier planes the Soviet Union had not transferred the entire range of technologies and production facilities to the Chinese for this aircraft. It took the Chinese nearly a decade to achieve mastery of the required technologies to produce these planes in some numbers. A number of modifications and changes have been made to this J-7 aircraft over the years to produce several variants.

With a change in US sentiments towards China after President Nixon's visit in 1972, China's access to international products and technologies improved. Companies like McDonnell Douglas,

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[29] Kenneth W. Allen et al "China's Air Force Enters the 21st Century" Rand Monograph MR-580 AF available at http://www.rand.org/content/dam/rand/pubs/monograph_reports/2005/MR580.pdf provides an overview of the development of military aircraft in China.

[30] The original factories for the production of aircraft were located at Nanchang, Shenyang, Harbin, Chengdu and Xian. These locations have been the hubs around which the industry has grown. The purchase from the Soviet Union included all kinds of aircraft – transports, bombers, fighters. However it was only for the MIG 21 that Soviet help included the transfer of knowhow for making the Tumanski R-11 F turbojet engine.

[31] China makes all kinds of aircraft and helicopters for both civilian and military use. Many of them were reverse engineered from FSU designs and production. This is also true for aero-engines.

[32] The more recent acquisitions include the civilian MD-80 and MD -90 from McDonnell Douglas in 1986 as well as the Su 27 and Il 70 from Russia in 1992 and 1993 respectively.

[33] The Chinese fighters are designated with the letter 'J' (Jianjiji). The export versions are designated with the letter 'F'

Boeing and Rolls Royce started doing business with China. Procurement of products and transfer of technologies also took place. Sales of complete planes were followed by transfer of technology and licensed production of both aircraft and their components.

In 1986 the US based company Northrop Grumman signed a deal with China for $550 million to upgrade the avionics for the J-7.[34] This contract was however terminated prematurely after the Tiananmen Square incident. In spite of ups and downs in deals with the US, the Chinese entered into a contract with McDonnell Douglas in 1992 for the licensed production of the MD 88 and the MD-90 civilian aircraft. Reports in the public domain suggest that the Chinese violated several provisions of the end user agreement they signed with respect to the location of some critical machine tools.

Though problems with supply from the US as well as the western world have affected China to some extent, it has over the last twenty years received substantial support from Russia. The end of the Cold War saw the emergence of Russia as a major commercial partner for China. There has been a significant expansion of commercial transactions between Russia and China that covers many strategic areas including the aviation sector. Using Russian help China embarked on a number of advanced aircraft development projects. These include the JF-17 aircraft in collaboration with Pakistan, who is also a major buyer of this aircraft.[35] This uses the Russian RD93 turbofan engine which has been cleared for export to Pakistan by Russia. With early help from Israel and later on from Russia, China has also developed and tested an advanced fighter aircraft termed the J-10. China has also ordered from Russia a number of Sukhoi 27/30 aircraft.

China has started development of a completely indigenous aircraft called the J-11. However information available in the public domain suggests that the J-11 that the Chinese are producing is a Chinese copy of the Sukhoi 27/30 with many of the components being made locally. Russia claims that these Chinese efforts at reverse engineering, is a violation of the original technology transfer agreement.[36]

The J-7, the J-10, a large number of Sukhoi 27/30 aircraft and the indigenous copy of the Sukhoi 27/30 aircraft called the J-11 represent Chinese evolving capabilities in aircraft development and production. Of these the J-10 as well as the J-11 would qualify to be state-of art aircraft. The plan seems to be to replace the imported Sukhoi 27/30 aircraft with their Chinese equivalents and use it to further advance indigenous capabilities.[37]

5.2 The Structure of the Chinese Aircraft Industry

The organisation of the Chinese aircraft industry initially borrowed heavily from the Soviet model. This typically involved a centralised organisation

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[34] http://www.fas.org/man/dod-101/sys/ac/row/fc-1.htm

[35] See the newspaper Dawn “Pak gets six JF-17 Thunder Aircraft”, March 15, 2008 available at http://www.dawn.com/2008/03/15/top8.htm

[36] Avio News, “The Chinese J11-B Fighter Aircraft Threatens Bilateral Relations with Russia” at http://www.scribd.com/doc/38158868/The-Chinese-J-11B-Fighter-Aircraft-Threatens-Bilateral-Relations-With-Russia

[37] http://www.fas.org/programs/ssp/man/rowwpns/china.html provides most of the information on these developments.

structure where five year plans with clear objectives, deliverables and targets were to be achieved. These plans, though using inputs from some of the technology developers working within the military industrial complex, were largely formulated by the top political bosses. The State through publicly funded and supported entities would provide the resources to achieve these targets. The division of work amongst R&D, design, production and operations as well as their coordination were all carried out by "Ministries of Machine Building". For strategically important programmes special high level inter-ministerial as well as political mechanisms for coordination of the complex tasks needed were created. The mechanisms for coordination as well as the organisation of work changed in response to changes in the political system and their perception of challenges arising from global geo-politics.[38] Informal networks of connections as well as family connections had an impact on these activities especially during the Cultural Revolution. In spite of these complications the Chinese have been able to achieve substantial mastery over key technologies and high technology products such as aircraft. However this pedigree of the evolution of hi-tech industries like aircraft does determine to some extent the ability of China to innovate and incorporate radical technology changes into the products or services that it produces through its military industrial complex.

As in the Soviet model each aircraft manufacturing set up has associated with it a set of R&D laboratories, test facilities as well as component and subsystem development and production entities. Originally in the Chinese approach all these were clubbed under one umbrella directly under the control of a Ministry of Machine Building.[39] However in 1993 the Chinese decided to corporatize all of it and created what is called the Aviation Industry of China (AVIC).[40] In 1999 they seemed to realise that in order for true progress and innovation to occur the various corporations needed some kind of competitive pressure. To promote competition they split the original AVIC into two separate companies AVIC 1 and AVIC 2.[41] This was also the time when decision makers in China realised that for China it was not sufficient to catch up with the west. It had to not only play catch-up but it also had to be a pioneer in taking new technology into new products and services and become more innovative as a country. Drawing some lessons from the US, the Chinese tried to leverage the successes they had achieved in the nuclear weapons and missile programmes and extend these kinds of approaches to other key sectors of the economy.[42] Many major players in the nuclear and missile industries went on to

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[38] For details of the organisation of the Chinese military industrial complex in the missile area early period please see John Wilson Lewis and Xue Litai, "China's Strategic Seapower: The Politics of Force Modernisation in the Nuclear Age", (Stanford:Stanford University Press, 1994)

[39] During the early period the 3rd Ministry of Machine Building apparently dealt with Aeronautics.

[40] The two companies between them control over 100 industrial enterprises, 33 Research Institutes and 42 other subsidiary organisations. The 2003 revenue of the two companies was $10 billion and they employed about 450,000 people.

[41] Though this was so, the way in which the work was divided between the two companies ensured that they were both making different products with very little overlap. So even though the purpose was to foster competition in practice a monopoly was converted into two monopolies. Evan Medeiros et al, "A new direction for China's Defense Industry", Evan S. Medeiros et al., Rand Corporation, 2005, Report number MG 334.

[42] One of China's earliest such programmes was called Programme 863. For more details of this programme please see Avio News, "The Chinese J11-B Fighter Aircraft Threatens Bilateral Relations with Russia" at http://www.scribd.com/doc/38158868/The-Chinese-J-11B-Fighter-Aircraft-Threatens-Bilateral-Relations-With-Russia

occupy major leadership position within the military industrial complex of China.[43] In 2008 AVIC 1 and AVIC 2 were again merged back into one entity. Another interesting feature in China, derived in part from the Soviet heritage, is that both AVIC 1 and AVIC 2 make a number of non-aerospace products. They derive more of their revenue from the non-aerospace sector than from the aerospace sector.

From these discussions we can see the special problems that latecomer countries have in trying to catch up and then forge ahead in complex technologies. The military industrial complex has several organisations and institutions that take part in providing the products and services required by the national system. The division of work and the coordination of work are therefore inherently complex. To deal with immediate problems all latecomer countries necessarily have to buy hi-tech products and services from other more advanced countries. These are needed to cope with immediate security threats. If countries aspire to be self-sufficient they also need to make the investments in organisations and people for the development of the required knowledge and capabilities. While some knowledge can be explicitly acquired many aspects of hi-tech products require significant amounts of tacit learning that can come about only by actually doing things. The organisational routines that are required are also quite crucial and this combination of technology and routines which is difficult to define quantitatively is often loosely called "Capabilities" or "Competences" in the management literature.[44] This combination of import and indigenous development creates major dilemmas for the military industrial decision-making system. As a consequence, the ability of the system to take risks and make the necessary choices in new and more radical technologies may be constrained by the system's ability to respond to and deal with such changes. As the system's complexity increases these problems may get compounded especially for a latecomer. While a centrally controlled overall structure dealing with closely coupled and interdependent technologies will promote efficiency and product delivery it may not be so efficient in coping with new challenges and changes that may be required to the overall plan arising from such changes.

These structural features of the Chinese aircraft industry are important for us to understand the ways in which decisions are made within the Chinese military industrial complex and how these decisions affect technological choices that need to be made. This is particularly important for us in our study related to the use of single crystal technology for the making of aircraft engine turbine blades in China.

