# AMPTIAC

## QUARTERLY

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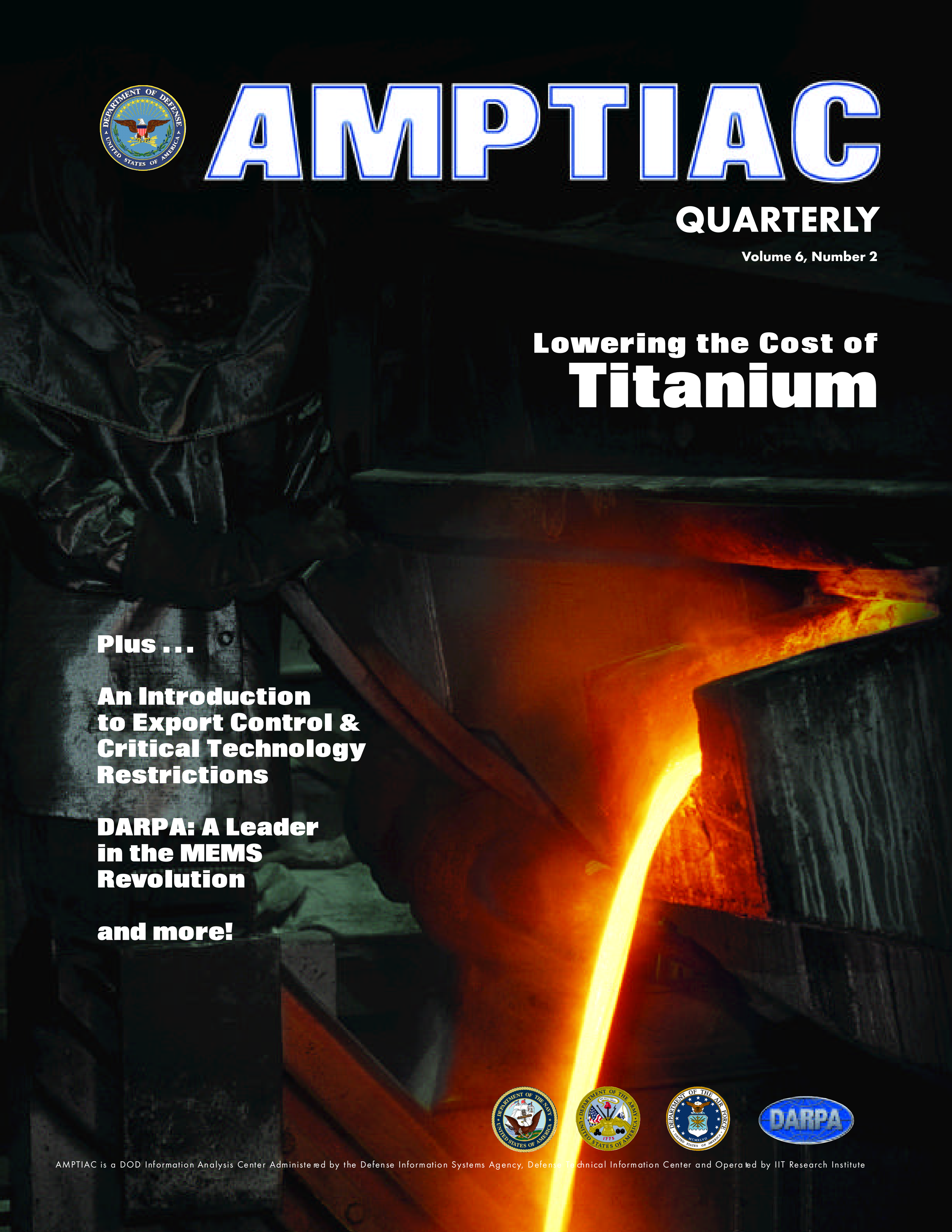

## Lowering the Cost of Titanium

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## Editorial: AMPTIAC at the Crossroads

For the highly observant among our readership, you may have noticed that this is the first issue of the newsletter in quite some time that does not sport a theme of any kind. Referred to as a “general issue” by our staff, it represents the more traditional format of the newsletter as it was published from our beginnings in the fall of 1996 through calendar year 2000. However, our newsletter paradigm has shifted so rapidly in the past fifteen months that it would be closer to the truth to call it revolutionary rather than evolutionary. Four consecutive themed issues – computational material science (two issues), aging aircraft, and most recently, nanotechnology – I can vouch for our entire staff that it was a busy and challenging year!

I would like to take this opportunity to thank everyone who has responded so positively to our recent special edition newsletter on nanotechnology. We are greatly encouraged by all the feedback: so much so in fact, that we are now in the planning stage for our next special edition newsletter, with several more concepts on the drawing table. Our hope is to make these special editions semi-regular occurrences, through which we intend to highlight a critical or emerging technology of prime interest to our readership. Interspersed between such special editions, we will continue to publish our general issues, as there never will be a shortage of late-breaking developments throughout the materials and defense communities. It is through this balance that AMPTIAC will continue to promote the activities and achievements in materials and related technologies, while also bringing noteworthy topics to the forefront on their own merits.

The developments with our newsletter are only one aspect of AMPTIAC’s continuing growth. In the nearly six years since our inception, we have evolved from a merger of five predecessor organizations (MMCIAC, MIAC, CIAC, HTMIAC, and PLASTEC), operating in parallel under one roof, each under the guidance of it’s own technical director; to a fully integrated information center serving the materials and processes needs of the entire materials and defense communities. In recognition of this milestone, the last vestiges of our segregated beginnings are being phased out. With the full integration of our technical and information services, AMPTIAC moves forward as a singular and united voice of the DOD’s materials and technology interests. If you peruse our directory page, you will see that it reflects much of this change.

