AF MATERIALS & MANUFACTURING DIRECTORATES' PROJECT TO REVOLUTIONIZE PRODUCTIVITY IN THE FORGING & CASTING INDUSTRIES

A Processing Science to Man Tech to Enaction by Industry Story

ABSTRACT

The Air Force Research Laboratory Materials and Manufacturing Directorates (AFRL/RX) commenced research projects in the 1970s that made a well-timed impact on National Security. The United States was in a period of economic stagflation, the Air Force and other government agencies were amidst a Reduction-in-Force (RIF), and the United States was in a Cold War (1946-1991) with the Soviet Union. In the fall of 1972, the U.S. Air Force and the U.S. Aerospace enterprise suddenly realized that the Air Force could not afford to build the warplanes necessary for maintaining air superiority over the Soviet Union. The Director acted expeditiously to reorient the laboratory's programs to arouse the engineers and scientists to become "innovation-driven" to consider cost as well as performance, so the Air Force could afford to build the systems in production during the 1980s. *Crummy productivity* was manufacturing's biggest problem in 1972. Notable participants from academia, industry and government gathered first in Cincinnati and then in Dayton to identify the problem and create an action plan. History verifies the success of the directed research projects. This story is about the people who succeeded in modernizing the forging and casting industries by creating and implementing transformative technologies that nudged the industry into a digital paradigm that would increase the productivity of all aerospace employees and thereby significantly reducing manufacturing costs.

Harold Gegel

AF Materials and Manufacturing Directorates' Project to Revolutionize the Forging and Casting Industries

Prolog

This is a story about a major accomplishment by the Air Force Materials and Manufacturing Directorate (AFRL/RX) between 1972 and 1987, a period of 15 years. It is about several outstanding executive leaders, scientists and engineers, who perform the research and management tasks of vital programs. The undertaking of this task was to "*put science into materials processing and manufacturing*." Phrasing it differently, our assignment was to transform experience-based process design to knowledge-based design using computer simulation methods suitable for implementation in a digital architype. It is a story about people, the impact of new technology, and digital-globalization on people hastened by the onslaught of the 21st century. The overriding mission was to create the most powerful, respected and sustainable Air Force in the world.

The purpose of this story is to illustrate how new technology evolves over a relatively long period. (1972-1995), and that good ideas remain stored in long-term memory waiting for the right set of conditions to merge. It is *exemplary* of how a government laboratory works as a science and technology broker between academia and industry.

The Cold War was still in progress, and the Western European countries were at the end of Thirty Glorious Years of economic growth—Trente Glorieuses[1]. During these thirty years between the late 1940s to the early 1970s, economic growth was unusually rapid—economists call this Catch-up Economics. In addition, The Soviet Union and the United States were embroiled in a Cold War that saw basic research playing a very significant role in maintaining a balance of power on both sides. At the Air Force labs, managing people and many different technologies across a spectrum-of jet engines, materials and manufacturing, avionics, and aircraft structures were the business of the Directors and employees, with the objective of making future weapon systems affordable, sustainable, and significantly reducing the time to deliver the first systems.

The Players of Technical Modernization

- Dr. Alan Lovelace, Director AFRL/RX—Planned for University-Government-Industry Cooperation
- Dr. Robert Lowey, Chief Scientist USAF—University-Government Exchange of Scientists
- Dr. Frank Kelley— "Turn the Crank"
- Dr. Harris M. Burte-"Drive Towards a Window"
- Dr. Gary Denman, Director AFRL/RX & DARPA-Allowed Research Success to Mature into Digital Manufacturing
- Unsung Team of Technology Stars—They Made It Happen

The AFRL/RX Story

On 4 October 1957, the Soviet Union launched *Sputnik 1 Earth Satellite*. The surprised success of this launch precipitated the American Sputnik Crisis and triggered the space race—a part of the larger Cold War. *Sputnik 1* ushered in new political, military, technical and scientific developments. The launching forced us to take up a more offensive stance, which resulted in an emphasis on scientific and technology research, and reforms in many areas from military to education.

The federal government began pouring unmatched amounts of money into science education, engineering and mathematics at all levels. President Eisenhower inaugurated a new era in education by imploring Congress to enact a bill called the National Defense Education Act, which he endorsed. The bill encouraged students to go to college and

[1] Piketty, Thomas. Capital in the Twenty-First Century. Harvard University Press. Kindle Edition, 2014, 96– 99.

study mathematics and science. Student fees would be paid.

Sputnik 1 set the stage *for* creating a new way science is conducted in the United States. Universities, industries and government began working together in teams to speed up the development of new technologies and to train engineers and scientist capable of creating new materials and processes that improve the efficiency of manufacturing at all levels from OEMs to vendors. *Government's role was to be the broker that made it possible for government, universities and industries to work together harmoniously.*

Laboratory leadership encouraged all—civilian and military—to continue our education, because a well-educated and informed Air Force could compete with the Russian technology-machine to win the Cold War. Many of us took advantage of this great opportunity to earn graduate degrees and make a career of the Air Force.

Stagflation

The period between 1972 and 1975 was a time in which much of the Western world was experiencing economic stagflation, putting an end to the general post-World War II economic boom.

Stagflation is characterized as a period of rising inflation and falling output. It is a condition of slow economic growth and relatively high unemployment—a time of wage stagnation, accompanied by a rise in prices, or inflation. Stagflation occurs when the economy isn't growing but prices and unemployment are rising.

When viewed in historical perspective, the 1945-1975 post WW II years were an exceptional period. Simply put, it was exceptional because Europe had fallen far behind over the period 1914-1945, and the United States, through the Marshall plan, helped Western Europe to rapidly catch-up during the *Trente Glorieuses*.[2] Once this catch-up was complete, Europe and the United States both stood at the global technological edge and began to grow at the same relatively slow pace—characteristic of economics at the forefront.

Economic Growth Rate in the U.S.

Concurrently, the United States was experiencing a slowdown in economic growth rate in 1972[3], and the Air Force was undergoing a Reduction in Force (RIF). Our economy was sluggish, and the cost of manufacturing aerospace structures and propulsion systems were surging higher. A cost analysis of the aerospace industry by the Manufacturing Technology Directorate of our laboratory revealed that as much as 80 percent of the cost of an airframe was the cost of manufacturing precision forgings and castings.

These structural components were labor intensive and based on experience-based design, where waste was high and work-in process was excessive. If the component shape was new, and if it had a complex shape, and if a company had not made it before, they could not meet desired delivery schedules. The high cost of developing new AF weapon systems based on antiquated methodologies (pre-*Sputnik 1*) could not be tolerated.

