

Materials by Design®

ADVANCED COMPUTATIONAL MATERIALS DESIGN

Accelerating the invention, design, development and insertion of new enabling materials

Such as Commercially-Available

Ferrium® M54®

Ferrium S53®

Ferrium C61™

Ferrium C64®

QUESTek®
INNOVATIONS LLC

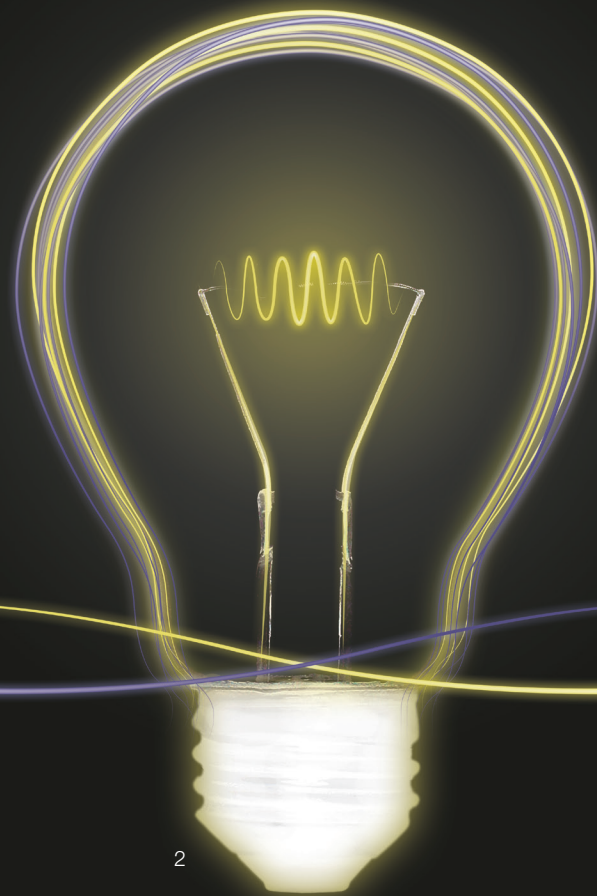
Having imagined, created and proved the field of ***Materials by Design***[®], QuesTek today designs, invents and brings to market never-before-conceived materials for breakthrough products across diverse industries, dramatically increasing efficiency in development while significantly improving product quality, cost-effectiveness and sustainability.

A Global Leader

QuesTek Innovations LLC is internationally recognized as a leader in computational materials design technology and its practical application. QuesTek rapidly designs, invents, develops, qualifies and inserts novel, valuable engineered materials using its proprietary *Materials by Design*[®] computational technology and expertise, reducing development times by as much as 50+% and costs by 70+% as compared to traditional empirical material development methods.



What if Edison could have designed a filament material, instead of testing thousands?



Turning Product Ideas into Reality

What if Thomas Edison could have designed a filament material for his electric light bulb instead of testing thousands, or if Shockley, Bardeen and Brittain could have designed semiconductors for transistors? Design engineers, R&D leaders, technical program officers and others can now work with QuesTek to rapidly design, develop and insert new engineered materials that meet specific user-defined properties and needs, instead of selecting off-the-shelf materials or trying traditional inefficient, time-consuming, trial-and-error methods to create materials. What impact could your product application or idea have if it was improved with unique, superior, purpose-designed materials?

Creating Competitive Advantages

QuesTek's mission includes providing a favorable return to our investors and stakeholders while creating real value and greater competitive advantages for our clients, licensees and development partners, such as:

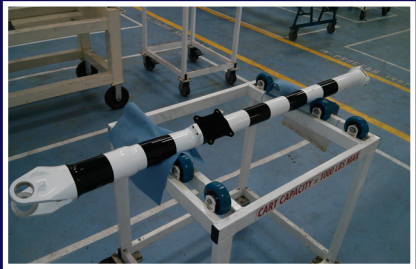
- new or better products that use superior, patent-protected materials
- lower capital, operating and maintenance costs for engineered materials and products
- reduced risks, costs and timelines for material and product development projects
- greater environmental protection
- optimized or more robust supply chains
- improved manufacturing, production and processing operations
- greater insights into tomorrow's products and technologies

Putting to Work a Materials by Design Vision

QuesTek's technology and business model disrupts the status quo. While the spiraling cost of traditional "trial and error" development methods has often reduced innovation in the materials industry, QuesTek is demonstrating its vision that many significant material inventions can be made using its Materials by Design computational approach. By integrating physics-based computational models within a systems-based framework on a proprietary software platform, QuesTek systematically optimizes material performance by computer (from concept through full scale-up), even before the first prototype is created and tested. And by licensing its intellectual property (IP) to leading producers, processors, or OEMs, materials no longer need to be discovered — they can be computationally designed and rapidly commercialized!