While most of these changes will be transparent to all but those who are most intimate with AMPTIAC’s operations, their effects will become quickly apparent to those who seek our services. AMPTIAC will be an even more responsive partner, providing timely, efficient, effective support to our DOD, government, and industrial clients in the areas of directed materials support, technology transfer, technology insertion, and information services. Moreover, AMPTIAC will serve as the advocate for critical technologies, raising awareness and bringing them to the attention of the community.

Lastly, the Newsletter, or Quarterly as we have now come to calling it, is at a crossroads as well, representing both an ending and a beginning. This is certainly the case here. This issue also marks the passing of the torch, as we bring new leadership to its helm. After two years overseeing the operations of the newsletter, I am handing over the reigns to our new Editor-in-Chief, Wade Babcock. Wade has been an instrumental force behind many of our themed issues in the past year and veritable fountain of creativity. He has helped forge this new vision for our most visible publication, and shares my commitment to serving you, our reader, as the clarion for reliable, relevant, and cutting edge information in materials and technologies. I wish him the best of luck in this great new adventure and ask that you give him the same enthusiasm and support that you have afforded me. Here’s to a bright future!

My sincerest thanks,

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# Lowering the Cost of Titanium

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## Introduction

To many, the mere mention of 'titanium' might conjure up images of an SR-71 Blackbird streaking through the upper reaches of the atmosphere at amazing speeds. Movie enthusiasts might envision the nearly indestructible space shuttle fleet in *Armageddon*. Discovered late in the 18th century, the engineering potential of titanium was not fully realized until the invention of the Kroll Process in 1948, making titanium available and feasible for defense and industry endeavors[1,2].

What makes titanium so attractive to designers and engineers? Titanium is lightweight, corrosion resistant, and has high strength. The density of titanium is about half that of copper and nickel and approximately 60% of stainless steel. Aluminum, magnesium, and beryllium are the only base metals that are lighter than titanium, none of which come close to titanium in mechanical performance (except beryllium with respect to stiffness). The strength of titanium and titanium alloys ranges from ~205 MPa (30 ksi) to ~1585 MPa (230 ksi).

Titanium exhibits the highest strength to density ratio of all metals to 550°C (1020°F) (see Figure 1). In many environments, particularly those where oxidizing conditions exist, it is more corrosion-resistant than stainless steels and copper alloys, especially when subjected to saltwater.

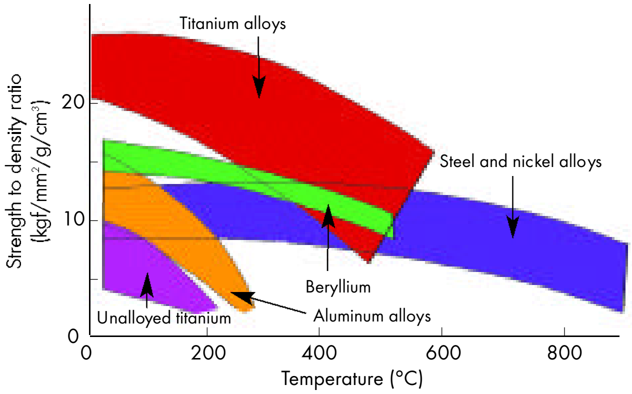


**Figure 1. Strength to Density Ratio vs. Temperature of Various Metals[3]**

Other potentially useful design characteristics are its low thermal and electrical conductivity, good ductility, excellent fracture resistance, non-magnetic property, non-toxicity, bio-acceptability, cryogenic properties, shape memory properties, and hydrogen affinity (for hydrogen storage). Titanium is very customizable through alloying and microstructural manipulation, which can be tailored to improve performance of a wide range of applications. In fact, titanium alloys often provide designers the best combination of mechanical properties available among metals.

## The Economics and Market Potential of Titanium

Those of us with the disease "titaniumitis" believe that all of the wonderful properties of titanium approach those of "unobtanium," a popular (and fictitious) material desired in many designs. Why is titanium not more widely used than say aluminum or steel? Is it a rare and precious metal? No, titanium is the fourth most abundant metal in the earth's crust (0.86 % by weight) behind aluminum, iron, and magnesium. The answer is cost! Titanium is difficult to extract from its ore, difficult to process, and difficult to fabricate. Just accounting for the extraction and processing costs to produce ingot, titanium is ~30 times more expensive per pound than steel and ~6 times that of aluminum. The cost gap for titanium widens when fabricating components and structures. Table 1 shows a cost comparison of the various stages of metal production.

If titanium were as cheap to produce as steel or even aluminum, performance standards on nearly everything we use would be much higher than what we see today; supersonic jetliners could be commonplace, automobile fuel efficiency would be substantially higher, structures would be safer, and so on. Most experts agree that the world production of titanium is much too small given the outstanding combination of favorable properties. With current production at ~50,000 tons (2001), one estimate puts titanium production and use at ~1/20th of its current potential world volume[5]. This severe under-utilization of titanium is easily understood when considering the cost drivers.

Historically, titanium has experienced anemic growth when compared with aluminum and stainless steel alloys. The high cost of production limited the use of titanium to applications requiring high performance or where life cycle cost analyses justified its use. The aerospace and defense communities stimulated initial development of titanium alloys in the early 1950's. Aircraft development during the Cold War was performance-driven without much regard to cost. A radical example of this was the SR-71 Blackbird reconnaissance aircraft, with over 90% of the structure being titanium.