5.3 Building Capabilities in Aircraft Engines

In the jet engine domain, China has over the years established eight factories and their related component, testing and development institutions. The original Soviet purchase of Soviet planes in

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[43] For a detailed discussion of this theme See Evan A Feigenbaum, "Who is Behind China's High Technology Revolution? How Bomb Makers Remade Beijing's Priorities, Policies and Institutions", International Security, Vol. 24, No. 1, Summer 1999. pp. 95-126

[44] To build an aircraft a number of complex technologies have to be put together. Apart from the hard core technology elements - since the technologies are coupled together tightly in delivering a product or a service - their development and integration pose special problems of organization. Project management capabilities and skills for the development of such interactively and tightly coupled multiple technology products are substantially more difficult than those required for say house construction. This involves a significant component of "learning by doing" which cannot be easily replicated or learnt without actually going through the process.

the 1950's included the MIG 17 as well as the MIG 19 transfer of technology. The technology for producing the power plants might have also been included in this deal. However, as mentioned earlier, the backbone of the Chinese fighter capability for a long time after the withdrawal of Soviet help was the reverse engineered MIG -21 aircraft which the Chinese called the J-7. Soviet help for the J-7 also included the transfer of the technology for producing the after burning Tumanski R-11 F-30 turbojet engine. The Chinese version of this engine is called WP-7. This and variants of this engine have used to power the different variants of the J-7.[45] Chinese efforts to develop their own power plants were apparently not very successful.

In the 1970's China acquired the license and the technology to make the Spey Mk 202 turbofan engines from Rolls Royce.[46] The engine factory at Xian makes these engines under licence. The Chinese version of this engine is called the WS-9.

In 1980 China had identified turbofan jet engines as a strategically important domain of technology and initiated a major Research and Development Plan to make all the key components and sub-systems for an indigenous engine. In 1989 this resulted in China embarking on an indigenous WS-10 Engine development project. This turbofan engine which is also of interest visa vis the single crystal turbine blade development, was to be a state-of art engine incorporating all modern technologies that would be used to power future Chinese aircraft.

In 1983 China managed to procure two numbers of CFM 56 II engines from the United States after getting export clearance. These engines were to be used for upgrading the civilian commercial Trident airliner. There was a big debate within the US for export clearance as the CFM 56 core and the hot sections are identical to F 101-GE-102 engine which powers the F-16 and the B-1B military aircraft. The US exported the engines after imposing stringent conditions for their use.[47] Under the terms of the agreement:

- no technical data was to be transferred with the engines;
- the Chinese were not to disassemble the engines;
- if the Trident retrofit programme had not begun within 1 year of the engines' arrival, the engines were to be repurchased by the manufacturer.

The Chinese offered to retrofit the engine at a Shanghai commercial aircraft facility where GE personnel would be able to monitor Chinese progress. China reneged on the end use claiming the engines were destroyed in a fire accident and probably stripped the engine for detailed study and reverse engineering.

Under the Sukhoi -27 / 30 deal that China has signed with Russia (the Chinese version of this is called J-10) the Russian AL-31 F turbofan engine is also being produced in China.

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[45] China has also set up a number of factories for producing the different kinds of engines that are needed to power the various planes. These are located at Shenyang, Xian, Zhuzhou, Pingba, Chengdu, Harbin, Shanghai and Changzhou.

[46] See www.thenews.com.pk/daily_detail.asp?id=181808

[47] See http://www.access.gpo.gov/congress/house/hr105851/index.htm Report of the Select Committee on U.S. National Security and Military/ Commercial concerns with the People's Republic of China, "Manufacturing Processes: PRC Efforts to Acquire Machine Tool and Jet Engine Technologies" Volume III Chapter 10.l

Other indirect technology benefits accrued to China. In 1986, China Aviation Trade Import Export Corporation (CATIC) obtained the technology of the Pratt and Whitney FT8 gas turbine engine—the deal included joint development, production and international marketing rights. In 1991 an agreement between GE and Shenyang Aero Engine Corporation resulted in the licence manufacture of parts of the CFM-56 engine. This was followed by purchase of LM-2500 a commercial gas turbine engine containing a hot section identical to the more advanced GE F 404 engine. These import, licensed production and reverse engineering efforts went hand in hand with efforts to develop a state-of-art turbofan engine indigenously.

5.4 Building a State-of-Art Turbofan Engine – the History of the WS-10 Development

We present below a brief history of the development of the most recent of the indigenous engine development projects – the WS-10 Engine.

The original purpose of the development of the WS-10 engine was to use it to power the J-10 and the J-11 aircraft both of which were being built with Russian help and both of which use a Russian turbofan engine.

As we had mentioned in the previous section China had identified the turbofan engine as a crucial technology and initiated a major research programme for the development of various components that go into such an engine in 1980. In July 1989, a project for the development of 'Medial Thrust Demonstration Turbofan Core Engine" (MTDTCE) was initiated. This project was identified by the Commission for Science Technology and Industry for National Defence (COSTIND) as one of most important technology projects of the eighth five year plan. This WS-10 engine was developed at the Shenyang Liming Engine Manufacturing Corporation.

The design and manufacture of the test engine was completed in 1991-92. Twenty one Factories and Research Institutes were involved in this effort. The Engine was Ground tested in 1992.

However in spite of completing all the ground tests on the engine in 1992, the first flight test took place only in 2002. The reason cited for this was the non-availability of a suitable aircraft for the Flight tests. The PLAAF did not want to risk the single engine J-10 aircraft that was being developed with Russian help by flying it with an unproven new engine.The WS-10 flight testing had to wait for the twin engine J-11 aircraft - - the Chinese version of the Sukhoi 27 / 30 aircraft - to become available before Flight testing began.

In 2004 there was a failure in the Flight Test. The Flight Tests were completed in 2005.[48]

Though the above chronology suggests a three year project (1989 to 1992) to make the aircraft, a lot of work on the various components and subsystems had preceded this starting from about 1980. It is quite likely that the Chinese gained from assistance provided by Russian engineers. Though inputs from the west were not available, Russia was helping China with the Sukhoi 27/30 licensed production including the power plants. This coupled with the fairly long preparation time from

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[48] Details from http://www.china-defense-mashup.com/this-is-the-real-face-of-taihang-ws-10-turbofan-engine.html

1980 to 1989 might have helped accelerate this process.

The chronology of major events also reveals that though the engine development was completed in 1992 it took at least 10 years for the flight testing to commence. This is a long gap between development and flight testing that seems to point towards a number of internal problems even for a high priority project like the WS-10. This long gap between ground test and flight test seem to suggest technical as well as organisational and institutional problems within the aircraft development ecosystem.

The J-10 was an indigenous development based on Russian technology and used the Russian AL 31 F engine. One of the purposes of the WS-10 turbofan engine development was to use it to power both the J-10 and the J-11. However because of the longer dimensions of the WS-10 the J-10 could not accommodate the WS-10. The obvious reason why the J-10 was not designed for the WS 10 engine was because decision-makers especially from the PLAAF expected major delays in the WS-10 engine. They might not have wanted to link an operational need with a risky development option. Therefore the J-10 was not designed to accommodate the WS-10 whose dimensions were larger than the dimensions of the AL31 F Russian engine. It is surprising to think that the development of the J-10 did not take into account the possible availability of an indigenous engine especially an engine which COSTIND considers to be a major nationally important project. This seems to suggest that there were indeed major problems with the WS 10 project and that the powerful user organization the PLAAF has sufficient clout within the system to rule out the incorporation of a higher risk indigenous power plant into its operational aircraft.

Even if WS-10 was larger it is possible that some changes could be made in the J-10 to accommodate the larger WS-10 especially for the flight testing programme. However it appears that the decision-makers in the PLAAF were not very keen on subjecting the single engine J-10 aircraft to testing with an unproven engine.

Because of these concerns, the flight testing had to wait till the J-11 twin engine aircraft that was also being developed became available. This J-11 was modified to accommodate the WS-10 engine by replacing one of its two original AL31 Russian engine with the indigenously developed WS-10 engine before flight testing could be completed.

Reports also suggest that the PLAAF has also placed a major order with Russia for the import of a few hundred AL-31F engines to take care of their immediate requirements. This seems to suggest that the users still have concerns about the reliability and performance of the WS-10 engine.

It is surprising that a strategically important project like the WS-10 turbofan engine had to wait for ten years before a suitable platform was available for flight testing it. It is also surprising that the design of both the J-10 and the J-11 had been conceptualised without the possibility of incorporating an indigenous power plant at a later stage.

This illustration of how decisions are made on technologically important projects makes it clear that decisions are not always based on straight forward technological considerations. Other factors including geo-political, organizational and power factors do seem to find a place in the way decisions are made within the military industrial complex of China. These events are not different from what happens in other similar placed countries who are trying to play catch up and also want to forge ahead to become leaders in critical domains of technology

This understanding may also give us some insights into the way the Chinese military – industrial complex deals with issues raised by radical technology changes and their absorption by the system. Single Crystal Technology for Aircraft Turbine Blades is one such technology. Let us try to understand what happened to this technology in the development of the WS-10 engine.

5.5 The WS -10 and Single Crystal Technology for Aircraft Turbine Blades

From a perusal of the specifications of the WS-10 engine available in the public domain it is clear that this engine developed by the Chinese only uses Directionally Solidified Columnar turbine blades in the WS-10 engine. This technology is one generation behind the single crystal technology.The available details make clear that the materials used for this are Chinese super alloy compositions with specific Chinese nomenclatures and designations.[49] It is also clear that the WS-10 does not use single crystal technology.[50] Figure 14 provides the window of opportunity available to Chinese decision-makers to catch-up.

As we had mentioned earlier knowledge about single crystal technology and its advantages for use in the hot sections of a turbofan engine would have become common by about 1985. Many western companies both in Europe as well as in the US had already initiated work to catch up with the pioneer Pratt & Whitney.