The Air Force had no choice but to develop innovative processing and manufacturing technologies

[2] The Marshall plan (Officially the European Recovery Program, ERP) was an American initiative to aid Western Europe, in which the United States gave $13 billion (approximately $130 billion in current dollar value as of August 2015,) in economic support to help rebuild Western European economies…

[3] The economic growth rate/capita was proceeding at a rate typical for an endogenous economy of about 2-4 percent. This theory holds that economic growth is primarily the result of growth from within and not external forces. Endogenous growth theory holds that investment in human capital, innovation, and knowledge are significant contributors to economic growth.

that were obligatory for achieving future performance requirements of aerospace systems—none of which could be afforded using the older design and manufacturing methods.

Air Force Moves to Modernize Material Processing & Manufacturing

Dr. Alan Lovelace and Dr. Robert Lowey

Dr. Alan Lovelace, our Laboratory Director, and Dr. Robert Lowey, Chief Scientist of the Air Force, who was on sabbatical leave from his position as Dean, College of Engineering, University of Rochester, were developing a plan to start an exchange program between research scientists in Air Force Laboratories, such as the Air Force Materials Laboratory (AFML) and universities. They believed that closer relationships between Air Force Laboratories and academia was essential if the United States was going to win the Cold War with the Russians.[4] One problem that seemed to be common for all universities was that the Air Force's contractual programs were not always synchronized with students' graduation programs, whose dissertations would be based on an Air Force Contract.

Air Force-University Exchange Program

The concern was always that the contract might be terminated when the student was more than halfway to completion. A second concern was that neither academia nor the Air Force understood each other's needs— the Air Force needed to understand that any abrupt change in the contract should not prevent the student from completing academic requirements, and the university professors needed to better understand the Air Force's goals and mission. Therefore, a University-Air Force exchange program seemed to be an appropriate way to improve the relationship between both organizations.

Selecting an Exchange Candidate

Schools and universities had already started, and it was urgent to choose a government scientist who would probably qualify to become an Associate Professor. The university faculty who would approve this candidate were not aware of the Exchange Program, nor did they know that the candidate's salary and benefits would not be coming out of their budget. The candidate had to satisfy the requirements and standards of the university.

Our family discussed the proposition that Dr. Lovelace made. I still remember him saying that this special assignment would get me out of the RIF mess that the laboratory was having. We had the weekend to decide whether we should accept this opportunity to live in Rochester, NY for one year while I worked as an Associate Professor in the Department of Materials and Mechanics—provided the faculty approved my appointment. This latter requirement was an uncertainty for me, because Dr. Lovelace and Dr. Lowey was gambling that my experience as an Air Force scientist satisfied their legitimate needs.

After hurried debates and discussions with our family, we decided that it would be in our best interests to accept the challenges of moving and satisfying the university's high standards. Finding a town house close to the University, and getting our children settled into school once again might present a problem on such short notice.

During a rushed visit to the University of Rochester, we found a Town House Development located on Elmridge Avenue, not far from the University of Rochester or the location where the girls would go to school.

Our temporary home was in the village of Brighton and very convenient to good shopping. This was an

[4] It was generally believed that government's role in creating new technology should be the broker between universities and industry—one of the "building-blocks" for being and becoming competitive with the Russian system.

area where many professors and doctors affiliated with the University's Hospital lived.

Our oldest daughter discovered that she liked her new school better than the one that she left, and our younger daughters both made good friends with children whose parents were affiliated either with the University or the Xerox Research Center. The University faculty wives made my wife feel at home. The year went fast, and the girls decided that they would like to stay in Rochester. The year that we spent in Rochester was the 1972-73 period.

Concurrent to finding a place to live, I had to go through a series of lectures and meetings with faculty, who would vote whether to offer me a position. Lucky for us, they recommended hiring me! The University of Rochester Board of Directors appointed me an Adjunct Associate Professor, and I was subsequently assigned to several university committees to give me a real feeling of how a university works in addition to doing its academic endeavors.

Dean Lowey assigned me the additional task of reaching-out to local industries to convince them that collaboration with the College of Engineering faculty and students would benefit both organizations. The University's goal was to create scientists that would be energized to develop strong Industry-Government-University partnerships. A goal was to understand how science and technology transfer gets done. In short, a lot was learned about technology transfer and how industry and universities can work together to develop new technology, train scientists and engineers, and develop new products.

Return to the AFML in the Fall of 1973

In 1973, I returned to the AF Materials Laboratory, and I was assigned to a Task Scientist Position. It was a new job for "putting science" into processing. This opportunity occurred at a time when the AF was still in a Reduction in Force (RIF) and resources were scarce. Hiring was frozen, and no employees were available to be assigned to the Processing Science Task, except for two co-op students from Wright State University. However, I could take on as many NRC Postdoctoral Fellows[5] as I could support. Much to everyone's surprise, there was an unusually large number of outstanding candidates. From this group, we selected a staff of diverse professors, and a *University-Government-Industry* long-term research program evolved. Which included a strong in-house program in processing science. It centered on material stability behavior during large-scale plastic deformation. The two co-op students were valued employees, as they were trained to conduct research by the NRC Postdoctoral Fellows, and they were eventually hired by the Air Force to become outstanding career employees.

Getting Started

The first thing that had to be done was to get the NRC Postdoctoral Fellows settled into a temporarily chaotic office environment. Our office environment was made temporarily chaotic by the fact that our Processing Group was moved suddenly into the former Aerospace Research Laboratory (ARL) space that was vacated when this laboratory was dissolved by the Air Force. I described the office situation in the following way.

We do not have enough vacant offices to give each person a private office that they may be used to having. But it was possible to make private space

]][5] The National Research Council (NRC) Research Associateship Programs (RAP) promote excellence in scientific and technological research conducted by the U.S. government through the administration of programs offering graduate, postdoctoral, and senior level research opportunities at sponsoring federal laboratories and affiliated institutions. In the NRC Research Associateship Programs, prospective applicants select a research project or projects from among a large group of Research Opportunities available through this website.

available whenever they needed it for thinking, writing, visitors etc. What we did have was a very large open space that could easily accommodate all of us along with a big coffee pot. I talked about the virtues of sharing space together, because working near would make it easy to share ideas with other scientists.

We discussed the fact that innovation and creativity were activities frequently involving a collection of "out-of-the-box" dreaming scientists with ambitious goals and a diversity of ideas. In a few high-tech corporations, some executives shared office space with scientists and discovered that the organization was more creative than when working in isolation. The scientists were willing to give it a try, since they could have privacy when they needed it. As time went by, the coffee pot became the center for great discussions, and everyone liked the comraderies and scientific stimulation.