The growth potential and cost cutting initiatives of titanium were severely limited by the dependence upon the cyclic nature of the aerospace industry, with the market experiencing 4-5 year cycles of boom and bust. During boom periods, users were only interested in rapid access to material, leaving very little time for development of low cost techniques; bust periods had few resources available for low cost techniques[5]. Cost conscious markets, such as the automotive industry, are reluctant to commit to titanium because of the unpredictability of the cost fueled by the boom and bust economics. However, with world production of 60 million vehicles annually, even 1 lb of titanium in 50% of the vehicles produced would increase titanium use by 30%, helping to stabilize the cost and reduce dependence on the aerospace industry.[4]

Cost cutting potential and initiatives as shown in Table 1, every stage of titanium production except the mining of ore has tremendous impact potential on the final cost of titanium products. Regarding ore mining, the cost of ore is highly dependent on demand, thus cost reductions will naturally result from a major increase in the demand for titanium products. When considering cost reduction, it is strategic to focus on the early stages of production, where any realized cost advantages would be carried through all production stages. The cost of metal extraction from the ore is approximately 20 times that of steel on a 1-to-1 weight basis, but roughly 11 times when accounting for the density advantage of titanium (less titanium would be required to perform the same function as steel).

In an effort to reduce the cost of producing titanium and other metallic structures the Metals Affordability Initiative Consortium (MAIC) was formed. It is comprised of a team of aircraft and jet-engine manufacturers, material suppliers, and aircraft component suppliers; and directed by the Air Force Research Laboratory's (AFRL) Materials and Manufacturing Directorate[6]. As part of this program, significant efforts are currently underway to reduce the cost of titanium products, many of which are covered in this review.

### Low Cost Extraction Initiatives

Shortly after the commercialization of the thermochemical Kroll process in the 40's and 50's Dr. Kroll himself predicted that an electrochemical process would soon make titanium production much more cost competitive:

> "It might…..be fair to say, that titanium will be made
> competitively by fusion electrolysis within the next 5
> to 10 years."[7]

This prediction has yet to be commercially realized, making the Kroll and Hunter[8] (similar to Kroll using Na in place of Mg) processes the norm even today. Unfortunately, thermochemical processes, such as the Kroll and Hunter processes, hold little potential for significant cost reductions beyond current technology.

Electrochemical extraction is still considered a key technology needed to significantly reduce the cost of titanium. Major advantages of electrochemical extraction are reduced energy consumption, automation, and continuous production. Following the evolution of the steel and aluminum industries, if a viable electrochemical extraction process were developed for titanium then there would be tremendous potential for evolutionary technological improvements and optimizations. As the process matures, it would facilitate continual cost reductions.

#### *Electrolytic Extraction of Titanium*

Since the invention of the Kroll process, much research has been directed in an attempt to develop an electrolytic extrac-

**Table 1.** **Cost of Titanium – A Comparison[4]**

| | **Steel** | **Aluminum** | | **Titanium** | | |
|---|---|---|---|---|---|---|
| Production Stage | \$/lb<br>(\$/in$^3$) | \$/lb<br>(\$/in$^3$) | Factor to Steel | \$/lb<br>(\$/in$^3$) | Factor to Steel | Factor to Aluminum |
| Ore Extraction | 0.02 | 0.10 | 5 | 0.30 | 15 | 3 |
| Metal Refining | 0.10<br>(0.028) | 0.68<br>(0.066) | 6.8<br>(2.3) | 2.00<br>(0.33) | 20<br>(11.8) | 2.9<br>(5.1) |
| Ingot Forming | 0.15<br>(0.043) | 0.70<br>(0.068) | 4.7<br>(1.6) | 4.5<br>(0.73) | 30<br>(17) | 6.4<br>(10.6) |
| Sheet Forming | 0.30-0.60<br>(0.085-0.17) | 1 – 5<br>(0.098 – 0.49) | 3.3-8.3<br>(1.2-2.9) | 15 – 50<br>(2.44-8.14) | 50-83<br>(29-48) | 10-15<br>(17-25) |

tion process. Many technical and economic challenges have hindered success in this endeavor, including: [5]

- Incomplete understanding of molten salts in fundamental electrochemistry[5]
- Boom-bust economics of the titanium industry[5]
- Difficulty developing adequate oxide diaphragms to divide the cell into anolyte and catholyte compartments,
- Not enough analysis of experiments performed on non-diaphragm cells.
- The multivalence of titanium ions requires a separation between anolyte and catholyte to avoid alternating oxidation and reduction with low current efficiency.
- In the chloride system, some electrolyte gets trapped in the Ti crystals, requiring additional processes to remove the electrolyte. This operation decreases the purity of the produced Ti.
- Fluoride systems did not receive enough financing because of the preference toward the chloride system.
- No real financial sponsor outside the titanium producer community.

Current research focuses on overcoming the technical challenges identified above from decades of electrochemical research on titanium extraction.

### *FFC Cambridge Process*

A novel new approach to electrochemical extraction is the patented Fray-Farthing-Chen (FFC) Cambridge process. Schematically shown in Figure 2, this process does not require the metal oxide ($TiO_2$) or chloride ($TiCl_4$) to be dissolved in the electrolyte as with traditional electrolytic processes; it remains in a solid state during the electrolytic process. This new technique shows tremendous promise and it has been projected that it could reduce in the cost of titanium extraction by as much as 50% or more by 2010.