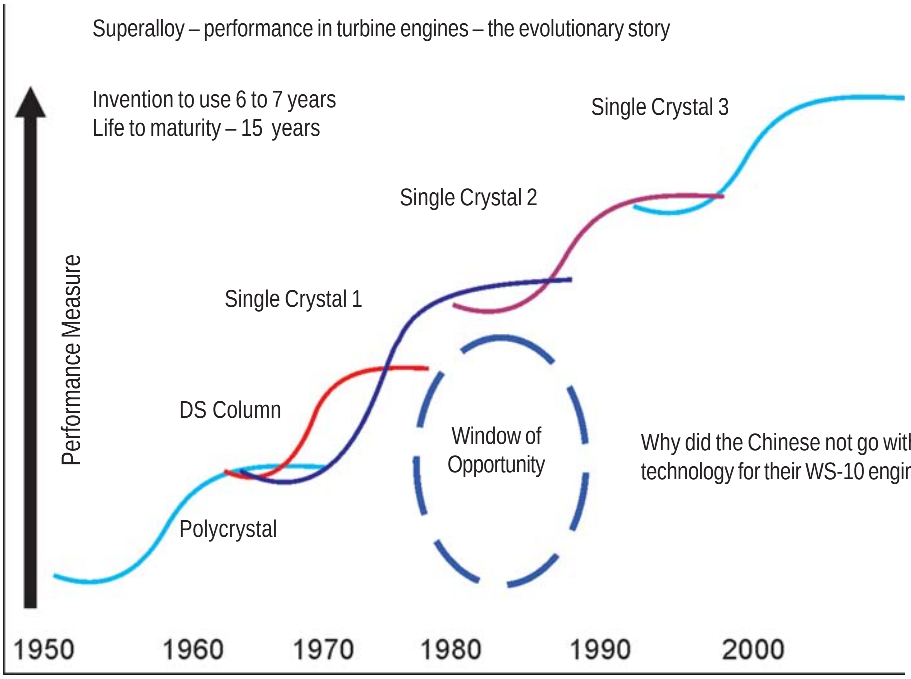

Figure 14: Trajectory of Development in Single Crystal

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[49] The alloys used in the high temperature part is mentioned as DZ125 or DZ125 L. From the literature, only the alloy DD 3 seems to correspond to a single crystal composition

[50] http://www.china-defense-mashup.com/?tag=turbofan-engine

The Chinese have demonstrated great capabilities in tracking key technologies and achieving mastery over them through a combination of imports and indigenous development.

The WS-10 programme was initiated in 1980. Even if knowledge of single crystal technology was not known, Chinese researchers would have soon come to know of it. If this were so the WS-10 programme should have taken cognizance of such a development and incorporated it in some form or the other during the development phase which stretched out over a fairly long period starting from 1980 and going on to almost 2005.

For some reason even though the Chinese had developed capabilities the Chinese decision-making system did not choose to go with single crystal technology.

This does raise certain fundamental issues about the ability of the Chinese system to cope with major changes in technology. To understand this a little bit better we need to understand in more detail Chinese efforts to develop this technology.

6. China & Single Crystal Technology for Aircraft Turbine Blades

As discussed in the earlier Section, China has not been able to design, build and produce a state-of art turbofan engine that uses superalloy single crystal technology. There could be several reasons for such a situation.

It is possible that even after a lot of effort Chinese engineers have not been able to develop the technology to the level required for use in an operational engine.

It is also conceivable that they do have the capabilities in this technology but due to either schedule or budget constraints they have not been able to develop it to the required levels necessary for use. Such development schedule and budget mismatches are normal for countries that are playing catch up since there will always be tradeoffs between immediate short term needs of user agencies and the longer term aspirations of developers and political strategists.

There is also the possibility that given the complex nature of the technology and its link with the military and political systems, development projects are subject to the pushes and pulls of the different power groups within the ruling establishment. These factors also influence the evolution of a particular trajectory of technology.

In the pursuit of our understanding of what happened with single crystal technology for aircraft turbine blades in China and what happened to it we analysed publications and patents data from China using the SCOPUS Database.

6.1 Single Crystal Superalloy Patents in China

As mentioned earlier China does not have any patent on single crystal superalloys in the USA.

As far as patents in China are concerned United Technologies, General Electric and Siemens Westinghouse (all US companies) have been granted patents on single crystals super alloys by China in the years 1987, 1992 and 2000 respectively. These seem to be defensive measures taken by the lead companies in the world to protect themselves in China.

The Institute of Metal Research, Shenyang (IMRS) filed a patent, "Third Nickel base high temperature single crystal alloy in low cost" in China in the year 2005 which was granted in 2007.[51] In the year 2008, Northwest Institute for Nonferrous Metal Research filed a patent "Hexahedron shaped sub-micron Ni core metal compound mono-crystal particle preparation" in China which was granted in 2009.

Patent protection does not appear to be a priority for development activities in China at least in this domain of technology. Clearly the patent scene in China is very different from what happens in the US where both protection of Intellectual Property and defending it aggressively is a key for commercial success. In the absence of a patenting culture, a scrutiny of patents in China offers little help in making an assessment of the status of super alloy single crystal technology for aircraft turbine blades.[52] This makes it necessary to look at the other source of information–published papers.

6.2 Single Crystal Published Papers from China – What Do They Reveal?

Using the keyword "Super alloys AND Turbines" in the SCOPUS Database, we were able to obtain the abstracts of 134 papers published from China during the period 1984 to 2009. There might have been papers published earlier but there could not have been many. We know from other sources that after Soviet help dried up in the early 1960's Chinese put in a lot of effort in reverse engineering the Soviet MIG -21 aircraft which they renamed the J-7. So work on many aspects related to both the production of the aircraft, the engine as well as critical technologies was definitely taking place inside China though this aspect may not be reflected in the papers.

The first Chinese paper that included the terms superalloys and turbines appeared in 1984. Of the 134 papers dealing with superalloys and turbines, 30 papers also referred to single crystals.

The first Chinese paper on single crystal appeared in 1986. It referred to a specific kind of single crystal alloy the DD3. This was followed by a paper that appeared in the Journal of Materials Engineering (Caliao Gongchen in Chinese) in 1993. This was authored by Wang Qingsui and Wu Zhongtong from the Beijing Institute of Aeronautical Materials (BIAM). The paper claims that DD3 is the first Ni based single crystal superalloy developed in China.Following this in 1997, Tang et al. claim that DD3 is comparable to PWA 1480 (the first single crystal superalloy developed by Pratt and Whitney) and that BIAM has been able to produce it at low cost and that it can be used in making aero engine turbine blades. Based on the date of publication of these papers, a time line of single crystal development in China can be drawn which is shown in Table 3.

From Table 3 we can see that the Chinese have been working on three types of single crystal alloys – the DD3 series, the DD4 series and the DD8 series. These may correspond to Generation 1, Generation 2 and Generation 3 single crystal alloys or they could refer to different alloys for use in different kinds of power plants.

From the published papers it appears that Beijing Institute of Aeronautical Materials (BIAM) has been in the forefront of development of single

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[51] www.ipexl.com

[52] The recent Chinese five year plan wants to change this approach. It emphasises innovation as well as aggressive pursuit of IPR. One should expect to see some dramatic developments in this area soon.

crystal in China. It was a part of the AVIC 1 consortium.

SCOPUS does not include many of the Chinese journals in its data base. An independent search on the single crystal development in China showed that a special issue was devoted to BIAM and its work on super alloys in China in the journal "Advanced Performance Materials." This appeared in 1995.

Three papers included in this journal are of particular interest.[53] Yan et al. mention that the single crystal super alloy DD3 has been used as turbine blades for some advanced aero engines. In their paper they also mention that a DS cast alloy IC6 developed by BIAM is a promising material for high temperature turbine blades of advanced jet engines operating in the range of 1000-1100°C.

Chen[54] in his paper "Developments of cast super alloys and technology for gas turbine blades" mentions that "for more than thirty years, a series of advanced performance cast super alloys have been developed for making blades, vanes and other high temperature parts of various aero-engines". There is a reference to DD3 single crystal super alloy which is supposed to have been developed using a method designed by Wu et al. in 1987.[55] The paper also mentions that the DS (Directional Solidification) technique for super alloys was initiated in BIAM in the mid 1960's. Chen goes on to say that the cast turbine blades, including DS and SC (Single Crystal) blades with complex internal air-cooling passage, are widely used for aero-engines in China.

Han et al.[56] in their paper refer to a new Directionally Solidified (DS) Ni_3Al alloy IC6 which has been developed for gas turbine blades and vanes. It is claimed to be a potential material for turbine blades of aero engines.

Many of the journals that were being originally published in Chinese are also now being published in English. The idea seems to that in order to improve international visibility and also to get cited more often you need to publish in English. A survey of the editorial board members in some of the journals clearly suggest that China has collaborations with Japan, Singapore, USA, The Netherlands, South Korea, Canada, UK and Sweden. However the collaborations are mostly with ethnic Chinese living in these countries.

The papers seem to suggest that the development of single crystal turbine blade technology had made significant progress in China starting from the mid 1980's and were being used in the final product.

6.3 Other Information on Single Crystal Technology in China

In 1995 the Asian Office of Aerospace Research and Development (AOARD) in cooperation with Oak Ridge National Laboratory (ORNL), the US Army Research Office, and the Office of Naval

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[53] Yan, M.G., Han, Y.F., Cao, C.X., and Wu, Z.T. "Some recent developments of Advanced Titanium Aloy and Nickel Base Super alloys in BIAM, Advance Performance Materials, 2, 217-229 (1995).

[54] Chen, R.Z. Development of Cast Super alloys and Technology for Gas Turbine Blades in BIAM, Advanced Performance Materials, 2, 249-257 (1995).

[55] Wu, Z.T., Wen Z.Y., and Chen, D.H. "Composition design and experimental study of SC alloy", Acta Metallurgica Sinica, 23 (4): B171, 1987.

[56] Han, Y.F., Wang, Y.M., and Chaturvedi, M.C. Strengthening in a DS casting Ni_3AL Base Alloy IC6, Advanced Performance Materials, 2, 259-268 (1995).