Everyone remembers the Blondie and Dagwood comic strips and how Dagwood always spread office rumors at the water cooler. The Coffee Pot took the place of the watercooler and served as the site for great scientific discussions. This group of scientists was highly compatible, but widely diverse in scientific backgrounds, which made our work very exciting and productive.

One cold winter day when we were having an Ohio snowstorm, a small man sporting a "hugh" smile and his family appeared at our doorway.

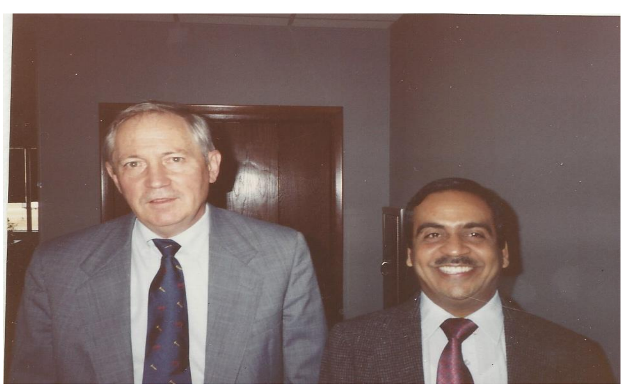

Figure 1 Sokka Arrives and Brings His Smile

He enthusiastically announced, "Sokka here. I'm ready to go to work!" The team gave Sokka a warm welcome and greeted his wife and two young boys. Sokka was a real people person, and he made friends very quickly. And as time passed, he devotedly became the Guru for our two co-op students, and a leader with great methodological ideas.

Sokka wanted to start work immediately but enquiring about where he and his family were living, we told him that it was better that he gets his family settled first, as the work will keep. The little man with the big smile and congeniality eventually adopted America as his home.

The Task Scientist's job was to write a Statement-of Work (SOW) that would transform the metalworking community from an experience-based technology to a knowledge-based technology that would have momentous impact on the cost of manufacturing advanced aerospace and propulsion systems and take the AF into the 21st century without breaking the bank.

Increasingly, new weapon systems were becoming unaffordable—80 percent of the cost of aerospace structures, per a study conducted by our Manufacturing Technology Division, was attributed to the manufacturing costs of critical structural components. Many visits and many extensive discussions with universities and the aerospace industries provided the technical and business background needed for writing a statement of work and well defined deliverable items. The highest technical priority, which was agreed on by everyone, was a new mathematical tool for simulating and analyzing all material shaping processes involved in component manufacturing.

Aerospace Engineers and designers of the major OEM and vendor industries stressed the importance of having a process design and simulation tool that was based on the finite element method (FEM) and material databases required for building the computation model for both forging and casting processes. Their rationale for ardently recommending the FEM was its ability to be easily generalized, and its applicability to solving a wide class of boundary value problems with few restrictions of geometry.

As the basic research program matured, a classical paper by R.H. Hays and K.B. Clark, Why Some Factories Are More Productive Than Others, *Harvard Business Review,*[6] provided a basis for refocusing technical efforts. The program began to transition from Processing Science to Manufacturing Science. Manufacturing Science funding allowed needed basic research in materials and processes, while at the same time begin merging the new design tools and databases with already developed commercial manufacturing systems. Hays and Clark identified three practices that make a difference:

- Investing in New Technology
- Reducing Waste
- Cutting Work-in-Process (WIP)

Reducing waste is predominantly a design issue and cutting Work-in-Process deals with business strategies and principles.

What matters is how the new technology is introduced and managed. A negative correlation between waste rates, i.e., scrap and rework, is expected, but no one suspected the magnitude of the effect of them on productivity until Hays and Clark reported it. High WIP is an indicator of the amount of chaos in the production system, which must be eliminated. Material waste can be addressed using design optimization methods, but work-in-process (WIP) requires workflow process modeling of all manufacturing and business processes.

University Professors Play Critical Roles

Before going into the professors' roles, I must mention Dr. Charlie Chen, a metallurgist for the Wyman Gordon Company, a major advocate of this work. Charlie invited me to give one of the invited papers at a symposium on workability at a Fall ASM International meeting, probably in the fall of 1974. He emphatically instructed me not to give the usual talk that everyone seems to give, which tend to match an engineering material with a given press, and when discussing an engineering alloy, such as titanium, they would describe its formability when in a primitive form; its extrudability, rollability, forgability and machinability. These are usually referred to collectively as the "-ilities." Charlie was asking for a more fundamental approach that would describe a material's *intrinsic workability.*

A method was proposed that was related to the partitioning of energy between potential energy and kinetic energy, where the partitioning agent was the strain-rate sensitivity parameter *m*. The input power absorbed by the workpiece material in *forced dissipated flow* as in forging or extrusion processing is dispelled both as heat and in the form of dissipative microstructures. The kinetic energy is converted into heat, and the negative potential energy gradient becomes the driving force for microstructure evolution. Some of these ideas came from the paper delivered by Ilya Prigogine when he received the Nobel Prize about the stability of chemical systems far away from equilibrium.[7]

University professors played critical roles in the Processing-Manufacturing Science project. We just mentioned that reducing waste (scrap and human-time waste) is both a design issue and a business issue. The business issue must do with having a better way to manage workflow in a factory environment, and the design issue—must do with managing the flow of energy into the workpiece material at a rate that does not exceed the rate of dispelling this input energy as heat and dissipative microstructures in a stable fashion.

Professor Rudy Speiser was my primary adviser at the Ohio State University throughout my graduate

[6] R.H. Hays and K, B. Clark, *Harvard Business Review,* Vol. 69 (No. 1, 1991, 66-73

[7] Ilya Prigogine, Time, Structure, and Fluctuations, *Science*, Vol. 201, No. 4358, 1978, p 777-785

education. His background was in physical chemistry and thermodynamics. He insisted that his students take courses on Irreversible and Statistical Thermodynamics, which at the time, was not my primary interest. However, as our research team progressed in its efforts to create a FEM simulation and design methodology, the FEM program required workpiece constitutive equations and a compatible material workability model. To avoid over constraining the FEM model, the workability model should be in the form of nonholonomic constraints.[8]

In Professor Speiser's Irreversible Thermodynamics course, he introduced the class to America's most important chemist at the time who was the patriarch of Irreversible Thermodynamics. The stability of chemical systems as defined by J. Willard Gibbs was controlled by three inequalities.