Ferrium C61 has demonstrated greater strength, durability and toughness than alloys 9310 or 8620 in more than 100 installations in SCORE off-road desert racing. Typical C61 applications include power transmission shafts and gears where weight savings, compactness, high temperature resistance, high surface fatigue resistance, and simplified manufacturing steps are valued.



Ferrium M54 offers ultra high strength and toughness for use in demanding applications such as the hook shank for the Navy's T-45 aircraft. In 2013, the Navy qualified M54 hook shanks (one pictured above) with more than twice the service life over incumbent Hy-Tuf steel. QuesTek is serving as the prime contractor and will deliver 40 components in 2016, with a cost savings to the Navy exceeding \$3 Million.

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QuesTek sees tremendous opportunity to apply ICME technology and its Materials by Design methodology to develop optimized chemistries for powder and wire-based additive manufacturing processes. QuesTek has led multiple projects to design additive manufacturing-friendly alloys based on Al, Ni and W, and our castable Ti-6-4 alloy is being evaluated for additive manufacturing processes.

Products

Commercialization Via Licensing IP

QuesTek commercializes its patented materials through licensees, such as leading commercial producers, processors, OEMs, trade associations, organizations or agencies.

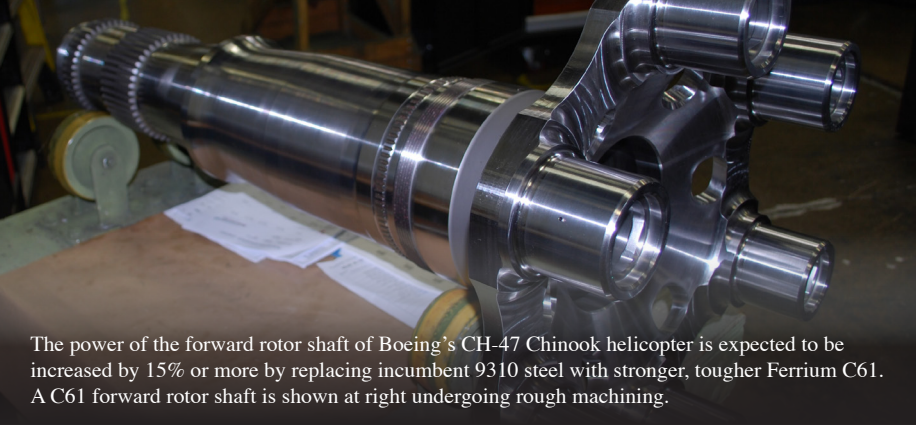
Commercially-Available Materials Include:

Ferrium® S53® (MMPDS; AMS 5922) is an ultra-high-strength, corrosion-resistant steel for structural aerospace and other applications where 300M and 4340 are typically used but more corrosion resistance is needed. S53 was computationally designed to have a unique combination of ultra high strength and much greater resistance to general corrosion, stress corrosion cracking (SCC), fatigue and corrosion fatigue than 4340/300M. S53 landing gear are flying without Cadmium plating on Air Force platforms such as the A-10, T-38 and C-5 and soon on the KC-135.

Ferrium M54® (MMPDS; AMS 6532) is an ultra-high-strength, high-fracture-toughness fatigue resistant steel with very high resistance to SCC considered a performance upgrade from 300M and 4340 where strength or SCC are an issue. M54 was computationally designed to be a cost-effective competitor to premium alloys such as Aer-Met® 100 (AMS 6532).

Ferrium C61™ (AMS 6517) is a high performance carburizing steel that offers high core strength, high fatigue strength, high fracture toughness, high temperature resistance, high hardenability and surface (i.e., case) hardness up to ~61 HRC. It is currently being qualified to replace 9310 on various flight critical components of drive system on Boeing's Chinook helicopter, with production starting in 2019.

Ferrium C64® (AMS 6509) is a high performance carburizing steel that offers high core strength, high fatigue strength, high temperature resistance, high hardenability and surface hardness up to ~64 HRC (exceeding that typically achieved by conventional gear steels such as 8620, 9310, EN36 or Pyrowear® 53). It was also designed to permit mild gas quenching and use conventional low-pressure/vacuum carburization technology. C64 steel is being evaluated in the U.S. Army-funded Future Advanced Rotorcraft Drive systems (FARDS) program with Bell Helicopter.



The power of the forward rotor shaft of Boeing's CH-47 Chinook helicopter is expected to be increased by 15% or more by replacing incumbent 9310 steel with stronger, tougher Ferrium C61. A C61 forward rotor shaft is shown at right undergoing rough machining.