Table 3: Time line of Ni Based Single Crystal Superalloy Development in China

Year	Journal	Item	Author Affiliation
1986	Conference Proceeding	Creep Behaviour of Ni based super alloy (DD3)	Beijing Institute of Aeronautical Materials (BIAM)
1993	Journal of Materials Engineering (Cailiao Gongcheng)	DD3 Single crystal Super alloy is mentioned in a publication	Beijing Institute of Aeronautical Materials (BIAM)
1995	Act Optica Sinica (Guangxue Xuebao)	Review of Single Crystal Super alloy development in China	Beijing Institute of Aeronautical Materials (BIAM)
1996	Theoretical and Applied Fracture Mechanics	Life study of DD3 Single Crystal turbine blades is discussed	North-Western Polytechnical University Xian (NWPUX)
1996	Journal of Propulsion Technology (Tuijin Jishu)	Calculation of Strength and life of a Single crystal turbine blade	North-Western Polytechnical University Xian (NWPUX)
1997	Journal of Materials Engineering (Cailiao Gongcheng)	Review	Beijing Institute of Aeronautical Materials (BIAM)
1997	Journal of Materials Engineering (Cailiao Gongcheng	Comparative Evaluation of DD3 and PWA 1480	Beijing Institute of Aeronautical Materials (BIAM)
1999	Acta Metallurgica Sinica (English Letters)	Creep study of DD3	Beijing Institute of Aeronautical Materials (BIAM)
1999	Journal. Of Aeronautical Materials	DD402 Single Crystal Super alloy introduced	Chinese Iron & Steel Research Institute (CISRI)
2001	Chinese Journal. Of Aeronautics	DD3 – Strength and life of anisotropic Single Crystal blade	Zhuzhou Aviation Powerplant Research Institute(ZAPRI)
2002	Chinese Journal Of Aeronautics	DD3 – Life prediction models	NWPUX and Aviation Institute Zhuzhou (AIZ)
2003	Scripta Materialia	DD8 new super alloy single crystal Thermal mechanical fatigue of DD8	Institute of Metal Research, Shenyang (IMRS) & Korea Advanced Institute of S&T (KAIST)

Research cosponsored an International Workshop on Ordered Intermetallic Alloys and Composites in Beijing, China. This team visited a number of research institutions in China. These included the North-Western Polytechnical University Xian (NWPUX), North West Institute for Nonferrous Metals, Institute of Metals Research Shenyang (IMRS), Shanghai Jiatong University (SJTU), Beijing University of Astronautics and Aeronautics (BUAA), University of Science &Technology Beijing (USTB) Chinese Iron & Steel Research Institute (CISRI) and Beijing Institute of Aeronautical Materials (BIAM).

On the Chinese Iron & Steel Research Institute (CISRI) they have the following comment "In super alloys, they are involved in the R&D; and production of Fe, Ni, Co, based super alloys, in the wrought, cast and Powder Metallic (PM) forms. In cast super alloys, this includes polycrystalline, directionally solidified (DS) and single crystal turbine blades and vanes"

Their comment on the Beijing Institute of Aeronautical Materials (BIAM) states "BIAM has 22 labs, including the National Key Laboratory of Advanced Composites. BIAM operates 13 small to medium size aerospace materials production lines, and some 20 jointly owned factories…….”

They then go on to say “BIAM’s processing and production capabilities and equipment are impressive for a research institute, having the capability to not only research new alloys and processes, but take them through to limited production in such areas as conventional, DS and single crystal investment casting, isothermal forging, PM fabrication, and super-plastic forming technology”.[57]

This makes it clear that at least two of the major research centres in the area of interest to us had the capabilities to research, develop and produce single crystal turbine blades in 1995 though we may not be very sure when they acquired the capability to do so.

If this were indeed so in 1995 it is puzzling to understand why these technologies that obviously were being researched and developed for quite some time before 1995 were not included in the development of turbine blades for China’s state-of–art WS10 engine that was also under development during this period.

6.4. Networks of Knowledge – Collaboration and Competition in China

As mentioned earlier there are 30 papers related to super alloy aircraft turbine blades using single crystals published in both international and Chinese journals by researchers from various China based organisations during the period 1986 to 2009.

These papers were scrutinised to look at various organisations within China carrying out research in this domain as well as various research collaborations these organisations had with other entities both inside and outside China.

Figure 15 presents an overview of the papers published by these entities including their

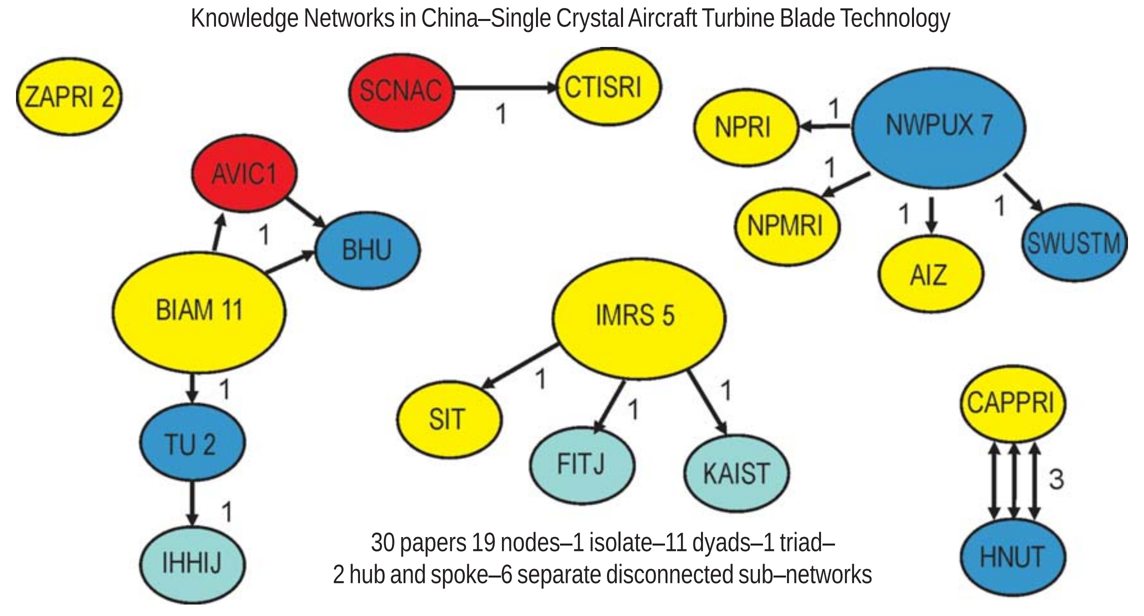

Figure 15: Knowledge Networks in China – Single Crystal Aircraft Turbine Blade Technology

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[57] From a Report submitted by Capt. Paul McQuay, accessed from http://www.fas.org/nuke/guide/china/contractor/9514.html

collaborations. The number of papers and the number of collaborative papers are both presented in this figure.

There are a total of 19 organisations carrying out research in this domain of knowledge. Out of these, three are entities located outside China. There is no significant collaboration with the USA.

There are nine institutes of research, 5 universities, two companies and 3 foreign research institutes in this network.

There are six distinct and separate unconnected components of this network. The two largest sub-networks have five nodes each followed by a sub-network of 4 nodes, two networks of two nodes each and one entity with no collaboration.

Zhouzhou Aviation Power Plant Research Institute located at Zhouzhou, (ZAPPRI) is isolated and does not have any joint papers with any other entity in the network.

South China Aero-motive Company, (SCNAC), Zhouzhou, and Central Iron & Steel Research Institute (CTISRI) located at Beijing have one joint paper that links them.

China Aviation Power Plant Research Institute (CAPPRI), Zhouzhou, and Hunan University of Technology, Zhouzhou, have three joint papers together but no papers with any other institution.

Beijing Institute of Aeronautical Materials, (BIAM) with 11 papers is a major node. It has one paper in which both Beihang University located at Beijing as well as the Aviation Industry of China 1 (AVIC 1) at Shenyang are joint authors. This is the only evidence of collaboration involving three (more than two) organisations in the network. BIAM also has one paper with Tsinghua University (TU), Beijing. Tsinghua University in turn has a joint paper with IH Heavy Industries Japan (IHHIJ). BIAM is a part of the AVIC 1 group and appears to be the major player in this sub-network.

The second major node in the network is the North Western Polytechnical University X'ian (NWPUX) with 7 papers. Of these seven papers 4 are collaborations with other entities. Three of these papers are joint collaborations with the Nanhua Power Machine Research Institute (NPMRI), Zhouzhou, the Nanhua Power Plant Research Institute (NPRI), Zhouzhou and the Aviation Institute Zhouzhou (AIZ) respectively. The fourth collaborator is South West University of Science & Technology, Mianyang (SWUSTM). NWPUX is a major node with the others linked to it and not directly to each other through a hub and spoke configuration.

The third major node in this network is the Institute of Metals Research Shenyang (IMRS) with five papers. This seems to be a node that specifically looks at working together with other research organisations outside China. Two of its collaborations are with Fukuoa Institute of Technology Japan (FITJ) and S. Korea Advanced Institute of S&T (KAIST). The third collaboration is with Shenyang Institute of Technology Shenyang (SIT).

Seven of the collaborating institutions are located in Zhouzhou. Four of them are located in Beijing with three of them in Shenyang. There are 3 foreign collaborating institutions and one institution each in Xian and Mianyang.

The Chinese single crystal knowledge network has the following structural features:

Isolates or entities with no collaboration – 1

Number of two entity collaborations or Dyads – 11

Number of three party collaborations or Triads – 1

Higher order collaborations - none

Each of the major nodes (BIAM, NWPUX and IMRS) represents a different power centre with a largely hub and spoke structure. They are not connected to each other. Research Institutes dominate the network followed by Universities. The role of companies appears to be minimal with only two of them directly represented in this network.