1. The compressibility of the workpiece, χ, must be greater than zero, $\chi > 0$. (*Mechanical Stability)*
2. The heat capacity, $C_v > 0$ *(Thermal Stability)*
3. The *diffusional stability* of the solute elements must be stable, such that $\sum \mu_{\gamma\gamma'\delta N_{\gamma'}} > 0$ where

$$\mu_{\gamma\gamma'} = \left(\frac{\partial \mu}{\partial N_{\gamma'}}\right)_{p.T}$$

These are necessary conditions for a stable chemical system, but we still need to define the dynamical (real) path that satisfies these conditions. The real path will be a stationary state (path of least action).

To carry the stability thought further, we turned to Professor J. F. Thomas, Jr. at Wright State University to define the material's rheological parameters that would determine if the material was flowing under stable conditions based on empirical constitutive equations. With the assistance of Dr. Ragu Srinivasan, who was one of our original Post-Doctoral Fellows, they succeeded at defining three stability parameters for a material undergoing large-scale plastic strains.

A new Post-Doctoral Fellow arrived at our Laboratory from the Indian Institute of Science, Bangalore, India. The new Fellow was Y.V.R.K. Prasad. Prasad was an expert in plasticity theory whose expertise

Figure 2 Hal, Jim, Prasad, and Thiru

was combined with our work to develop constitutive equations led to a deeper understanding of the theory of dynamic material modeling and its fundamental relationship to material workability.

To validate the concept, the group experimentally studied a wide range of complex materials and used the dynamic material model to define a processing map for each of them. We could produce perfect extrusions and small forgings without any defects always on the first trial. With these successes, we submitted a paper to the *Metallurgical Transactions Journal*[9] and waited for almost a year without a response. The editor said the review committee could not find anyone qualified to review it, so he sent it to a physicist that he knew and who accepted the task of writing a critique of the paper.

"Publish it without any changes," was his response! Paraphrasing the reviewer, "I don't believe many

[8] A nonholonomic material system is one whose state depends on the path taken to achieve stability.
[9] Y.V.R.K. Prasad, H.L. Gegel, S.M. Doraivelu, J.C. Malas, J.T. Morgan, L.A. Lark, and D.R. Barker, *Met. Trans.* **15A** (1984)1883; the names are the people who generated the constitutive equations and workability models for a very large number of engineering alloys.

people will understand this paper, in fact, most will not understand it, but it is the type of paper they should be reading."

The Postdoctoral Fellows making up this in-house team now included Professor Prasad, Dr. Sokka, Professor Jay S. Gunasekera, Chris Lark, Doug Barker, Jim Malas and Jim Morgan, the two co-op students, professors Dr. J. F. Thomas, Jr. and Dr. R. Srinivasan, Wright State University. Professor Gunasekera was an important addition to this group. He brought an expertise in numerical methods, especially the FEM, and he was also an expert about CAD/CAM technology and engineering design of metalworking processes. He designed the streamlined dies used in the experiment to validate the Dynamic Material Model. Professor Rishi Raj, Cornell University and later the Colorado School of Mines at Boulder worked with the material behavior team during the summers. Rishi created the first Material Processing Map. The idea of maps that define stable temperature, effective strain-rate space probably originated from deformation and fracture maps for pure metals, which do not have any value for designing material forging processes, etc.

Our research suggested that a network of atomistic processes would provide the degrees of freedom required for shaping complex materials such as intermetallic compounds and high-temperature alloys, which is consistent with the Gibbs stability criteria previously mentioned. Therefore, an atomistic approach to thinking provides a fundamental means for understanding the concepts of workability and the evolution of dissipative microstructures because of energy-dispersal mechanisms.

Rishi Raj took note of this possibility and quantified the mechanisms and constructed the first processing map. Mechanistic modeling has limitations although it gives much insight into the fundamental problems of workability. The dynamic material modeling approach provided a method to describe the dynamic (real) path that material elements take in response to instantaneous changes in effective strain-rate, temperature at any time.

Critical Roles

University professors played critical roles throughout the project: (1) they developed the first Rigid Viscoelastic FEM code for modeling large plastic deformations for strain-rate sensitive materials; (2) they trained the graduates who would be needed by industry to implement the new process design

Figure 3 Taylan Altan, Soo-ik Oh, Lee Semiatin, the Battelle Science Team & Hal

technology that industry desperately wanted and needed. Professor Shiro Kobayashi, University of California-Berkeley, and his graduate students undertook the task of creating the FEM-based plasticity code known as ALPID—**A**nalysis of **L**arge **P**lastic **I**ncremental **D**eformations. Because work gets done through people, Battelle Columbus Laboratories (BCL) was selected to be a "Prime Contractor" for this technical effort. BCL was the leading Industrial Manufacturing research laboratory in the United States at the time, and they had the capability to establish subcontracts with academic institutions or individual scientists on an as-needed basis.

BCL played a major software development role in the project, which was critical to technology transfer. Their development role was to make ALPID user-friendly, because it was a university research code at the time. They helped the Air Force to distribute the new ALPID code to other U.S. universities both for code testing and to train potential users of the new analysis tool. Our goal was to have enough trained users who could go directly to the U.S. metalworking industry. Prof. Vinod Jain, Univ.

of Dayton, validated the accuracy of ALPID predictions by doing visioplasticity studies.

The Wyman-Gordon Forging Corporation volunteered their metalworking capabilities and experience to help make this program a success. The first important thing that they did for the project was to forge a Ti-6242 titanium billet such that it ended with two standard forging preform material structures—one had an $\alpha + \beta$ microstructure preform, and the other had a transformed-β microstructure. Enough high purity material was processed from the same ingot for the entire program. The company also provided us with empirical die design rules that would be needed in later stages of the project. In this respect, the late Charles Gure was a great contributor and teacher.

The Basic Research Project & the Laboratory of Last Resort

The basic research (6.1 program element) effort lasted approximately six years culminating with the ALPID FEM code with pre- and post-processing and a material database. In-house basic research using visio-plasticity methods verified the accuracy of the ALPID predictions.

Our in-house Processing Science team solved a wide range of AF problems for AF Flight Dynamics (FD), and Propulsion Laboratories, and we became known as the Laboratory of "Last Resort."

The FD Structures Laboratory program manager, Vern Johnson, came to us out of desperation for help in designing an extrusion process for manufacturing a Wing Spar cap made from a Ti-6Al-4V short-fiber SiC material. Their contractor could not extrude the material without causing the extrudate to fracture. We developed the appropriate constitutive equations for the workpiece material, so we could decide the correct process temperature and ram velocity. Dr. Gunasekera designed a streamlined die to eliminate any material flow turbulence. The streamlined die was manufactured by our 4950th machine shop, who received the NC-coordinates via our fail-safe sneaker net. Success was achieved on the first extrusion.