Materials in Design and Development

As illustrated on the following pages, QuesTek is designing and bringing to market materials across a wide variety of base element systems, including:

aluminum 13 Al 26.982	titanium 22 Ti 47.867	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94
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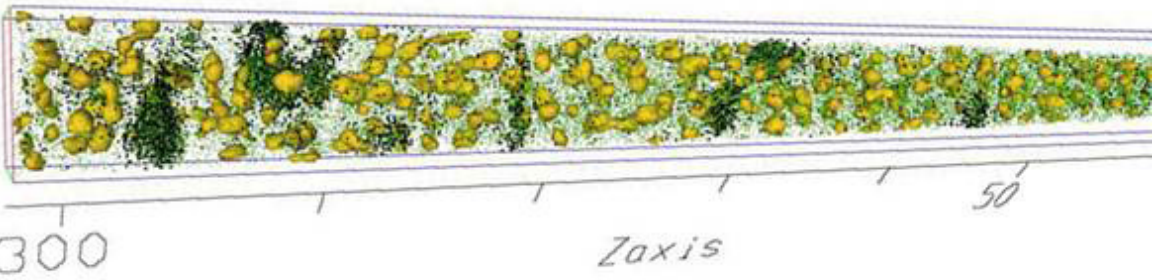
Services

Material Design

QuesTek computationally designs, invents, develops, qualifies and inserts new engineered materials into practical real-world service, working for and with industry/OEMs, end-users, governmental agencies, associations, producers, processors and others, to capture opportunities or solve problems such as:

- Reduce product cost or weight
- Improve product durability
- Eliminate excessive wear
- Increase high temperature operability
- Reduce hydrogen embrittlement
- Minimize galvanic, SCC or general corrosion
- Extend low-cycle or high-cycle fatigue life
- Eliminate/reduce undesirable or toxic coatings
- Reduce use of strategic, rare or toxic elements
- Establish competing material options

QuesTek's computational design technology applies to many material systems including alloys, polymers, ceramics, and composites. QuesTek designs materials with our client's end goal in mind (considering full-scale processing issues from the start), and uses mechanistic design models to achieve material properties such as: tensile or fatigue strength; general corrosion or SCC resistance; fracture toughness; creep; ductile-to-brittle transition temperature (DBTT); coefficient of thermal expansion (CTE); electrical conductivity; martensite start (Ms) temperature; thermal stability; thermal conductivity; solidification segregation; and others.



Technology Development

QuesTek continues to advance the forefront of computational material design science, technology and physics-based modeling tools (including underlying theory), working both independently and with highly-regarded partners from industry, government and academia. For example:

Digital 3-D Microstructure Design Modeling

During 2006-2010, QuesTek led a team that integrated various multi-scale tomographic microstructural characterization tools with higher-fidelity 3D microstructural simulation tools to enable greater accuracy in materials design and development. Our team members in this \$5.7 million program funded by the U.S. Defense Advanced Research Projects Agency and the Office of Naval Research were: Colorado School of Mines; Georgia Institute of Technology; Massachusetts Institute of Technology; Northwestern University; Scientific Forming Technologies Corp.; and the University of Michigan.

Microstructure Modeling

During 2006-2009, QuesTek completed a NASA-funded project entitled "Microstructure Modeling of 3rd Generation Disk Alloys." Using its PrecipiCalc software, QuesTek modeled, validated and predicted precipitation microstructure evolution for 3rd generation Ni-based gas turbine disk superalloys during processing and service.

Fatigue Modeling

During 2011, QuesTek is performing a U.S. Air Force-funded project entitled "3D Tomography-Assisted Mechanistic Fatigue Modeling and Life Prediction for Dual Microstructure Heat Treated Aeroturbine Disks." QuesTek partnered with a leading OEM and with Prof. David McDowell of the Georgia Institute of Technology, and others to use a microstructure-sensitive fatigue modeling framework to predict location-specific life of DMHT disks.

Serving Private and Public Sector Clients

QuesTek serves commerical clients, governmental clients and others. Most of our work for commercial clients is confidential. The U.S. government has been a leader, supporting the creation and development of computational material design technology. For example, QuesTek’s Materials by Design technology was a key component of two programs sponsored in 2000 by the Defense Advanced Research Projects Agency (DARPA) that were instrumental in establishing this field: the Accelerated Insertion of Materials (AIM) program; and the Structural Amorphous Metals (SAM) program. A representative listing of QuesTek’s customers and project goals/deliverables follows:

U.S. Government

ARL	Ballistic Armor Steel
DARPA	MoCr Superalloys for High-Temperature Service
Dept. of the Air Force	High Strength Soft Magnetic Alloy
Dept. of the Air Force	High Strength Thermally-Stable Aluminum Alloy for Aircraft Wheels
Dept. of the Army	Low Cost Castable Titanium Alloy
DOE	Oxidation- and Creep-Resistant Niobium Superalloy for High Temperature Turbines
DOE	Oxidation- and Creep-Resistant Alloys for Coal-Fired Power Plant Boilers
DOE	Advanced Oxide-Dispersion Strengthened Steels for High Temperature Use
DoD SERDP	Corrosion Resistant Steel for Structural Applications in Aircraft
Marine Corps	Low-Cost, High-Strength, High-Toughness, Corrosion-Resistant Steel
Marine Corps	Thermally Stable Cobalt-based Alloy
NASA	Microstructure Modeling of 3rd Generation Disk Alloys
NAVAIR	High-Strength, High-Toughness Steel for Carrier-Based Aircraft
NAVAIR	Alternative Materials for Beryllium Copper in Military Aerospace
NAVAIR	Functionally Graded Nano-Composite Steel for Helicopter Gear Applications
NAVSEA	Tuned Low-Voltage Sacrificial Anode
NAWCAD	Impact/Erosion-Resistant Environmental Barrier Coatings for CMCs
NAWCAD	Analysis and Modeling of Foreign Object Damage in Ceramic Matrix Composites
NSF	Nano-structured High Performance Shape Memory Alloys
NSF	Highly-Processable, High-Performance Nickel Superalloy for Heat Exchangers
ONR/DARPA	Dynamic “Digital 3D” Microstructural Design Modeling Consortium
OSD	Innovative Multiscale Modeling and Tools to Simulate Corrosion Behavior
OSD/ONR	SCC- and Corrosion-Resistant High Strength Aluminum Alloy

Commercial

Private Co.	Lead-Free, High-Strength Bronze Bearing Alloy
Private Co.	Structurally Integrated Coatings for Wear and Corrosion Resistance
Private Co.	Nickel-Based Super Alloys for Propulsion Application
Private Co.	High Silicon Cast Iron
Private Co.	Gypsum-Based Material Design
Private Co.	Hydrogen Storage Materials for Fuel Cells
Private Co.	Low-Cost, High-Strength Alloy for Drilling Applications

“*Ferrium S53®* was developed with only five prototypes over a two-year period resulting in a development cost savings of approximately \$50 million.”

DoD - DOE - EPA Strategic Environmental Research and Development Program Information Bulletin Number 15

Case Study



Ferrium C64 for NAVAIR

High-Strength, High-Case-Hardness, High-Temperature-Resistant Gear Steel
QuesTek computationally designed and developed Ferrium C64, a high-strength, high-surface-hardness, high-temperature-resistant, secondary-hardening steel for applications such as flight-critical rotorcraft drive shafts and transmissions, under STTR Phase I and Phase II funding from the U.S. Navy (NAVAIR). C64 was developed to reduce weight, improve fatigue performance, and provide high-temperature operating capability (e.g., better emergency oil-out survivability) relative to incumbent alloys Pyrowear® 53 and 9310. C64 can benefit high-performance power transmission applications where weight, compactness, durability and high-temperature capability are valued. C64 is emerging as the leading steel to replace Pyrowear 53 in next generation military helicopter transmissions. QuesTek has licensed production and sale of C64 to a leading U.S.-based specialty steel producer.



Ferrium S53 for DoD SERDP

Corrosion Resistant, Ultra-High-Strength Structural Steel
QuesTek computationally designed, developed and qualified Ferrium S53 to be an ultra-high-strength, corrosion-resistant steel in order to eliminate or reduce the DoD’s use of toxic cadmium plating on the incumbent steel 300M (BS S155). QuesTek’s efforts were funded in part by the DoD’s Strategic Environmental Research and Development (SERDP) program, with targeted applications being U.S. Air Force aircraft landing gear and other DoD platforms. QuesTek was awarded a “Pollution Prevention Project of the Year Award” by SERDP for its computational design of S53. QuesTek spearheaded the effort to obtain key industry codes and standards to adopt S53, such as inclusion in the MMPDS Handbook and SAE AMS 5922. S53 is being applied in both commercial and governmental service, and being considered across aerospace, power transmission, fastener and other diverse markets. QuesTek has licensed production and sale of S53 to two leading U.S.-based specialty steel producers. A T-38 landing gear in flight service without Cadmium plating is shown above.