6.5 The US Single Crystal Knowledge Network

There were 115 papers published in the United States between 1970 and 2009 that included the terms "super alloys", "turbines" and "single crystal". Of these 6 papers did not have any clear institutional affiliation leaving 109 papers in our data sample.

These 109 papers were produced by 45 different entities. 43 of the 45 entities were US based while two of them were based outside the United States in Germany and Japan.

Of the 43 US based entities 18 were companies, 19 were educational institutions (either Institutes of Technology or Universities), four are government supported research laboratories and two of them are government supported mission research agencies.

Fifteen of the 45 organisations have no collaboration with any of the other nodes in the knowledge network. Eight companies out of 18 do not collaborate. Five Universities out of 19 do not collaborate.

There are three other network components that are connected but separate from the largest component sub-network. Georgia Institute of Technology has a total of five papers one of which is in collaboration with Washington State University (WSU). WSU in turn has another paper with a company Special Metals Corporation (SMC). These three entities linked by WSU constitute the first sub-component of the US network.

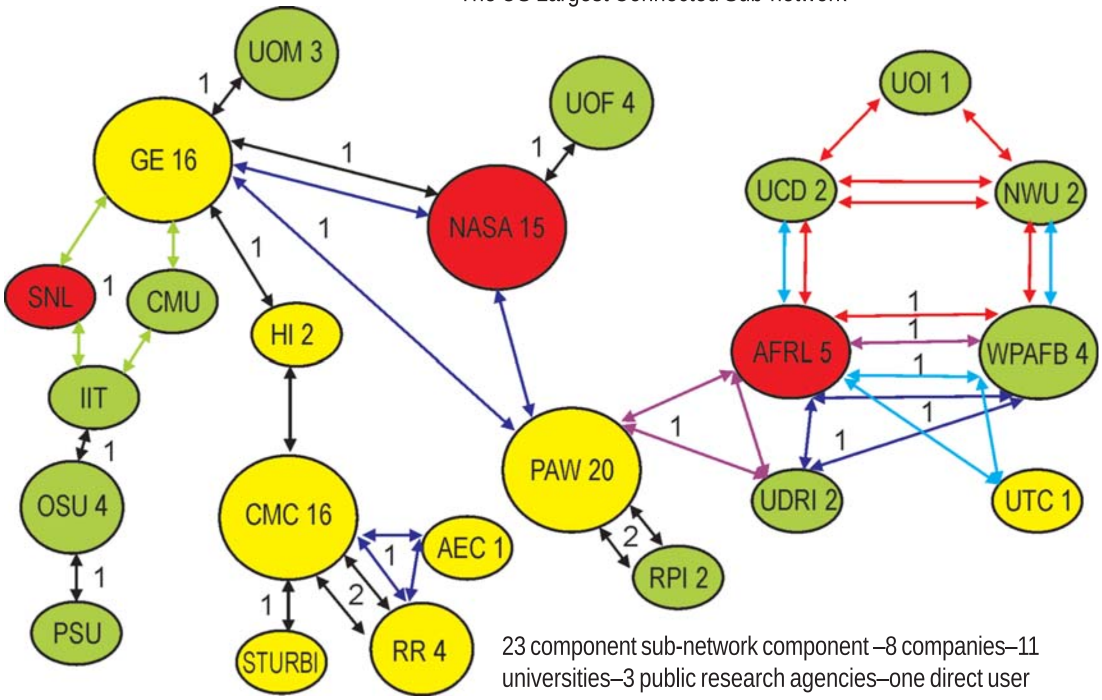
The two other unconnected components involve two organisations each. The Oak Ridge National Laboratory (ORNL) has a total of 3 papers with one joint paper with the German Aerospace Agency (DLR).

The third dual collaboration is between the University of California at Los Angeles (UCLA) and a company Universal Analytics Incorporated (UAI) with one joint paper.

The remaining 23 nodes are all connected with each other through some form of collaboration. Figure 16 provides the details of this 23 node component of the US network.

The major nodes in the above component network are Pratt & Whitney (PAW) with 20 papers, General Electric (GE) and Canon Muskegon Corporation (CMC) with 16 papers each, and NASA with fifteen papers. The Air Force Research Laboratory (AFRL) and the Wright Patterson Air Force Base (WPAFB) with 5 and four papers are also key links in the network. Another company Rolls Royce with four papers is also a player.

The US Largest Connected Sub-network



23 component sub-network component –8 companies–11 universities–3 public research agencies–one direct user

Figure 16: The Largest Component in the US Knowledge Network - Single Crystal Aircraft Turbine Blade Technology

Of the 23 nodes in this largest component of the network, 8 are companies, 11 are Universities, three are public research entities engaged in both mission specific as well as general research in aviation/aeronautics. The Wright Patterson Air Force Base is also a key node.

AFRL and WPAFB are strongly connected. They are also linked to the University of Dayton Research Institute (UDRI). Through UDRI they are linked to Pratt & Whitney (PAW) through a 3 party paper. andto Universal Technology Corporation (UTC) through another three party papers. They are also linked to the University of California Davis (UCD) and North Western University (NWU) and the University of Illinois (UOI) through four and five party joint papers. AFRL, WPAFB and UDRI are all Dayton based. Amongst the various nodes in this component network these seem to be the most well-connected and coordinated network driven by the Dayton-based Air Force organisations. UDRI is the key node that links this closed ring to the rest of the nodes. If UDRI is removed this connected sub-network splits into two major unconnected components.

Pratt & Whitney (PAW) has a fairly strong link with Rensselaer Polytechnic Institute (RPI) with two joint papers.

Canon Muskegon Corporation (CMC) and Rolls Royce (RR) are strongly connected and together linked to another engine company Allison Engineering Company (AEC). CMC is also linked through one joint paper with Solar Turbine Inc. (STURBI). Honeywell International (HI) links CMC with a major node General Electric. If Honeywell International is removed the network breaks down to two separated components.

NASA, a major node, links two big companies GE and PAW through one three-party paper. If this three party link is taken out the larger network breaks down into two separate unconnected networks. Apart from the three-party paper that NASA has with PAW and GE it also has one additional paper with GE. So comparatively NASA and GE are fairly well connected. NASA is also weakly linked to University of Florida which has a total of four papers.

Apart from the one paper with Honeywell International(HI), GE has a four party paper with Carnegie Mellon University (CMU), Illinois Institute of Technology (IIT) and Sandia National Laboratory (SNL). GE also has one paper with University of Michigan (UOM) which has a total of 3 papers.

Ohio State University with four papers is also a fairly big producer of papers. It is very weakly linked to the GE node through IIT. It also has one paper with Princeton University (PCU).

An overall assessment of this largest component of the US network reveals the following features:

- There is one very closely coordinated and centrally directed closed ring under AFRL and WPAFB. Through UDRI they are linked to the larger network especially to companies.
- Canon Muskegon Corporation (CMC) and Rolls Royce (RR) are strongly linked. They are also linked to Allison Engine Corporation (AEC).
- GE is linked with NASA which also provides a weak link between GE and PAW. Honeywell International provides a weak link between GE and CMC.
- PAW is also fairly well connected to Rensselaer Polytechnic Institute (RPI).
- In terms of linkages with Universities and Research Institutes there does not appear to be any major difference between GE and PAW.
- UDRI, Honeywell International (HI) and NASA are the key links that make this network remain connected.
- The largest component of the US knowledge network - with the exception of the AFRL / WPAFB and the CMC / RR / AEC rings -appears to be a fairly weakly connected network.

6.6 Comparative Evaluation of the Knowledge Networks in China & the USA

There are two aspects along which we need to compare these knowledge networks related to “super alloy”, “turbine” and “single crystal”. Since knowledge in this particular case relates to the production of papers we need to understand who produces these papers and how many of these papers are produced by individual organisations and how many are produced jointly with other organisations.

The second aspect requiring attention are the specific structural features of the network which will provide some idea on the nature and kind of linkages that different organisations have within the network.

Based on these comparative evaluations we can then make some inferences about the two knowledge networks. Tables 5 and 6 provide details of the knowledge networks of China and the USA based on these aspects.

Companies and Universities dominate the US Knowledge Network. Publicly supported Research Organisations and Foreign Collaborators are relatively small components of the overall knowledge network.In contrast Publicly-supported Research Organisations dominate the China single crystal scene with universities playing an important but secondary role. The role of companies in the Chinese knowledge network appears to very much smaller than in the US network.

The data also makes clear that the Chinese network has much more collaborative work (47% of all papers) going on than the US network where only 22% are collaborative papers and 78% are single institution papers.

Table 5: Knowledge Generation in China & the US

Parameter	China	%	USA	%
Network size - nodes	19	NA	45	NA
Number of papers	30	NA	109	NA
Number of single institute papers	16	53%	85	78%
Number of collaborative papers	14	47%	24	22%
Number of papers per node	1.58	NA	2.42	NA
Number of papers per year	2.14	NA	3.63	NA
Number of companies	2	11%	18	40%
Number of Universities	5	26%	19	42%
Number of Research Organisations	9	47%	6	13%
Number of Foreign Collaborators	3	16%	2	4%

Table 6 provides details on the structural features of the two knowledge networks.Table 6 reiterates the point and makes clear once again that the US network is more individualistic and less collaborative than the Chinese network. Companies dominate the US network whereas publicly supported Research Institutes dominate the Chinese scene.

Table 6: Knowledge Diffusion in China & the US

Parameter	China	%	USA	%
Network size - nodes	19	NA	45	NA
Number of major nodes	3	15.8%	7	15.7%
Number of unconnected components of the network	6	NA	18	NA
Size of the largest network component (number of nodes)	5 nodes	NA	23 nodes	NA
Number of isolates	1	5.3%	15	33.3%
Number of two-party links	11	6.4%	16	1.6%
Number of three party links	1	0.1%	5	0.04%
Number of four party links	0	0%	2	~ 0%
Number of five party links	0	0%	1	~ 0%
Two party or more connections Total	12	6.5%	39	1.7%
Density of the network	0.094	9.4%	0.051	5.1%
Number of patents	Small		1775	

The largest component of the US network is a 23 node sub-network whereas the corresponding components in China are two 5 node networks. Since the power of the network increases as the square of the number of nodes, the US network is several orders of magnitude more powerful than the Chinese network in terms of the diffusion of information and ideas.