We also designed a hot die forging process for producing a composite aluminum structural forging. We did it right the first time by establishing the correct forging temperature and ram speed. The forging engineers at Wyman-Gordon at first did not like the parameters that we selected, because they were afraid that the lower forging temperature and higher strain-rate selected by us would fracture the stem on their 50,000-ton press. Vern Johnson asked them how much it would cost to replace the stem should it fail.

The forging engineers gave him a cost of $200,000, and Vern Johnson said without hesitation, "Make the forging as specified." He also reminded them that the project had already spent half of the funds of the project without any success. The forging engineers at Wyman Gordon were shocked when they observed a "perfect forging" on the first attempt as predicted by the ALPID FEM code. The observed forging load also agreed with the predictions. Per Vern Johnson and to my recollections, we saved the Air Force $20,000,000 dollars.

Dr. Charles Oberly, the AF Propulsion Laboratory, had a contract to build an airborne superconducting power generator capable of powering powerful airborne lasers. Their contractor was supposed to produce superconducting wire cables by co-extruding composite titanium alloy consisting of embedded rods of a high tin-bronze alloy and reacting the two materials after the extrusion was completed. Both materials had to be continuous without any fracturing of the resulting wire material that was to be the superconducting part of the product. Again, we succeeded on the first attempt. Using the ALPID code, our material database along with our workability model for the composite material, the in-house Process Modeling Team design a streamlined extrusion die process, selected the extrusion temperature and ram speed and produced the extrusion product successfully on the first, second and all additional attempts.

These in-house processing demonstrations of difficult to process materials helped establish the confidence needed to obtain support for two additional Manufacturing science funded programs. *The first Manufacturing Science*[10] *effort resulted in a "Tool Box" for integrating the new process modeling capabilities into real manufacturing environments using the KI-Shell™.* This software integration shell was developed at The Ohio State University by Dr. J. Ramanathan as a research tool for changing the way engineering software tools could be integrated with CAD/CAM tools created by different manufacturers flawlessly. Part of the program included training the vendor industry to use these tools and how to electronically exchange process design data with the OEM's.

The second Manufacturing Science effort created a full-scale demonstration program by completely integrating the Shultz Steel Company, in South Gate, California, which was founded in 1947 by Mr. Gordon W. Shultz. This was a demonstration program to completely integrate a commercial forging company that we had never worked with before and to generate the economic and technical benefits of implementing our integrated design system in a full-scale operating environment.

The U. S. Government listed Shultz Steel as a small business at the time, and this contract was awarded as Small Business Set-aside Initiative Research (SBIR) contract. In our eyes, it was more like a mid-size company that was equipped with the latest presses and support technologies. Today, it is a leading worldwide supplier of forgings for commercial and military aircraft, as well for Spacecraft, Nuclear and Industrial applications. The Shultz Steel Company volunteered to participate in our *technology transfer* effort, and they agreed to share all results with the industry. The Shultz Steel project yielded the following important benefits:

1. Improved the *Design Lapse Time* by 5 To 1 Ratio for A Productive Gain of 400 Percent
2. Improved the Design Time by 13 To 1 Ratio for A Reduction in Engineering Labor of 1200 Percent
3. Captured the Ability of Experienced Engineers
4. Dramatically Reduced Training Time for New Users
5. Remembered and Interpreted Design Rules in A Consistent Way Each Time
6. End User Developed Flow Charts Converted into Process Management Software
7. Standardized the Design Process

Summary of Program

Productivity enhancements were attributed to three factors: (1) New Technology, (2) Scrap Reduction and (3) Elimination of WIP. Other quantitative benefits included a higher quality product, a significant reduction in product design time (1200 percent) and delivery times (400 percent) and a reduction in manufacturing costs. *It verified the system engineering rule—design drives everything: manufacturing costs, product delivery time, product consistency and quality.*

[10] The Manufacturing Science fund line was created by Dr. Vince Russo to allow both basic science and manufacturing technology to run concurrently. It facilitates—makes possible— transferring advanced technology to U.S. Industry. Dr. Russo has held a variety of senior positions within various AFRL laboratories and retired as the senior civilian responsible to the Commander of the Air Force's center of excellence for development and acquisition of systems.

The Forging Tech Mod Program

All AF Technical Modernization programs are based on proven, verifiable technologies. The "Putting Science into Processing and Manufacturing" began in 1975. It systematically grew from a basic research (6.1 program element) project, where a new FEM ALPID code was conceived and developed along with new concepts for material stability modeling and empirical constitutive equations evolved. Technology transfer began slowly with two Manufacturing Science programs that employed system engineering principles in addition to using knowledge-based integration methods. Critical to verifying the new design and manufacturing principles was the consistent way the AF In-house Processing Science team could solve tough problems that could not be solved by commercial metalworking companies.

This group was under a microscope by the Doubting Thomas clutches that were certain this program was going to stumble. We had colleagues who would constantly tell us to… "go back to your laboratory and play; they have a different way of doing things." The team was under pressure to be successful on every attempt to solving problems where industry failed using traditional experience-based methods. Change in work patterns is difficult to accept!

Our success was based in-part on the suggestion made by Dr. Frank Kelley, Chief Scientist of the AF Materials Laboratory, to "Turn-the-Crank" on the elements of the evolving design system. And Dr. Harris Burte, Director Metals & Ceramics Division, who advocated "Driving the Research Towards a Window." A Man Tech Program for Modernizing the Metalworking Community was our window of opportunity. The Tech Mod effort was based on quantitative, verifiable data and a stream of engineers trained by American Universities. It was made possible by prevailing University-Government-Industry collaboration throughout the entire program between 1975 and 1987.

Jointly Managed Man Tech Program

The Forging Tech Mod program was jointly managed by the Manufacturing Technology Division and the Metals & Ceramics Division. The Processing Science team made technical decisions "regarding the decision to forge" at each vendor facility—Wyman-Gordon, Cameron Iron Works and PWA Columbus, Ga. The Manufacturing Technology Division managed the Business part of the program.

It's a fact, all participants turned a lot of cranks before reaching the Grand Forging Event (GFE). One crank involved each vendor learning how to send and receive engineering data from their OEM. The engineering staff had to learn how to use ALPID and generate a CAD/CAM file. Much had to be learned by everyone, but they learned all aspects easily.