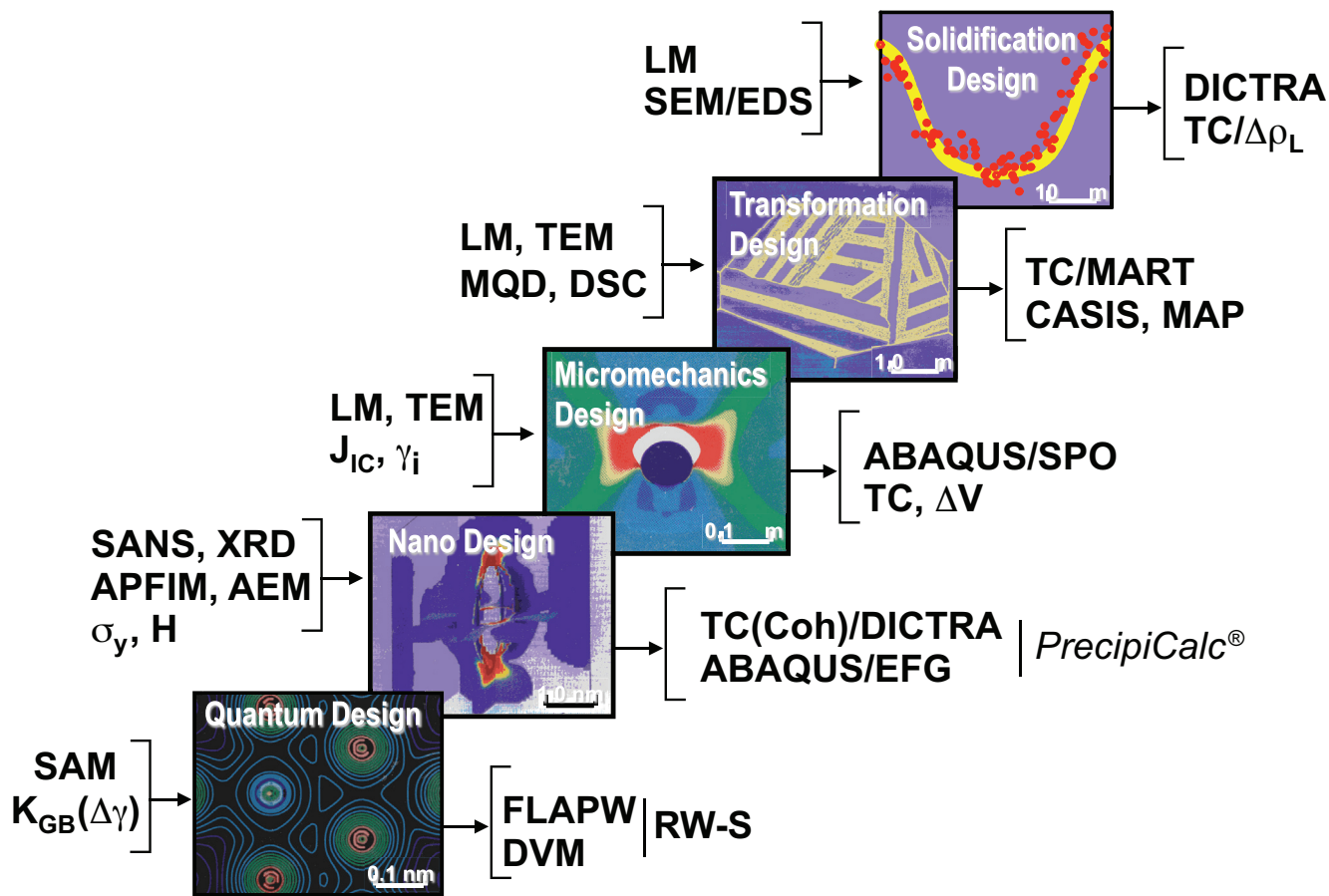
Core Competencies and Key Skills

Technology

QuesTek stands at the forefront of the technological shift from the historical “trial and error” method of materials discovery to computational materials design. The foundation of QuesTek’s technology is its systems-based and physics-based design framework that considers various interactions between chemistry, processing, microstructure and properties in order to achieve desired material performance. This foundation was laid by Gregory B. Olson, Sc.D., QuesTek’s Chief Science Officer and the Wilson-Cook Professor of Engineering Design at Northwestern University’s Department of Materials Science and Engineering, who has led more than 30 years of fundamental research to create a more productive and efficient method for materials development.