Like many useful inventions, the FFC Cambridge Process was discovered by accident. Originally, Derek Fray, Tom Farthing, and George Chen were experimenting with electrolysis of titanium in molten $CaCl_2$ to remove oxygen impurities from titanium. Oxygen impurities (dissolved oxygen interstitials in a titanium matrix) can strengthen the material, but at the same time make it brittle, so the intent was to purify titanium metal and remove the dissolved oxygen (note that the dissolved oxygen impurity is not the same as the $TiO_2$ layer that a titanium surface immediately develops upon exposure to air).

The purification experiment revealed something quite unexpected; the titanium oxide layer was converted to low oxygen titanium. This process was counterintuitive because $TiO_2$ is usually considered an insulating material, so the researchers did not even expect the electrolysis experiment to affect the $TiO_2$ layer. They then tried the same experiment on pure pellets of $TiO_2$ and produced pure titanium sponge with a similar structure as that produced using the Kroll process. The researchers discovered that the slight removal of oxygen from $TiO_2$ through electrolysis resulted in Magnelli phases, which are good electrical conductors, ultimately enabling the complete electrolysis of $TiO_2$.

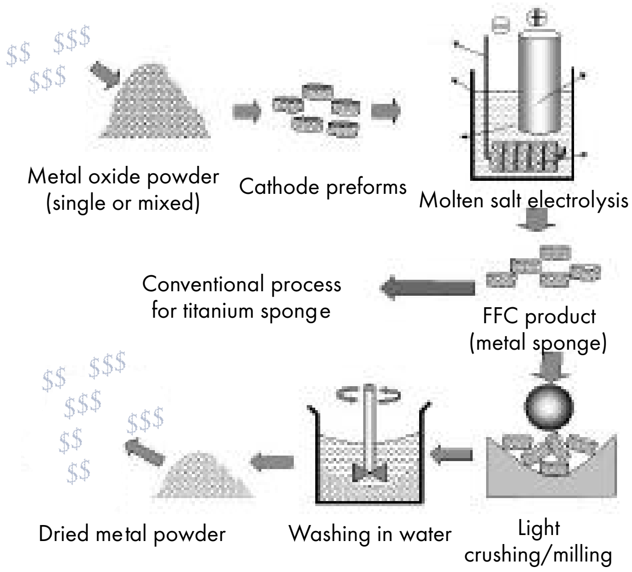


**Figure 2.** **Schematic of the FFC Cambridge Process (courtesy D. Fray, Cambridge University)**

The FFC Cambridge process has the potential to revolutionize the titanium industry. Potential and real advantages over the Kroll and Hunter processes include:

- Low cost feed material ($TiO_2$ instead of the costly $TiCl_4$);
- $CaCl_2$ is readily available, inexpensive, non-toxic, water soluble, and has a high solubility for oxygen;
- Rapidly produced titanium sponge (~1/5th the time required using the Kroll process);
- Potential to directly produce alloys by mixing oxides of various metals;
- Potential for continuous production which enables significant cost reductions (Kroll and Hunter processes are batch processes requiring significant time, labor, and resources);
- Potential to produce high purity titanium and alloy powders for use in near net shape powder metallurgy technologies.

The FFC Cambridge process has yet to reveal any major pitfalls for scaling up. In fact this new process may revolutionize metal extraction for numerous metals including zirconium, niobium, chromium, vanadium, and numerous other periodic groups (III-X) and rare earth elements.[9, 10, 11]

## Low Cost Melting Initiatives

### *Ingot and Wrought Stock*

Introduced in 1952, the vacuum arc re-melting (VAR) process is still the most common process for alloyed titanium and aerospace commercially pure (CP) grade titanium (unalloyed)[12]. Analogous to the Kroll and Hunter processes for extraction, VAR is still utilized because a commercially viable alternative has not emerged to completely replace this expensive process. The disadvantage of VAR is that the material must be double- and sometimes triple-melted to produce adequate purity and microstructure. Much of the research in this area is focused on replacing or optimizing VAR.

Electron beam hearth-melting (EBM) has seen limited success and is the primary method for producing industrial CP grades[13]. EBM and plasma hearth-melting (PAM) are strong candidates for producing high quality alloys for jet engine applications, reducing the likelihood of inclusions seen with double melt VAR. Advantages of EBM and PAM are improved quality, scrap recycling, and shaped ingot production. These technologies are beginning to be utilized for alloy production by the major titanium producers (Timet, Allegheny Teledyne-Oremet Facility, RMI Titanium).

Additional initiatives to reduce cost of these technologies are to optimize process control and develop process-modeling capabilities in order to optimize quality and minimize cost. A strategy that is gaining momentum is to eliminate this step altogether and use near-net shape technologies such as investment casting and powder metallurgy processes.

### *Casting*

The high cost of titanium often forces designers to look for ways to minimize waste material often associated with the more conventional manufacturing processes such as machining.One cost reduction strategy that has received considerable focus and development resources is on near-net shape techniques such as casting, powder metallurgy (P/M), superplastic forming (SPF), and forging.

Often, cast metals show much lower mechanical properties as compared with wrought metals, however, cast titanium properties compare very well with their wrought counterparts and in some cases, exceed those of wrought, especially when considering crack growth and fracture properties. This makes casting of titanium products a very attractive option to reduce cost and optimize engineering performance. However, titanium casting technologies have historically experienced technical challenges that have hindered development and widespread use.