Importance of Manufacturing Science Program Element

Of special interest was the Manufacturing Science (6.7 Program Element) funding created by Dr. Vince Russo that permitted both basic research and manufacturing to be done concurrently. The spending flexibility in the Manufacturing Science fund line made it possible to create an advanced design and manufacturing system that was a Ground-Breaking Effort. It is logical to conclude that technology transfer cannot be accomplished until every aspect of the new technology has been evaluated and verified.

The new technology must be demonstrated in a full-scale production environment. The "pigeon-holing" of program element funds by whether it is basic research, exploratory development, or manufacturing technology complicates the technology development process. Manufacturing Science is not complicated by something outside itself. It simplifies the problem of integrating new technology with existing state-of-the-art manufacturing technologies.

The Grand Event—Make-the-Forging!

The final exam on the Forging Tech-Mod program was a *live demonstration* by each vendor that they could go through a complete forging process design, which included exchanging technical information electronically with the OEM, going through the design stages, generating a digital traveler, and manufacturing a full-scale "Integral Blade and Rotor" (IBR)forging—a complex forging never made. Approval to forge was decided by the AF team.

The Cameron Iron Works was ready to attempt to produce their first IBR for the General Electric Gas Turbine Engine Division at Cincinnati, OH. I was about to give our team's decision when the GE official observer was showing anxiety, so I asked him if he would like to make the decision—he was a worry-wart. His response to my question was that he would prefer that the AF team make the decision, which I confidently believed his answer would be. I announced that our AF team approved their final process and product design, and we gave the approval to "Make-the-Forging!"

Everyone watched with great anticipation the forging process proceed, and, when the IBR-forging was removed from the dies and the forging scrutinized, it was graded a perfect forging on the first trial. Consistency was demonstrated with additional assessments and metallurgical studies. At the end of the day around 4:00 P.M., the whole gang went to a small Houston sidewalk cafe and had a mess of Crawdads.

The demonstration trials were repeated at the PWA Columbus, GA Forge Shop and at Wyman-Gordon.[11] The live demonstrations ended the Forging Tech-Mod program that changed the way precision forging companies competed and made quality parts with high efficiency. Little did we know at the time that this successful manufacturing event would lead to another program to modernize the aerospace casting industry. This time it would be a DARPA project with Dr. Gary Denman, our former Director, at its helm.

70 Years of Excellence

The 70th Anniversary of the AFWAL Materials Laboratory was celebrated August 1987. Concurrently with the birthday celebration, we celebrated the Dedication of a new laboratory and facilities. It took 25 years of planning to provide the world-class space to pursue materials technology excellence for the Air Force and our great nation.

At that 70th birthday celebration, Dr. Gary Denman, acknowledged the Laboratory's increased emphasis on the science and technology related to manufacturing, and future emphasis in manufacturing technology will continue in the areas critical to the development of the enhanced aerospace systems of the future.

The path to the future started in 1972 when Dr. Lovelace and the AF Chief Scientist saw the importance of establishing an exchange program with Universities, because American university participation in AF research is critical to educating future scientists and engineers and doing most of the basic research needed for the enhanced aerospace systems of the future. I was selected to be the first scientist to begin the exchange program with the University of Rochester. They intended for me to develop a better understanding of the challenges research professors face when doing sponsored AF research and satisfying academic requirements. It was hoped that a visiting Post-Doctoral Fellow would acquire an understanding of AF future system requirements and its basic research needs. When I returned to the AF I was assigned to a Task

[11] Wyman-Gordon is a company that designs and manufactures complex metal components. Founded in 1883 as a manufacturer of crankshafts for looms, it has a long history of making forged metal components, particularly for the aerospace industry. Wyman-Gordon is now a subsidiary of Precision Castparts Corporation, and is based in Houston, Texas, United States. It has 13 plants in five countries and employs about 2,500 people.

Scientist Position with the responsibility of putting science into material processing. I was given much flexibility to get the job done, probably because the global economy was in a recession and the AF was amid a reduction in force (RIF). The one thing that was good was a guarantee that the budget would be long-term and at a modest level.

Our in-house team established a *Technology Transfer* path from R&D to Manufacturing, which involved a series of stages:

Basic Research →Man. Sci. I →Man. Sci. II→ Forging Tech-Mod

Celebration of the 70th Birthday was also a celebration of the aerospace forging industry's nudge into the digital world. It was reasonable to conclude that *technology transfer* can only be accomplished after every aspect of any new technology has been tested by "turning-the-crank" on all systems before implementing by generating manufacturing data that verifies the total process; and making certain the availability of engineers that understand design and are trained to use the new technology. Finally, "driving through the window of opportunity" was verified by carrying out a full-scale factory demonstration of the new technology.

Modernization of Vendor Industry Not Complete

Modernization of Aerospace parts vendors was not completed. The project to put science into processing and manufacturing started with the bulk forging process, because the physics associated with it is less complex than it is for the casting processes. However, much of the software needed for implementing the numerical process simulation and design tools are applicable to both processes. Both the aerospace industry and the Air Force team agreed that the forging process should begin first.

The fact that we could reach the Forging Tech-Mod phase of the work and complete it in a record time of approximately 10 years indicates that this initial choice was a good one.

The 70th Birthday of the Materials Laboratory also witnessed a changing of the guard. Dr. Alan Lovelace was the Director of all Air Force Laboratories, and Dr. Gary Denman was destined to become the Deputy Director of DARPA.[12] *A new strategy had to be developed for completing the task of making the nation's aerospace casting industry the most productive in the world.*

The U.S. Air Force has always played a major role in changing the way structural parts are manufactured. Because this technology is a duo-use technology, it is available to U.S. Industries. It is a driver for national economic growth. Most people do not understand that military research and development laboratories are research organizations for thousands of small to mid-size companies that manufacture critical structural components for aerospace and industrial applications.

The primary reason seems to be that each of these companies are capital-intensive manufacturers that are burdened to maintain a modern company and highly qualified technologists. Different organizations have different values for return on capital. Manufacturing sectors are more capital intensive than service sectors of the economy. Metal and energy sectors are more capital intensive than textile and food processing sectors. *The amount of capital available for doing research to increase productivity is highly limited for small capital-intensive Metal Sector companies, and affordable, maintainable weapon systems result generally from capital intensive manufacturing.* The U.S. Industry and the national government must find a way to modernize these SME industries or give up competing in the global arena.

[12] Dr. Gary Denman, after serving as deputy Director in 1990, became director of DARPA in 1991 and left in 1995.