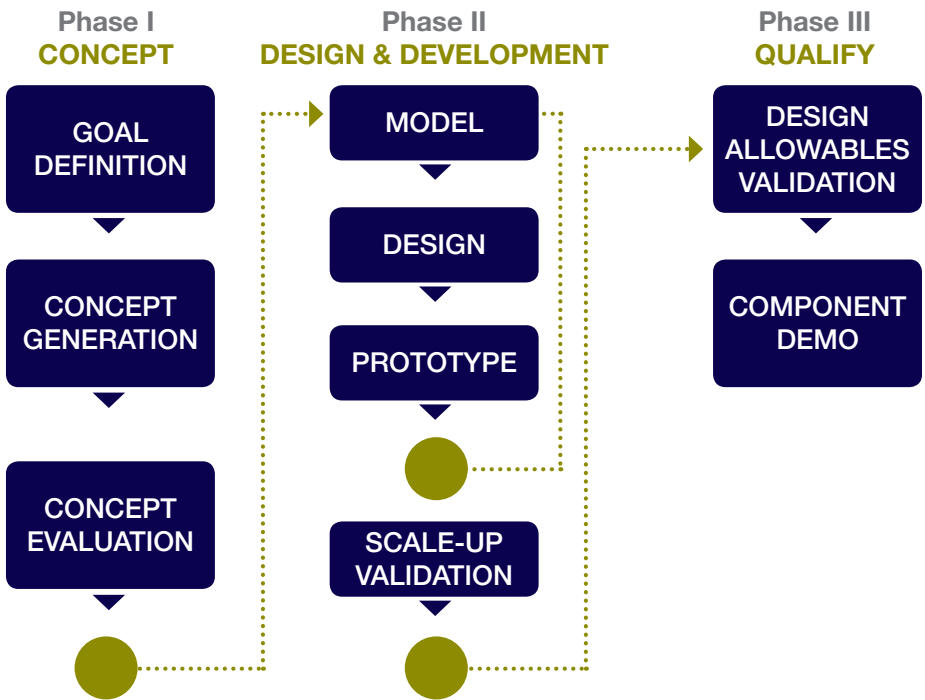
The result is QuesTek’s *Materials by Design* technology and approach, which evaluates materials as systems and uses a proprietary, robust computational modeling platform that integrates fundamental physical parameters of materials and material databases with higher-level, physics-based modeling tools (such as QuesTek’s *PrecipiCalc*® multicomponent, multiparticle precipitation code, and strength, solidification, intergranular cohesion, toughness, and martensite/bainite transformation kinetic modeling tools). These higher-level modeling tools (which are mechanistic and modularized) can be extended to a wide range of material systems and fundamental material parameters in order to rapidly explore and optimize material solutions, and design materials that deliver desired properties when produced at commercial scale using robust processing paths.

Materials by Design uses a hierarchy of computational modeling (right) and analysis tools (left).



Design and Development

QuesTek integrates its *Materials by Design* computational approach and technology with a comprehensive stage-gate design and development process. QuesTek believes that it is the first firm to rigorously apply proven stage-gate development process steps to system-based, computational materials design and development efforts. This logical, deliberate methodology provides a means to: give Program Managers greater control and better understanding of risk factors associated with material design, development and scale-up; rapidly evaluate potential material design alternatives; invent unique, valuable, viable solutions; reduce project development risks and costs; achieve rapid speed-to-market; and use resources wisely. QuesTek typically divides its efforts into three stage-gate phases: Phase I-Concept, Phase II-Design and Development, and Phase III-Qualify.



Integrated Applied Focus

QuesTek is focused on delivering valuable new computationally-designed materials into real-world service rapidly, reliably and efficiently. To reduce our client’s project costs and risks, QuesTek provides Integrated Computational Materials Design™ service and augments its technology platform and stage-gate design and development process with other key iCMD™ skills, resources, and expertise.

Expertise in material prototyping and characterization to calibrate material models, validate material designs, procure sub-full-scale prototypes, and evaluate their structures at numerous length scales through a combination of: in-house laboratory equipment; external QuesTek-operated equipment; and independent laboratories, material testing firms, and niche producers.

Working to scale-up manufacturing by partnering with a wide group of producers, processors, suppliers and other firms to produce, process, test and insert materials at sizes ranging from pilot scale to full commercial scale.

Obtaining important industry certifications for materials by actively participating in governing technical associations in order to help develop the necessary codes and standards for design engineers to implement materials.

Obtaining valuable intellectual property by employing QuesTek’s rigorous stage-gate design and development process, and long-term relationships with leading legal firms.

Licensing IP and commercializing new materials with our licensees by negotiating and establishing licensing agreements, and then working with our licensees to accelerate sales and production.



History

QuesTek Innovations LLC began operations in 1997 to apply the disruptive computational materials design technology that originated from decades of fundamental research conducted at Northwestern University under the direction of Professor Gregory B. Olson. Dr. Olson has received numerous honors, including: election to the National Academy of Engineering; a Fellow of ASM International; and a TMS Structural Materials Distinguished Materials Scientist/Engineer Award.

Dr. Olson's vision was to create a technology that would use newly-available computing power and emerging physics-based models to design material structures from subatomic- to macro-scale, in order to rapidly create novel materials with tailored properties and performance. Olson and one of his graduate students created the first computationally-designed material — a patented steel for the demanding application of the Space Shuttle main engine turbo-pumps, under a grant from NASA. The success of this program led to the formation of QuesTek as an independent company. Both QuesTek and its principals have subsequently won numerous prestigious awards and honors for their accomplishments in technology and business.

Other Key Advantages

Staff and Management

QuesTek's staff are among those who have literally "written the books" and developed compelling real-world results that materials should be evaluated as systems, and that computational tools and methods can be used to predict properties and design materials. Today, QuesTek is professionally managed by a Board of Directors and its staff includes many of the foremost materials design engineers in the world, who advance the forefront of technology development and apply the deep insights of a market leader to the practical real-world application of computational materials design.