To get a better understanding about the differences between the US and China in this domain of knowledge we also tried to understand how the US ecosystem evolved historically. We choose to divide the US knowledge network into two parts – a period up to 1990 that coincides with the approximate period of the expiry of the first single crystal patent–and the period after 1990. The comparison of the structural features of the US network up to 1990 with the current Chinese network may be more appropriate given the different historical settings of these two countries.

The US published 32 papers during the period 1970 to 1990. The major nodes were NASA with 12 papers, PAW with 8 papers CMC with 3 papers including one collaborative paper with Honeywell International and a number of other players contributing individually. A special feature of the network up to this time is that it does not exhibit even the very loose connectedness that is revealed in 2010. Each of the major nodes and all the smaller nodes are working independently with the only exception being provided by the joint paper between Honeywell and CMC.

Tracing this evolution further, GE becomes a node only in 1992 when it publishes its first paper. The joint paper produced by AFRL, UDRI and PAW (see Figure 16) was published in 1999 and the PAW / NASA / GE joint paper is put out in 2004.

This makes it clear that the US network has emerged from a very strongly individualistic and competitive orientation to its current status of a loosely connected set of very dominant players. This evolution of the US network is consistent with the maturing of the industry and the slowing down of the growth in the market for the current offerings of the aircraft industry. These collaborative initiatives in knowledge reflect the larger consolidation and cooperation that is taking place between the major players in the US market.

This also reiterates in a sense the major differences between the US and China in the organization of their respective ecosystems of knowledge and innovation. In contrast to the US network which is individualistic, competitive and driven by companies the Chinese network is collaborative, top down and driven by publicly supported research institutes.

Figures 17 and 15 and Tables 4 and 5 substantiate the company driven market oriented individualistic approach of the United States eco-system of knowledge generation and diffusion in contrast to the State sponsored Research Institute driven eco-system of knowledge generation and diffusion in China.

Having understood the process of knowledge generation and diffusion in China and the US as revealed through the published papers route it is time for to integrate the different insights into a cohesive picture of how knowledge gets generated and transmitted within the knowledge ecosystems of China and the US. This may help us better understand Chinese capabilities in Science & Technology and how these capabilities get translated into value-added products and services.

7. Ecosystems of Innovation – Comparing China & the US

7.1 Technology & Products – Overview of Happenings in China & US

It is clear from the analysis carried out so far that China had identified the development of a high thrust indigenous turbofan engine as a key element in their strategy by 1980. Development work on the related super alloy materials including the single crystal route for the making of the turbine blades had also begun around the same time.However the WS-10 indigenous engine that they have developed and qualified by about 2005 did not incorporate the single crystal technology in the turbine blades of this engine. The blades were made with the earlier generation DS columnar grain technology.

The recently developed J-10 aircraft and the J-20 Stealth Fighter use Russian supplied power plants and not an indigenously developed engine.

These developments seem to suggest that in spite of a lot of effort China's ability to build a state-of art-engine incorporating key component technologies such as single crystal super alloy turbine blades has not matured to the level where it can be incorporated into a product that can be produced and used in large numbers.

Independent assessments going back to the mid-nineties by US experts as well as claims made by Chinese researchers in the technical literature seem to suggest that researchers have been able to satisfactorily resolve the knowledge problems associated with single crystal technology. If this were indeed so, it is surprising that this technology has not been incorporated into the WS-10 engine even after more than twenty years of development effort.

In contrast the same single crystal aircraft turbine blade technology and other similar technologies went from invention to innovation in the United States within a period of six to seven years. Other countries in the west as well as Japan and the former Soviet Union were also able to catch up and match the pioneer within the space of a few years.

Though the historical contexts between China and the US within which these developments have taken place are different, a clearer understanding of the way in which technologies used in hi-tech dual use products are identified and pursued to fruition may be of interest.

7.2 Framework for Comparison of Country Capabilities

There are a number of frameworks in the business strategy literature that offer some insights into these aspects. One such framework uses a product or industry life cycle model that is interactively coupled to a technology life cycle model and an organisation choice model. Since technological change is exponentially increasing, the ability of organisations and networks of inter-connected organizations to deal with change are often constrained by organizational, political and economic factors.

The historical setting within which countries and organisations within these countries make decisions also affect in some form the ability of a country and its military industrial complex to respond to emerging challenges. To deal with these kinds of problems, models that are based on "interactively coupled", " open system" "dynamic" approaches may provide superior insights into the phenomena we want to study – the ability of follower countries to catch-up and match the more advanced countries in strategic dual use technologies.

Figure 17 provides an overview of the choices that China faced in trying to catch-up on single crystal super alloy turbine blades technology.

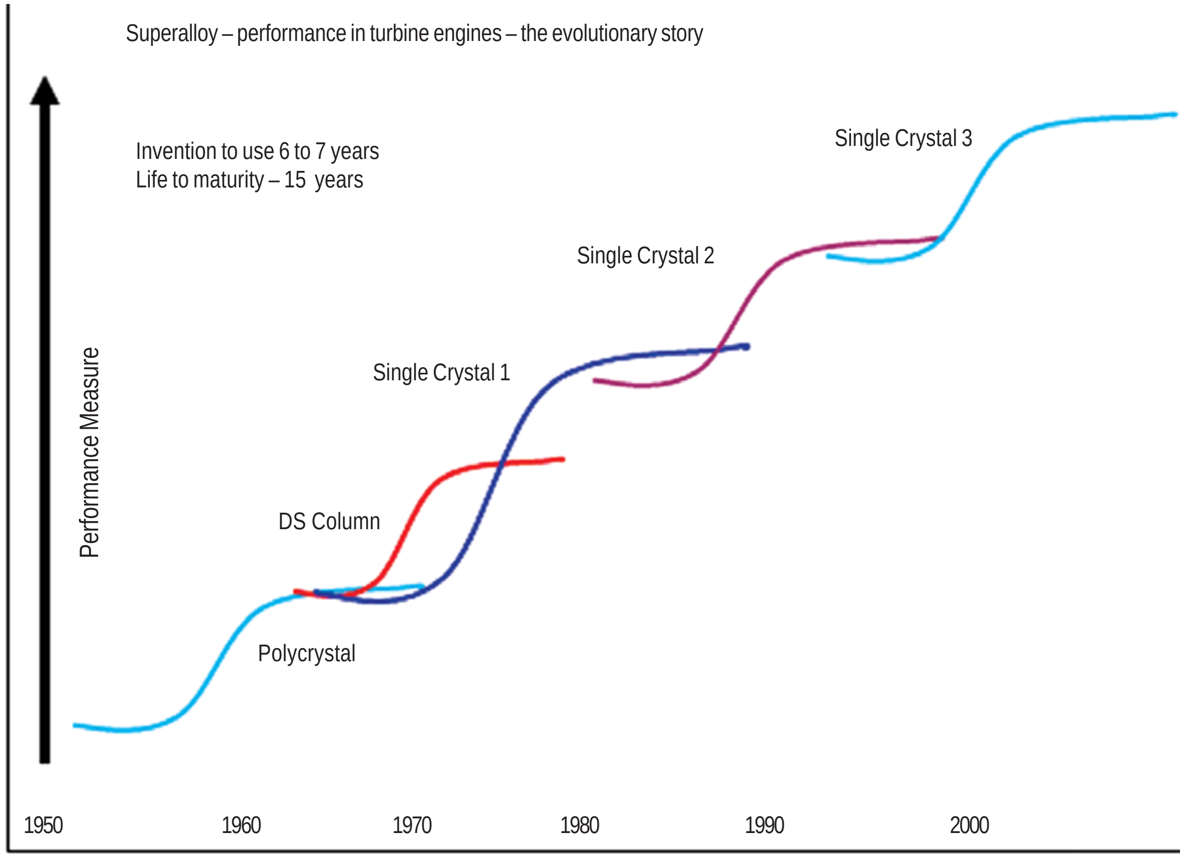


Figure 17: Trajectories of Development

One way for a country or even a company to catch-up with the leader is for it to move faster and skip an entire generation of technology. In the case of the aircraft turbine blade technology for China this would mean skipping the Directionally Solidified (DS) columnar technology and directly moving to the next generation single crystal technology. For such a choice to be exercised the following conditions may be necessary:

- There must be experts within the ecosystem who have been tracking and working on the more advanced technology.

- There must be reasonably powerful champions within the ecosystem who understand the potential of the new technology and who are able to bring in the required resources to take it forward.

- Finally there must be decision-makers at the higher level who are able to and sometimes forced to take the risks associated with the new and more uncertain trajectory of the emerging technology.

If there are major constraints that a country or organisation faces – such as export restrictions or bans - then all three components may work in tandem. Such constraints could often force engineers to go back to basics and come up with different approaches to the solution of technological bottlenecks that they face. Both middle level and top level decision-makers are also more amenable to new ideas and approaches.

The challenge to the Chinese ecosystem based on our review of aircraft, aircraft engine and single crystal aircraft turbine blades can be conceptually presented in the Figure 18 below.