Retirement from Government Employment

I made the decision to retire from Government employment to finish the modernization of the U.S. Casting industry, which was planned as part of the first basic research project to "put science in processing." I received an unsolicited job offer from UES, Inc. and others at the time, so I gave them consideration. I took the offer of UES to become the Director of the Processing Science Division. Dr. Sokka was the Chief Scientist and Marketing Director, and he had already started a casting research program aimed at providing software support for the U.S. Casting industry. Additionally, Dr. Sokka had hired a graduate of Swansea University in England who had already developed a FEM code for simulating the casting process, which was the casting analog of the ALPID forging application. This casting code after further development was named ProCAST™.

Using this casting program was labor intensive, because FEM programs require technical support to manage its progress in reaching a solution. Its graphical users interface (GUI) needed to be upgraded from that of a code under development to an intuitive GUI that would be easy for an engineer to navigate. Discussions with the U.S. Aerospace Casting Industry defined the goals for further code development.

We subsequently entered partnership with the National Institute of Science and Technology (NIST) to create an algorithm that would calculate the phase diagram for any alloy and any number of constituents. Any casting calculation requires knowledge of alloy melting points as a function of temperature and composition, especially when the engineer needs to model microstructure evolution on cooling. The research team accomplished the development of a user-friendly GUI and an application for calculating n-component phase diagrams. This was done with in-house support. To fund our in-house research, we took on other government work to run the AFML Processing Laboratory. The profits from this endeavor were used to cover our expenses. Despite our initial struggle, financial help unbeknownst to us, was on its way to support the enhancement of ProCAST™.

The DARPA Casting Opportunity

Dr. Thomas Tom of Howmet Castings[13] met with Dr. Gary Denman, Director of DARPA, to pitch a Howmet project for DARPA funding. Dr. Denman informed him politely that he was not interested in that type of casting project. In short, he wanted a program that would accomplish what our forging modernization effort succeeded in doing. This meant he was interested in an initial manufacturing science effort followed by a technology transfer effort to put it into all U.S. foundries that manufactured critical components for the U.S. Aerospace Industry.

He said emphatically that he wanted a "Hal Gegel" program. Dr. Thomas Tom asked, "Who's Hal Gegel?" The next day, Dr. Tom called me to decide for the General Electric and Pratt and Whitney Aircraft (PWA) to visit UES, Inc. to see our FEM casting software, and, of course, he wanted to size up our company. It was a good initial meeting, and for UES it was what we were looking for to help fund the development of the code to become a total casting design code and a database for the casting materials and their mold materials. Additional work was needed to create a mesh geometry needed for modeling the total process. The industrial group

[13] Howmet Castings, a division of Alcoa, is an American world leader in the investment casting of super alloys, aluminum and titanium primarily for jet aircraft and industrial gas turbine engine components. Headquartered in Cleveland, Ohio, Howmet also provides hot isostatic pressing, titanium ingots and protective coating services.

decided to go forward with a DARPA Casting Modernization Program, and the success of this program rested entirely on UES's Processing Science team to complete the technical part of the program. We were the technical leaders of the program and Howmet was the business leader, much like how the AF Man-Tech Forging Tech-Mod program was set up.

Writing the proposal was no easy task, because there was a lot of "deal-making" along the way mostly between UES and Precision Cast-parts Corporation (PCC), the largest aerospace casting corporation in the world at that time. The Vice-President of PCC's research division was concerned about the size of UES, and always argued that we may not be around when the industry needed them. He remained an impasse to further discussions until I called his bluff.

It was late one Sunday afternoon at the PWA factory at West Palm Beach, FL when this debate was in progress, and I was concerned with the amount of time and money we were wasting not dealing with the program content. I stood up and said, "Since this discussion was about our capability to deliver results, we will go out of the room and you can vote to either work with us or exclude us from the DARPA casting program." My stand shocked some of the people, including Dr. Kris Joshi, the President of our company.

They voted to keep us as the software developer, and the proposal writing proceeded without any glitches. Sometimes one must take a stand! One minor glitch did occur when a group of scientists at Oak Ridge National Laboratory (ORNL) held a workshop via announcement in the *Commerce Business Daily* to seek funding (about $50,000/company) from the Casting Industry to create new casting software. I responded to the call for participation and was denied permission to attend. Interesting enough, an acquaintance from ORNL called me and said, "the reason you were not invited was because they considered me to be a competitor."

The reason for not allowing me to participate in the workshop was a joke. ORNL, at that time was getting more than one-billion dollars/year from the Department of Energy to support their research program. ORNL is the largest science and energy national laboratory in the Department of Energy by annual budget. So how could a small business like UES compete with them.

The constituents of our DARPA proposal, represented by Howmet, General Electric, and Pratt and Whitney Aircraft asked the ORNL if they had seen our software, and their answer was they had not! While the Oak Ridge meeting was in progress, I contacted Dave Hobson our Representative in Congress to appraise him of the situation and learned that national laboratories should not compete with small businesses.

ORNL sent several representatives to UES to see a demonstration of our FEM ProCAST software, and they were greatly surprised at what they saw. To bring our disagreement to an end, UES offered to give ORNL our software to use, and they accepted our offer and put it on one of their massively parallel supercomputers in exchange.

The DARPA casting initiative had another government agency cooperating, which was NIST—the National Institute for Science and Technology. The ProCAST code could now model every industrial casting process, model microstructure evolution, and compute the phase diagram of n-component casting alloys. The capability to calculate stress was added as a new feature. ProCAST™ also had a new robust and advanced automatic mesh generator.

Using this casting program was labor intensive, because it required technical support to manage its progress in reaching a solution. Nevertheless, a solution was possible in the form of Computer-Aided Optimization (CAO) that would also act as a software robot. Optimization software was the missing software element. It was needed to dramatically reduce optimal-product design time, engineering labor and manufacturing costs.

Another DARPA Project

Jack Welch[14] made a strategic decision when touring the GE Gas Turbine Engine Division, Cincinnati, Ohio. He saw that the GE engine designers were spending more time writing software code for design optimization than they were designing engines; he remarked, "GE's job was designing engines, not software." He subsequently gave the optimization code, to the Corporate Research Division (CRD) and told them to own the code and improve it, and he went one step further. He told these scientists that if they resigned and started their own business he would give them the code. These GE scientists took the challenge and founded Engineous Software Inc. This act paved the way for another DARPA project to advance the state of the art of design. A Multidiscipline Process Design and Optimization (MPDO) metasystem is compulsory to overcoming major obstacles to producing good products and process design rapidly. DARPA's direction switched from analysis to design for productivity enhancement.[15]

Invariably, a team of engineers from diverse disciplines meld their knowledge in ad hoc ways to obtain a solution. Although it may be acceptable, it will not be optimal. To reach an optimal solution, the simulation codes must be used correctly, and to avoid errors caused by tedious labor of manual operations. A software robot is needed to free engineers for other duties. DARPA decided to support development of a versatile MPDO metasystem.