Licensing Approach

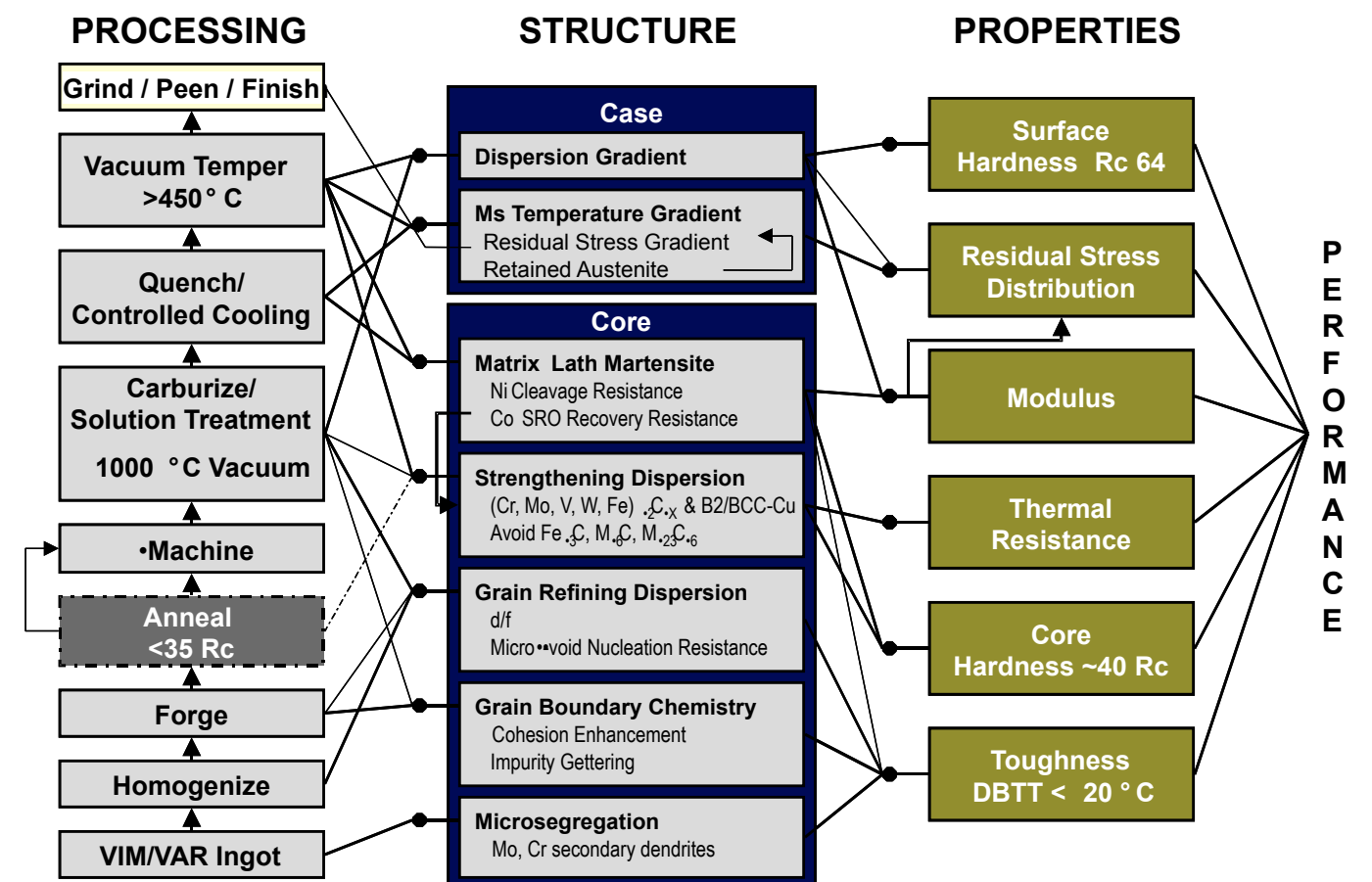
QuesTek's business model of licensing its intellectual property to others offers significant flexibility to its clients and partners:

- accelerate speed-to-market
- leverage industry expertise and infrastructure
- create optimized or more robust supply chains
- reduce risks and costs for material development/R&D projects
- improve manufacturing, production and processing operations
- bolster key industries for economic and employment growth