Recent technology and process improvements (many through the MAIC program) have enabled significant improvements in the quality of cast parts, helping to meet stringent aerospace specifications. Investment casting comprises most of the current capacity, however, some development has taken place to enable permanent metal-mold die-casting of titanium[14]. Advantages of metal-mold casting include improved microstructure and elimination of ceramic inclusions and alpha-case (a shell of alpha-phase titanium), however, this technology is size- and shape-limited.

Investment casting technologies have matured nicely. Induction skull-melting (ISM) and VAR melting produce titanium melts with minimal contamination. Ceramic and metallic mold materials have been selected to minimize reaction with the titanium melt. Hot isostatic pressing (HIPing) is used to improve the density by eliminating porosity, thus improving the overall quality of the casting. Investment castings can be quite large and complex, combining many components into one complex structure, making them a clear choice for many complex aerospace applications[15]. An additional advantage is that lead times for castings tend to be shorter as compared with conventional processing such as forging and machining.

Information technology initiatives such as computer-aided design and computer-aided machining (CAD/CAM) and process modeling are drastically improving investment casting capabilities and quality. CAD/CAM technologies are being used in conjunction with rapid prototyping to produce complex parts for making investment molds. Process modeling techniques are being developed to optimize gating and risering of investment casting molds to optimize microstructure, reduce shrinkage and voids, and improve quality[12].

Other research on titanium investment casting technologies includes novel cold crucible induction melting and centrifugal casting. Induction technologies enable the charge to be superheated. When combined with centrifugal casting, this promotes the filling of thin section cavities, improves properties, dimensional accuracy, form, and detail and reduces the cost of melt stock as compared with VAR investment casting. Some induction technologies enable partial to full levitation of the charge, reducing the cost of melt stock and reducing waste.[16, 17]

## Low Cost Processing Initiatives

### *Forging*

Computer and sensor technologies have been incorporated into forging processes to control heating time and strain rate, improving die filling and reducing forging defects. Isothermal forgings are also being investigated and developed, taking advantage of technology since this process lends itself to more control and flexibility.[18] Process modeling and control technologies are also used to time impacts enabling metadynamic and static recrystallization and to dissipate adiabatic heating.[12]

### *Powder Metallurgy (P/M)*

P/M techniques afford designers the ability to produce significantly complex near-net shape parts at a potentially significant cost savings, with very little wasted material. Traditionally, P/M techniques required high volume runs (generally above 10,000 pieces) and relatively small parts to be cost effective. This is due to the high cost of equipment for P/M processing. Also, concerns remain regarding the quality and properties of P/M produced parts, especially from lower cost blended elemental powders (BE). The much higher priced prealloyed (PA) powder, produced by gas atomization (GA), or the plasma rotating electrode process (PREP) lead to mechanical properties equivalent to cast-and-wrought products [19-22]. Good news is on the horizon on several fronts of P/M technologies.

Powder Production Technologies The lower cost BE titanium powders coming from titanium sponge produced through conventional Kroll and Hunter processes contain chloride impurities. Chlorides inhibit production of 100% dense compacts, resulting in reduced weldability and fatigue properties.[23, 24] Recent developments in titanium extraction (FFC Cambridge Process) and powder production are aimed at reducing the cost and improving the quality of titanium powders.

Research is currently being carried out on an Army Research Lab small business innovative research (SBIR) project to produce very low cost titanium powders from cleaned machine turnings using the hydride/dehydride (HDH) process.[21] The aluminum-titanium (AlTi) process is one such approach for

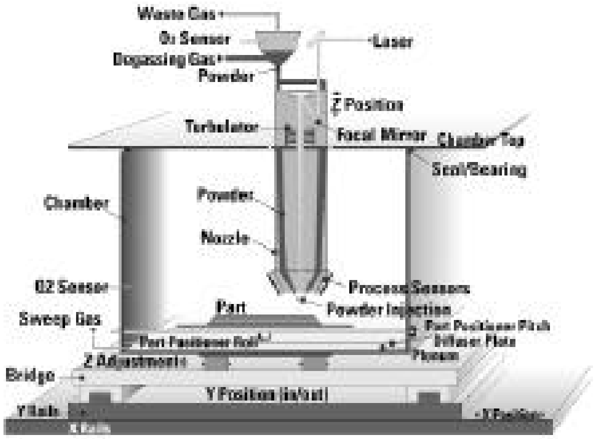


**Figure 3.** **Schematic of Laser Additive Manufacturing Process (courtesy AeroMet Corp., www.aerometcorp.com)**

**Figure 4.** **Laser Additive Manufacturing (courtesy AeroMet Corp., www.aerometcorp.com)**

producing these powders. It involves a reaction of $TiO_2$ with fluorine salts followed by reduction with aluminum. This process originally also produces very low chloride levels, however, it is not widely available.[22] Significant efforts are also being applied to optimize and adapt an elevated temperature metal hydride reduction (MHR) process developed in Russia[25] in conjunction with ADMA Products, Twinsburg, Ohio. This new process involves mechanically alloying (in a high energy ball mill) $TiO_2$ and/or $TiCl_4$ with $CaH_2$ to induce chemical reactions that produce Ti.[26]