The metasystem should be capable of driving simulation codes from multiple disciplines for achieving superior designs in less time. The iSIGHT system by Engineous Software[16] evolved from this program. It is a comprehensive application with a user-friendly graphical interface. This new development allows engineers to produce products with optimal shapes, weight and performance, which eliminates material waste and WIP, and numerous other benefits for the products manufactured.

These new digital technologies are providing a means for vastly improving process and product designs that are truly *optimal*—a new way for them to become globally more competitive while enhancing their profits**.** Manufacturing companies have become software companies and a trained workforce is essential. Jobs are "plentiful," but we do not have the skilled technicians and engineers to fill the slots**.**

Forging & Casting Companies Merge into Parts Manufacturing Organizations

An interesting business event happened because of these developments. Wyman-Gordon became a subsidiary of Precision Casting Corporation, and Howmet Castings became a Division of Aluminum Company of America (ALCOA), which makes precision forgings. What has happened is these companies changed from being either casting or forging manufactures to becoming parts manufacturing enterprises. The two forging and casting simulation codes driven by the iSIGHT application allows these companies to manufacture optimal products by the most suitable processes and materials.

Lessons Learned in Hindsight

All of us are influenced in life by many different people and events and new technology, such as wars, depressions, recessions, floods, droughts, tsunamis, fires, teraflop and laptop computers, smart phones, and manufacturing by 3D Printing. Lessons

[14] John Francis "Jack" Welch, Jr. is a retired American business executive, author, and chemical engineer. He was chairman and CEO of General Electric between 1981 and 2001. During his tenure at GE, the company's value rose 4,000%.

[15] DARPA awarded GE Corporate and Engineous Software Inc. a project to create a *Rapid Design and Exploration and Optimization* MPDO meta system. MPDO accomplishments are documented in: *Handbook of Workability and Process Design, edited by* G.E. Dieter, H. A. Kuhn and S. L. Semiatin, ASM International, Metals Park, Ohio, 44073-0002, 2003, 323-376. `

[16] A small business very good in process integration and optimization.

learned in hindsight teaches us much about how to develop and implement new technology in industry to improve manufacturing productivity and to maintain an educated middle-class work force. History is a good teacher!

Productivity has always been a periodic issue over the centuries. The U.S. Aerospace industry's problem in the 1970s was related to the obsolescence of process design technology, worker productivity, waste and work-in-process (WIP) that took place in the Machine worldview that was instituted during the Industrial Revolution of 1750. Nowadays, in 2018, it is still a productivity issue— except it is occurring in a new Digital archetype. In the Industrial Revolution, machines complemented human skills, while in the 21st century, computing-power and robotics are substituting for workers with low skill sets.

In hindsight, the Materials and Manufacturing Directorates during the 1970s kicked-off the digital revolution with the AFCAM and Processing science projects that were launched by the then AF Materials Laboratory, the U.S. Aerospace Industries and American Universities. Contributions that were made by all laboratory employees tell the story of how the U. S. metalworking industry once again became a global leader in manufacturing. Let's examine a few of the many individuals that drastically changed the productivity of workers and the cost of manufacturing Air Force weapon systems.

History Is a Good Teacher

Looking back at the people who made it all happen and contemplating about why things happened as they did almost always provide some insights and wisdom that should be passed on to future workers and managers of technology. Drs. Lovelace and Lowey recognized the importance of academia and government scientists understanding each other's needs and barriers for effectively working together. Dr. Kelley understood the necessity of testing new ideas by experimenting with small systems. He called this "Turning the Crank." Dr. Burte always stressed that each project leader should be continuously looking for a future "Window of Opportunity." The Air Force does research and sponsors research and development because they are looking for a path to achieve national security goals and a path to controlling mission costs.

The "Putting Science into Processing and Manufacturing" taught us that one of government's key roles is being a broker—whose prime responsibility is to bring scientists, engineers, technologists and managers together. Thus, government's role is that of a third person facilitator between industry and providers of new technology.

Air Force scientists generally do research to understand the idiosyncrasies or nature of the problem that they must help solve. These government scientists will write the statement of work, define its scope, suggest an approach, and define the deliverable items. And they must make certain when writing this statement of work that no new and better approach to the problem is excluded.

These government scientists are motivated by what is best for the United States. The United States Government as a broker of new technology assures that new advances in science and technology are shared among academia and the industrial base. This sharing promotes economic growth and education of all workers.

Diversity of talents and personalities plays the most important role in achieving project goals. We witnessed how diversity was instrumental in steering the project on a dynamical path of least action. Diversity is essential because changing from an analog to a digital system is very complex, and change is too complicated for a single person to manage the program alone.

The project manager's job is like that of a symphony conductor leading a group of musicians, where each performer is capable of being a soloist. All soloists must play in harmony for the orchestra to deserve standing applause from the audience. Three decades later, after reviewing the collaborations between the Air Force, DARPA, Academia and Industry, this program was a resounding success. It is still alive today, and the primary design, optimization and integration technology used to manufacture structural elements for aerospace and industrial applications is continuously improving.

Who Contributed and What Did They Contribute

- The CEOs of the Aerospace Industry gave the research teams full access to every stage of the manufacturing operations and permission for workers to share their honest ideas. This is important, because a manufacturing organization consists of a collection of activities; and each activity has inputs, controls over the work, a means to accomplish the activity, and outputs to other activities. The workers in each activity were free to share information about how work gets done and where they thought improvements in efficiency could be obtained.
- The engineers, activity leaders and technologist provided the information needed to establish the AS-IS state to enable the knowledge workers to create a new TO-BE organization. This is the requisite information needed for re-engineering a company and its manufacturing activities— some vital information cannot be obtained from the executives, because they typically are unfamiliar with the exact details of how production work is done.
- The senior laboratory executives shared their experiences gained as they rose through the business and manufacturing hierarchies to provide different approaches that can be used in the planning and execution of the research project and beyond basic research. For example, the Chief Scientist's sharing of his positive experiences associated with "Turning the Crank" to assess and check hypotheses on small systems. The Director of a Research Division provided guidance for achieving the intended project goals by driving toward a "Window of Opportunity" rather than simply doing research to just publish a paper which would build his or her resume.
- The project manager's role was setting the stage for the "soloists" to become trusting friends that share enthusiasms about each other's work, which almost always leads to innovative break-through ideas.

The AFRL Directorates of Materials and Manufacturing Technology are a community, a collection of people working together and with others for a common purpose.