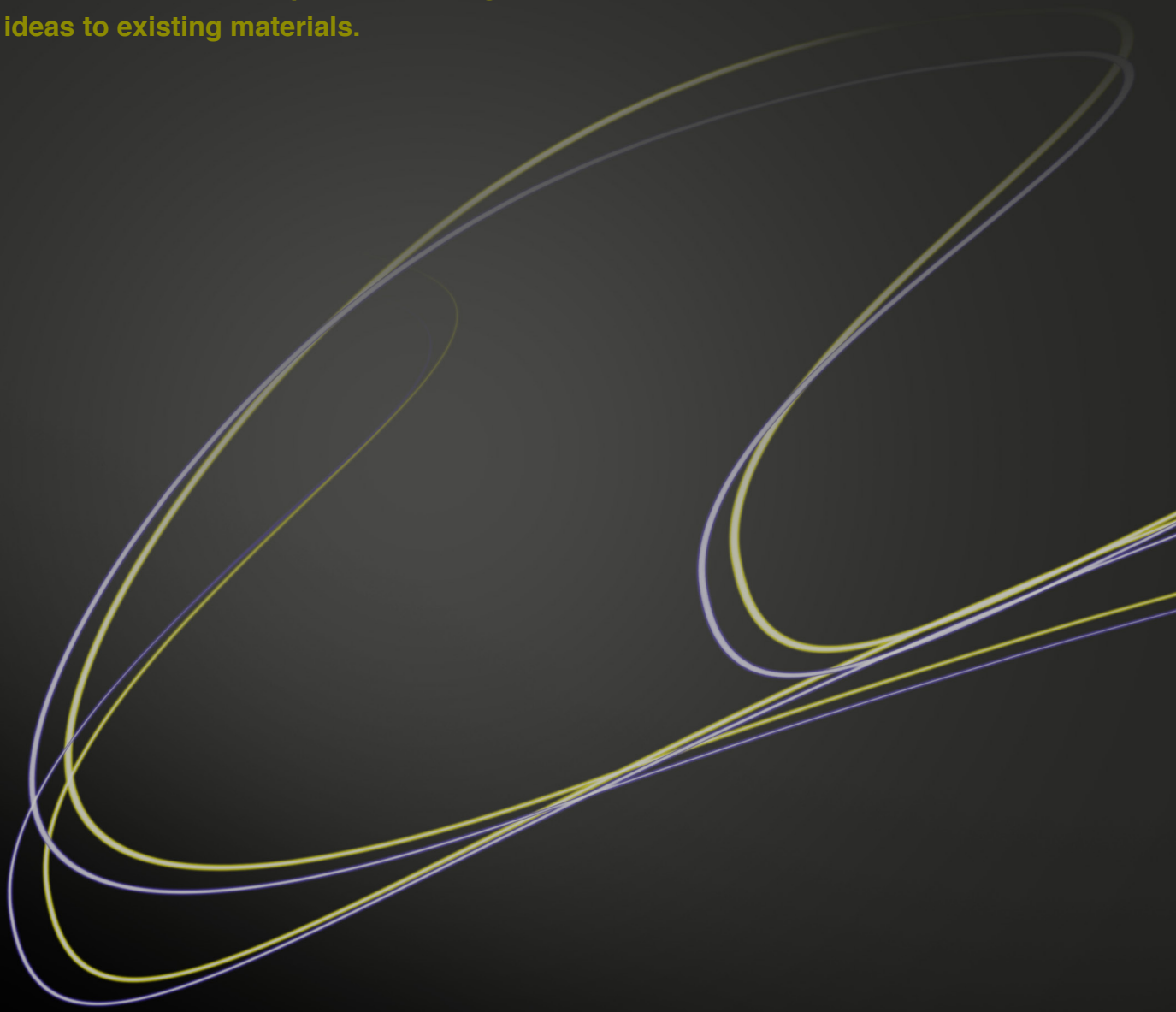
Resources and Relationships

QuesTek is located at 1820 Ridge Avenue in Evanston, Illinois, USA, approximately 0.75 mile (1.2 km) west of Northwestern University's Evanston campus. It operates from a wholly-owned, 12,000-ft² (1,100-m²) facility, which contains offices as well as infrastructure for computational materials design, characterization (such as Scanning Electron Microscopy and standard metallography) and some prototype production. QuesTek's state-of-the-art computational resources for modeling, design and software development include advanced engineering workstations and its proprietary software platform. To augment its in-house testing facilities and expertise, QuesTek has close relationships with individuals at many leading companies/OEMs, governmental agencies, academic institutions, associations, producers, processors, and testing and evaluation companies. For example, QuesTek is a member of Northwestern University's Tech Corporate Partners program, and personally utilizes a variety of sophisticated analytical facilities and techniques, including Atomic Absorption Spectrometry, the Electron Probe Instrumentation Center, high-resolution transmission electron microscope, and surface characterization equipment. QuesTek also has access to the university's Atom-Probe Field-ion Microscopy Center, which contains a new 3D LEAP atom-probe for atomic characterization at the nanoscale level.

"System Design Chart" used by QuesTek for initial design of Ferrium C64



With QuesTek, product designers, engineers and users can create or improve products using new, purpose-designed materials, rather than limit their products, designs and ideas to existing materials.



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