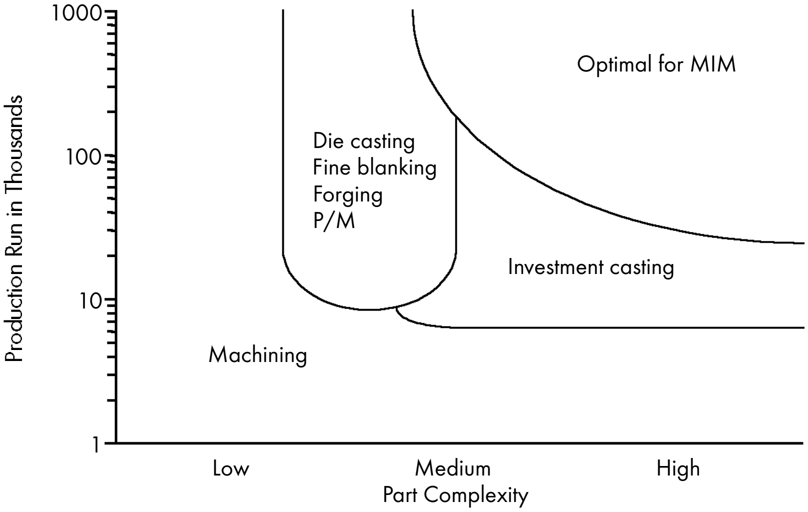
Laser Forming One of the most significant developments in the application of metal powders is the use of laser forming technologies to produce highly complicated, low volume parts (Figures 3 & 4). Advantages of this technology include short lead times, high complexity, significant cost savings, moderate size, and greatly reduced machining requirements. Costs are projected to be 15-30% less than conventional approaches and up to a 75% reduction in delivery time for low run, high complexity parts.[27]

Metal Injection Molding (MIM) Metal Injection Molding, also known as MIM, is an analog of plastic injection molding. It is a high-volume technology, where powdered metal is mixed with a binder and injected into a mold, de-bonded, and sintered to produce small complex parts at a low cost (relative to other techniques). Figure 5 shows where P/M and MIM processes are beneficial from a cost perspective. MIM technology currently exists with world volume at about 3 to 5 tons of parts per month. Recent and current developments are focused on improving density and properties through selection of improved binders (effective, but not adding significantly to the oxygen content of titanium) while maintaining its cost effectiveness. Titanium MIM is poised for substantial growth as a low cost means of producing high volume parts. A primary driver for this growth will likely be development of the low cost powder technologies previously discussed. [20, 28]

Traditional Powder Metallurgy Techniques Traditional P/M techniques include press and sinter, elastomeric bag cold isostatic pressing (CIP), and ceramic mold or metal can HIP. These processes can be carried out using BE or prealloyed (PA) powders.

The BE approach is potentially the lowest cost titanium P/M process available. Unfortunately, parts are limited in size and complexity, as well as less than 100% of theoretical density, which would adversely affect mechanical properties. Recent developments, such as using hydrided powders, have enabled the fabrication of BE parts to over 99% of full density, resulting in significantly improved properties. Further studies and developments show that this approach may be well suited to reduce the cost of producing automotive parts making titanium more cost competitive with other materials commonly

**Figure 5.** **Relative Applicability of P/M, MIM, and Other Ti Processes.[20]**



used in many automotive applications.[20]

PA powders are much more costly than BE powders, however, typical P/M parts produced using PA powders demonstrate superior properties than typical BE produced parts. In fact, the properties of both BE and PA parts are beginning to compare well with cast and wrought products, making P/M techniques increasingly attractive and cost effective alternatives to traditional processing.[20]

**New P/M Research and Development** Significant efforts in P/M research continue on numerous fronts such as spray forming, rapid solidification, mechanical alloying, and vapor deposition. All of these research initiatives are aimed at exploiting the outstanding characteristics of titanium and its alloys. Some of these processes are aimed at producing new alloys that improve and customize properties; alloys that cannot be developed through traditional processes.[20]

### *Superplastic Forming (SPF) and Diffusion Bonding (DB)*

SPF/DB is a technology receiving interest for its potential to reduce cost and improve the structural efficiency of aerospace components. The technology involves the bending and forming of titanium at slow strain rates under temperature and pressure to produce complex geometries at a much reduced cost over conventional processing. SPF/DB requires material that will superplastically form, and many titanium alloys work well using this technology. Current development efforts are attempting to make this process much more predictable and controllable through complex process modeling algorithms.[29]

### *Mass Production Initiatives*

As noted earlier, titanium usage remains at depressed levels as compared with its engineering potential. A major factor hindering widespread usage is cost, and it remains high because of low volume and the cyclic nature of the aerospace market. The automotive and other high-volume industries have shied away from titanium because of the prohibitively high cost. If these conditions were to change, then the cost of titanium products would rapidly and dramatically decrease. This is especially true when leveraging the manufacturing ingenuity of high-volume industries to optimize production and life cycle costs of systems.