7.3 A Comparative Evaluation of the US and China Ecosystems

We can see that the development of the WS-10 engine that took place between 1980 and 1990 provided a window of opportunity to the Chinese aircraft development ecosystem to bypass the earlier generation DS technology and go directly for the single crystal technology. Papers available in the technical literature as well as independent evaluation by outside entities suggest that the Chinese had achieved substantial capabilities in this domain between 1984 and 1995. In spite of this supply side technological capability the Chinese decision-making system was not able to take the additional risk of going with a newer technology. Even if it was difficult for Chinese top-level decision makers to exercise such a choice early in the development of the WS-10 engine, the decision to go with the earlier generation DS columnar grain technology could have been reversed as development and capabilities in the pursuit of single crystal technology gained momentum and the risks became lower. Even this did not happen over the approximately 25 year development and qualification cycle of the WS-10 engine.

The US and the other advanced countries do not appear to have such a problem. This is because their ecosystems are not playing catch-up. Technological bottlenecks and solutions to such

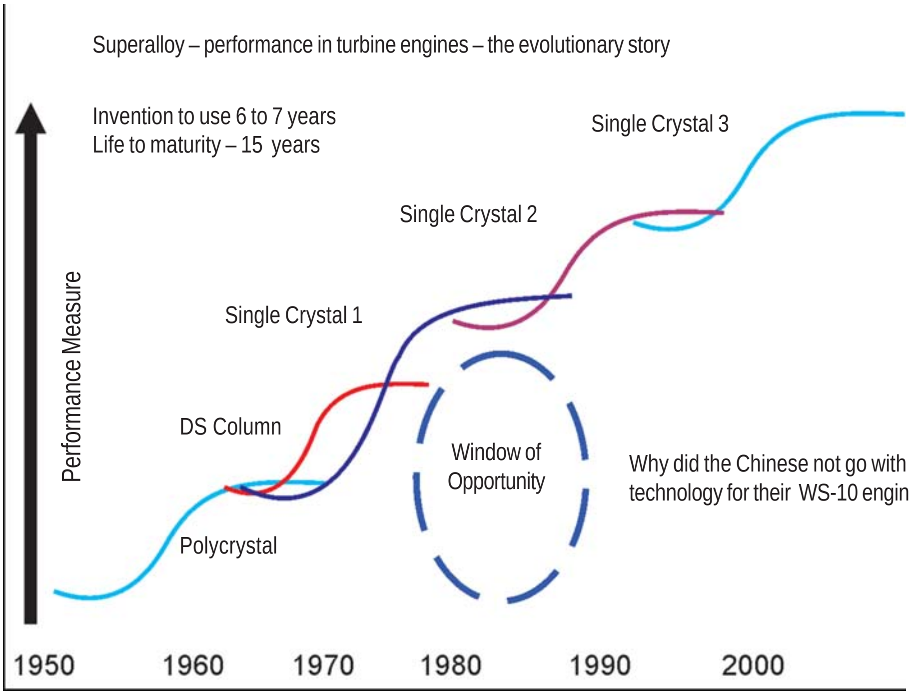


Figure 18: Window of Opportunity for China

bottlenecks are relatively clearer for such advanced technology powers and the trajectory of evolution of technologies and their incorporation into products and services is a logical result of an evolutionary process in their respective ecosystems. Knowledge developed somewhere within their ecosystem, if found useful, is assimilated by other entities who bring in new variations of the knowledge into the ecosystem. Competition in every level of the aircraft engine development and production value chain is a critical element in the ecosystems ability not only to create a lot of technological opportunities but also to pick from this basket of choices those technologies that have the maximum potential to push the envelope of performance of the product. The US system is of course the biggest and the most powerful of these ecosystems. But the ecosystems of other countries in Europe, Japan and even Russia seem to be able to play catch up fairly quickly.

Our analysis clearly reveals that though the technological supply side of the Chinese aircraft engine development ecosystem had the capabilities to make a single crystal super alloy turbine blade, the larger political and economic side of this system was unable to take the decision to incorporate this capability into the WS-10 engine.

This seems to suggest that there are fundamental differences between the Chinese and the US ecosystems for the development and use of complex high technology dual-use products. We will try to draw upon the different strands of our analyses to make comparisons between the Chinese and US ecosystems. We will use the results of our analyses to also address the question of China's ability to respond to and manage technology-driven innovation.

The US ecosystem as revealed through both patents and published papers is a much larger ecosystem than the Chinese ecosystem. Our knowledge networks analyses based on published papers suggests that the US is a 45 node ecosystem whereas China is only a 19 node ecosystem. There is obviously a major difference in scale between these two systems. Our patent data on the US system reinforce these inferences.

The Chinese knowledge network has fewer major nodes and these nodes are not connected to each other. In contrast the US network has more major nodes and many of these nodes are loosely connected to the other nodes. This would suggest that the Chinese knowledge networks are more tightly coordinated and managed than knowledge networks in the US. The Chinese system appears to be a more top down planning driven system than the more bottom-up competition driven US system.

The largest connected component of the Chinese knowledge network has only 5 nodes. The largest connected component of the US network has 23 nodes. This reinforces the large difference in scale between the two ecosystems. It also suggests that knowledge generated anywhere within the US network is able to diffuse relatively quickly to the other nodes in the network. Knowledge generation and diffusion within the Chinese network would not be as quick or rapid as in the US system.

The Chinese network is much more collaborative than the US network which is much more individualistic. The percentage of collaborative papers in the Chinese network at 47% is much higher than the 22% in the US network. The percentage of dyads and triads (two and three party collaborations) in the Chinese network of 6.5% is far greater than the percentage of dyads and triads in the US network which is 1.7%. The density of the Chinese network is 0.09 which is much higher than density of the US network which is 0.05. These substantiate the greater individualistic nature of the US knowledge network as compared to the more collaborative Chinese network.

Even the current loosely coordinated US network that is there has evolved from a significantly more individualistic and competitive past. Since China is currently where the US was about 20 years ago, this reveals the stark contrasts between the two systems. Taken together these differences indicate that the Chinese network is made up of clusters of coordinated top down activities with the clusters themselves not being connected. The US network on the other hand is much more loosely coordinated or individualistic with many of them very weakly connected to other nodes in the system.

The composition of the generators and users of knowledge are also different in the two systems. Companies are the major nodes in the US network. Though Universities also figure as major players in the US they are not significant nodes in the system. They are linked loosely to companies or to publicly funded research institutions or function as independent entities.

The early patents make clear that breakthroughs in both DS as well as single crystal technologies occurred at the research laboratories of companies and not in universities or publicly funded research institutions. The US culture also values patents much more than publications at least in this domain of knowledge with the number of patents exceeding the number of publications. Patents also precede publications in the US indicating that Intellectual Property Rights have high value in the ecosystem. China on the other hand does not seem to set much value on patents. The emphasis is more on papers rather than on patents.

The major players in the Chinese system are government supported research institutes like the Beijing Institute of Aeronautical Materials (BIAM) or the Institute of Metals Research (IMRS). Though there are two companies one of which is the Aviation Industries of China 1 (AVIC1) they do not seem to figure prominently in the knowledge network.

Though Companies dominate the innovation landscape in the US, our study reveals that many of the pioneering companies had received critical risk reducing R&D support from a number of government-supported mission & R&D organizations. Our review of the Patent record reveals this fact clearly. The role of the various arms of the defence forces seem to be particularly important in supporting early R&D that offer promise for the removal of technological bottlenecks. The US appears to be particularly well-endowed in this aspect since there appear to be several independent entities in the ecosystem that support such risk reducing initiatives. Though China may also have several such schemes to support early risk reducing R&D they may be more centrally coordinated and may not be really independent of each other. Clearly the US scale of operation stemming from its status as a global player that wants to preserve its dominant role in world affairs enables it to be particularly munificent in supporting several such independent initiatives. What our study revealed through our analysis of the early patents is reinforced in our knowledge network analysis of the US system. In this knowledge network we can see that the role of the various Air Force related research and operational units and NASA in providing critical links even between competing companies like GE and PAW. The US therefore appears to have a competitive market for the support of new ideas. The Chinese have tried to emulate this US practice with several different approaches for the promotion of new technologies such as the 863 Plan. Such efforts might help improve the supply side but without a commensurate change in the demand side such initiatives by themselves may not contribute in a major way to the realization of value.

Apart from multiple sources for critical R&D support during the early phase of technological development, the US also has many independent buyers for high technology performance enhancing products. So for a company trying to promote a novel performance enhancing technology there could be several potential buyers for the new product. The single crystal development period in the US coincided with a major unprecedented expansion of the national security system. The US had a number of independent buyers many of whom were willing to pay a premium for performance enhancing products. Companies that came up with path-breaking responses to challenges faced by the national security establishment could therefore have several potential buyers for their products. This significantly reduces market risk for companies promoting such technologies.

The other characteristic of the US system is that once the technology has been demonstrated in a military system that often involves some form of subsidy, it moves from the security domain into the domain of civilian applications without any major problems. Companies like Boeing, Lockheed, Grumman, TRW and many others that compete with each other have been able to do this for aircraft. GE, PAW, Rolls Royce and several others have done this successfully for aero-engines. Though some consolidation is happening on the demand side of the US ecosystem currently, it is still a fairly competitive market with several big buyers and several big sellers. Global dominance, large scale and multiple large users are of course the key drivers of this ecosystem and even today with all the talk about the decline of US Power, this has not changed significantly.

In the case of China there may not be that many buyers for performance enhancing products. For companies and countries playing catch-up, time bound delivery of products and services that are adequate is more important than being contemporary in all dimensions of performance. In case imports of products or licensed production or even technology transfer agreements have been worked out, the incentive for pushing new approaches is significantly reduced and maybe perceived as risky by the larger and more powerful user community which in the case of the single crystal technology could have been the PLAAF. Thus part of the problem in catching up arises from the creation of new entities within the ecosystem that are responsible for the production and reverse engineering of imported technologies. The dilemma of choice between make and buy options become exacerbated and more difficult to resolve in such situations. Wherever such choices are foreclosed and there is no choice but to do things on your own, the abilities to catch up and move up the value chain become significantly superior. China's progress in the domains of nuclear weapons, missiles and space technologies where imports were not possible seems to validate reaching such a conclusion.