As the mindset shifts from ultra high-quality and high-performance aerospace applications to mass production applications, many are discovering that costs of titanium components have become much more competitive, in large part because of the ingenuity of the commercial sector. As a result some initiatives are aimed at mass production techniques and how they can apply to existing applications.[4, 30]

## Applications and Outlook

### *Defense/Military*

Significant efforts and resources are being expended by DOD to help reduce the cost of titanium and to introduce titanium in applications to improve performance and reduce life cycle costs. MAIC (led by AFRL) is aimed at reducing the cost of metallic components in aircraft by 50% and accelerating the implementation time for these components. Much of the research through MAIC is directed at titanium technologies because of the added emphasis on life cycle costs and performance criteria of aircraft.[6]

The Navy's National Center for Excellence in Metalworking Technology (NCEMT) is investigating a single-melt cold hearth PAM process to help reduce the cost of titanium ingot. NCEMT is also aggressively identifying candidate systems and components that would benefit from the use of titanium. As part of this investigation, they are identifying low cost processes that will help them justify changing to titanium.[31]

The Army is actively and aggressively investigating the feasibility of using low cost titanium armor for combat vehicles. Experimental results are showing that titanium alloys maintain high mass efficiencies compared with rolled homogeneous armor (RHA) across a broad spectrum of ballistic threats. It also shows good multihit ballistic capability. This all equates to improved armor at a potential weight savings of 40% over RHA.[32, 33]

As part of the Army's initiative to transform itself into a lighter, more transportable force, they are investigating numerous other potential applications such as the use of Ti6Al-4V receivers for use in the M240 machine gun.[34] Titanium is also very attractive for personal armor because it possesses excellent ballistic properties and is lightweight.

### *Commercial Aerospace*

Titanium usage in the aerospace community has been widespread for years and will continue to be a material of choice for years to come. In fact, titanium usage continually increases on newer models of commercial aircraft. It is expected that usage will increase even further as unit costs come down and quality improves on new processes.

### *Industrial Markets*

Industrial markets primarily include the energy and chemical processing industries (CPI). This market segment accounts for the largest (~39%) consumption of titanium just ahead of commercial airlines (~36%).[35] The corrosion resistance of titanium makes it an ideal candidate for usage in many energy and CPI applications. Titanium is gaining significant interest in drilling and offshore production systems.[36, 37] It is predicted that the industrial market for titanium will grow 50% by 2010.[35]

### *Consumer Markets*

Consumer markets include automotive, medical implant, sporting goods, and specialized consumer goods such as wheelchairs. Titanium manufacturers are immensely interested in breaking into the family automobile market.

Any significant use of titanium in automobiles would help to significantly stabilize the economics of titanium supply and demand, enabling suppliers to ensure prices and supplies to customers. Immediate potential applications include exhaust systems, drive shafts, connecting rods, valves, valve springs, coil suspension springs, front and rear bumper supports, retainers, lug nuts and studs, shock center rods, sway bar fittings, strut center rods, and wrist pins, just to name a few.[4] One of the most significant uses of titanium in a production automobile is in the Corvette Z06 exhaust system, resulting in an 18 lb. weight savings over the stainless steel version. In life cycle cost studies, Chevrolet estimates that the titanium model will result in lower overall costs due to increased life and a drastic reduction in warranty claims.[38]

Sporting goods manufacturers are very interested in the performance enhancing characteristics of titanium in many applications. One attractive aspect to manufacturers is that sporting goods consumers are often willing to pay a premium for performance and prestige.[39] The corrosion resistance and biocompatibility of titanium has also generated wide interest in the medical community for transplants.

## The Future

More and more, engineers are coming to realize the benefits of titanium. This trend will continue and be enhanced through user education – potential consumers need to be made aware of its outstanding properties, emerging lower cost processes, and its potential benefits to the life cycle of new applications. Some have predicted that the 21st Century will be the 'Century of Titanium'. If so, what an exciting journey it will be!

## References

[1] W.J. Kroll, Z. Anorg. Chem., 234 (1937), p. 422.

[2] W.J. Kroll, Trans. Electrochem. Soc., 78 (1940), p. 35.

[3] F.H. Froes class notes, generated with source information from Lockheed Martin Co.

[4] K. Faller and F.H. Froes, "The Use of Titanium in Family Automobiles: Current Trends", JOM, 2001 April.

[5] M.V. Ginatta, "Why Produce Titanium by EW?", JOM, 2000 May.

[6] R. Martin and D. Evans, "Reducing Costs in Aircraft: The Metals Affordability Initiative Consortium", JOM, 2000 March.

[7] W.J. Kroll, Trans. Met. Soc. AIME. V. 215 (New York AIME, 1959), pp. 546-553.

[8] M.A. Hunter, J. Amer. Chem. Soc., 32 (1910), p. 330.

[9] G. Chen, D. Fray, and T. Farthing, "Direct Electrochemical Reduction of Titanium Dioxide to Titanium in Molten Calcium Chloride", Nature, 407, 21 September 2000.

[10] D. Fray, "Emerging Molten Salt Technologies for Metals Production", JOM, 2001 October.

[11] G. Chen and D. Fray, "Electro-Deoxidation of Metal Oxides", Light Metals 2001, Ed. J. L. Anjier, TMS, 2001.

[12] D. Eylon and S.R. Seagle, "Advances in Titanium Technology – an Overview", J. JILM, 50 (2000), pp. 359-370.

[13] E. Poulson, "Status of the Melting of Titanium Using VAR and/or Electron Beam or Plasma Hearth Technology", AIME Annual Meeting, Cincinnati, OH, 1999 November.

[14] R.R. Boyer, J.C. Williams and N.E. Paton, "Evolving Aerospace Applications for Ti Alloys" Proceedings of the 9th World Ti Congress, St. Petersburg, Russia, June 1999.

[15] S. Veeck, D. Lee, and T. Tom, "Titanium Investment Castings", Advanced Materials & Processes, January 2002.

[16] G. Broihanne and J. Bannister, "Using Cold-Crucible Melting for Titanium Precision Castings", JOM, May 2000.

[17] S. Reed and J. Narayan, "Induction Skill Melting Offers Ti Investment Casting Benefits", Industrial Heating, January 2001.