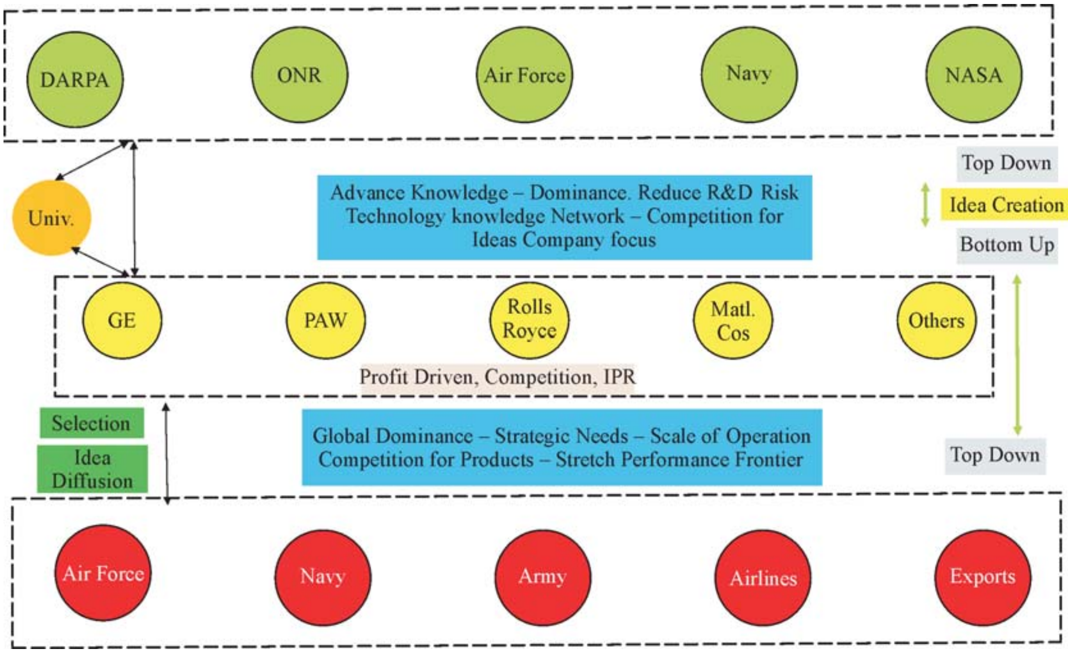


Figure 19: The US Eco-System for Knowledge Generation & Use-Single Crystal Technology for Aircraft Turbine Blade

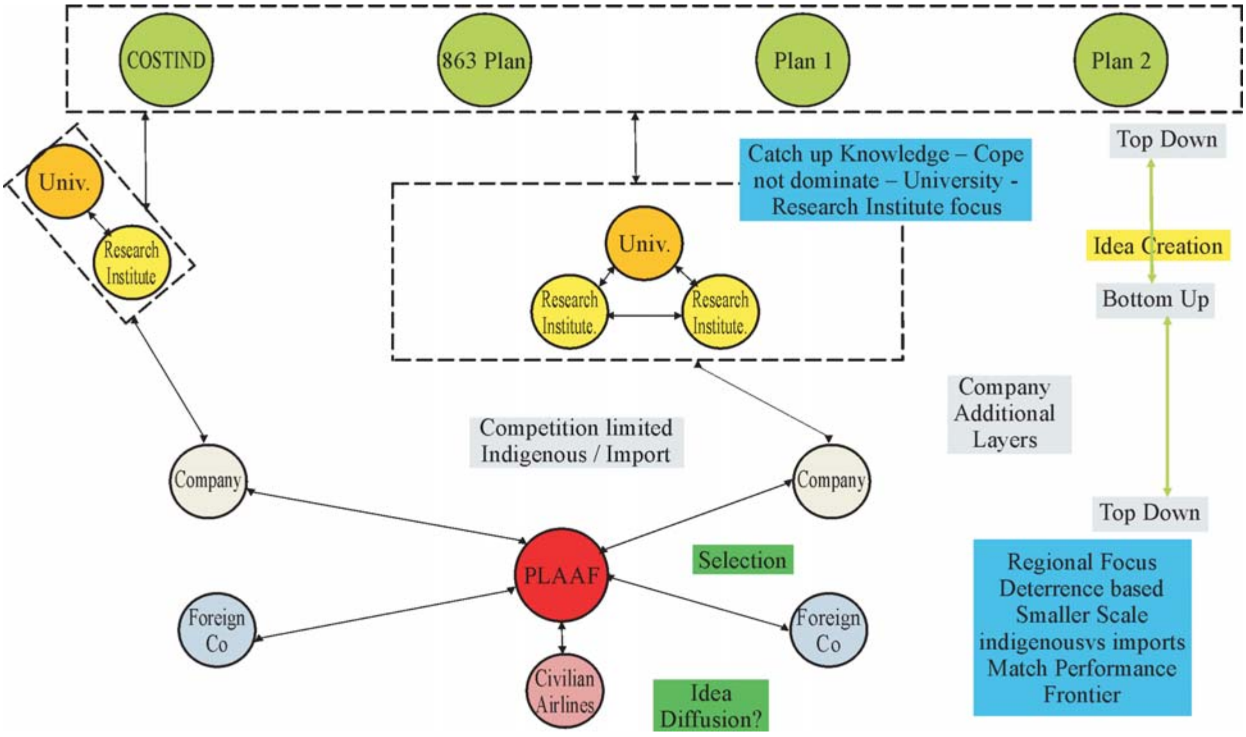


Figure 20: China's Ecosystem for Knowledge Generation & Use - Single Crystal Technology for Aircraft Turbine Blade

China has identified and tried to correct some of these deficiencies. It has tried to create several parallel sources for early funding support through several independent expert review processes along the lines of funding support extended by many publicly supported US advanced research organisations. This approach does help in facilitating one critical activity in the chain from idea generation to product development. However managing the demand side does raise a number of structural issues.

To facilitate competition at the company level China broke up its large Aircraft development and production complex called the Aviation Company of China (AVIC) into two separate companies called AVIC 1 and AVIC 2. However if one studies this re-organisation carefully the division of work between these two companies ensures that these two entities do not directly compete with each other. This suggests that political factors are still important in many of the periodic re-organisations that take place in many parts of the military industrial complex of China. More recently the Chinese have again merged AVIC 1 and AVIC 2 back into one entity. This raises the question whether planned top down interventions can substitute for competition driven evolutionary approaches to the technology creation, selection and diffusion problem.

There is also the question of scale. Currently China may lack the scale to support several independent players in each part of a dual use technology value chain. However as China becomes richer and its strategic interests expand to cover the globe this issue may become less important. Viewed from this perspective China may still need more time to be able to catch up with the more advanced countries of the world.

While this problem is evident in areas where China is trying to catch up this is not always true in all domains. China's creative solution to the threat that it faces from US aircraft carriers in the western Pacific Ocean clearly reflects a back to basics approach of the Chinese ecosystem that deals with the domains of space and missiles. This does indicate that if conditions are suitable the Chinese can respond creatively with novel and innovative approaches. However in the more traditional domains where such constraints are not present such as the aircraft industry, playing catch up and then reversing the disadvantage to an advantage appears to be more problematic.

Figure 19 presents an overview of the US value chain as revealed through our study of single crystal technology. Figure 20 presents a similar overview of the Chinese system.

The critical links in the Chinese ecosystem are research institutes that are connected but organizationally separated from aircraft companies. There is therefore one additional element in the value chain that is not there in the US where the R&D element in a company directly comes under the ambit of a company's control and direction.

Clearly the demand side of this value chain in the case of China is very different from that of the United States. These differences may represent fundamental differences between the two systems in the management of hi-tech dual use technologies and products. While some of the differences between these two systems can be bridged by some alteration of the structures as China becomes richer, the ideological differences in terms of the role of the State and the power equations that determine the direction of change appear to be different between these two systems.

Annexure 1

List of institutions in China involved in Single Crystal turbine blade research and development

Institute of Metal research, Shenyang	IMRS
Fukuoka InstituteOf Technology, Japan	FITJ
BeihangUniv	BHU
Beijing Institute of Aeronautical Materials	BIAM
Tsinghua University	TU
I H Heavy industries, japan	IHHIJ
Hunan University of Technology	HNUT
China Aviation Power Plant Research Institute	CAPPRI
Southwest University of Science &Technology, Mianyang	SWUSTM
Northwestern Polytechnic University, Xi'an	NWPUX
Nanhua Power Machine Research Institute	NPMRI
KAIST, South korea	KAIST
Shenyang Institute of Technology	SIT
Aviation Institute,Zhuzhou	AIZ
Zhuzhou AviationPowerplant Research Institute	ZAPRI
South China National Aeromotive Co	SCNAC
Central Iron and Steel Research Institute	CTISRI
NanhuaPowerplant Research Institute	NPRI
Failure Analysis Center of AVIC	AVIC

List of institutions in USA involved in Single Crystal turbine blade research and development

National Aeronautical Space Association	NASA
Air Force Research Laboratories	AFRL
University of Florida	UOF
Illinois Institute of Technology	IIT
University of Michigan	UOM
General Electric Company	GE
Sandia National Laboratories	SNL
Ohio State University	OSU
Princeton University	PSU
Carnegie Mellon University	CMU
Honeywell International	HI
Cannon-Muskegon Corporation	CMC
Solar Turbines Inc	STURBI
Rolls-Royce	RR
Allison Engine Company	AEC
Pratt and Whitney	PAW
Rensselaer Polytechnic Institute	RPI
University of Dayton Research Institute	UDRI
Universal Technology Corporation	UTC
Wright-Patterson AFB	WPAFB
Northwestern University	NWU
University of California, Davis	UCD
University of Illinois	UOI

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