[18] D. Furrer, "Forging Aerospace Components", Advanced Materials & Processes, March 1999.

[19] F.H. Froes, P/M in Aerospace and Defense Technologies, ed. F.H. Froes (Princeton, NJ: MPIF, 1991), pp. 5-33.

[20] F.H. Froes, "Developments in Titanium P/M", Future issue of Metal Powder Report.

[21] V.S. Moxson, O.N. Senkov, and F.H. Froes, "Innovations in Titanium Powder Processing", JOM, May 2000.

[22] F.H. Froes, "The Production of Low-Cost Titanium Powders", JOM, September 1998.

[23] F.H. Froes and D. Eylon, Int. Mats. Reviews, 35 (3) (1990), p. 162.

[24] S. Abkowitz and D. Rowell, JOM, 38 (8) (1986), p. 36.

[25] B.A. Borok, *Trans. Of Central Research Institute for Ferrous Metallurgy*, Moscow, Russia, 43 (1965), pp. 69-80.

[26] V.S. Moxson, O.N. Senkov, and F.H. Froes, "Production and Applications of Low Cost Titanium Powder Products", Int. J. of PM, 34 (5) (1998), p. 45.

[27] F. Arcella and F.H. Froes, "Producing Titanium Aerospace Components from Powder Using Laser Forming", JOM, 52 (5) (2000), p. 28.

[28] F.H. Froes and R.M. German, "Cost Reductions Prime Ti PIM for Growth", Metal Powder Report, 55 (6) (2000), p. 12.

[29] E.D. Flinn, "Stretching the Uses of Titanium", Aerospace America, 36 (6) 1998, p. 20.

[30] C. Sommer and D. Peacock, "Mass Production Methods for Titanium Automotive Components", Titanium '95, Vol. II, (Birmingham, UK: Institute of Materials, 1996), p. 1836.

[31] *National Center for Excellence in Metalworking Technology: 2001 Annual Report*, Concurrent Technologies Corporation, 2001.

[32] J.S. Montgomery et al., "Low-Cost Titanium Armors for Combat Vehicles", JOM, 49 (5) (1997), p. 45.

[33] J.S. Montgomery and M.G.H. Wells, "Titanium Armor Applications in Combat Vehicles", JOM, 53 (4) (2001), p.29.

[34] "Development of Robotic GMAW Workcell for Fabrication of Ti6Al-4V Machine Gun Receivers", *The Newsletter Dedicated to Titanium*, 2002 (II) (ITA, 2002).

[35] F.H. Froes, "The Titanium Image: Bouncing Back", JOM, 53 (4) (2001), p. 26.

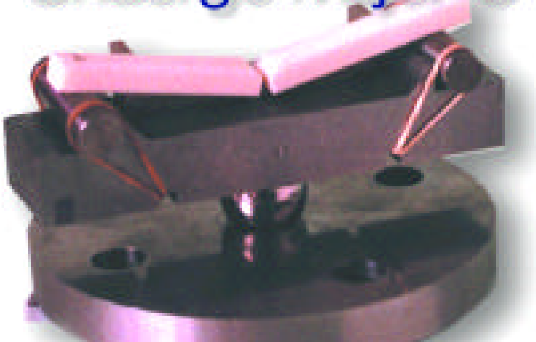
[36] R.W. Schutz and H.B. Watkins, "Recent Developments in Titanium Alloy Application in the Energy Industry", Materials Science and Engineering, A243, (1998) p. 305.

[37] R.W. Schutz, C.F. Baxter, and P.L. Boster, "Applying Titanium Alloys in Drilling and Offshore Production Systems", JOM, 53 (4) (2001), p. 33.

[38] "Chevrolet Corvette Demonstrates Titanium is Priced Right for Production Cars", *The Newsletter Dedicated to Titanium*, I (IV) (ITA, 2000).

[39] V.S. Moxson and F.H. Froes, "Fabricating Sports Equipment Components via Powder Metallurgy", JOM, 53 (4) (2001), p. 39.

# Standards Update:
## Flexural Strength Specimens Undergo Major Overhaul



According to industry sources, 90% or more of the flexural strength specimens for advanced ceramics prepared in the United States conform to the “B” size (3 mm x 4 mm x 50 mm) in ASTM Standard C 1161, Flexural Strength of Advanced Ceramics (Figure 1). After 12 years on the books, this standard, which superceded the earlier MIL-STD-1942 was given a major overhaul to meet the contemporary needs of the ceramic community. ASTM Committee C-28 approved 26 revisions. The obsolete 1/8" x 1/4" x 2" specimen was dropped from C 1161. More guidance on the interpretation of fracture patterns was added to help users determine the fracture origin location. The biggest change was a major revision to the standard specimen preparation procedure.

The new surface grinding specifications include a requirement for final finish longitudinal grinding with diamond wheels between 400 to 600 grit as opposed to the former 320 to 500 grit range in the old C 1161-(1990) and the 200 to 500 grit range allowed by MIL STD 1942 (1983). The new finer finishing requirements are in response to industry requirements for strength test specimens that more closely match the finishes and preparation steps applied to today’s ceramic components (Figure 2).

The revised C 1161 became effective in March 2002 when ASTM printed the revised standard. Free detailed engineering drawings (shown schematically in Figure 3) of the new “B” specimens with the new machining specifications included are available upon request from Mr. George Quinn, Stop 8521, Ceramics Division, NIST, Gaithersburg, MD 20899, email: geoq@nist.gov.

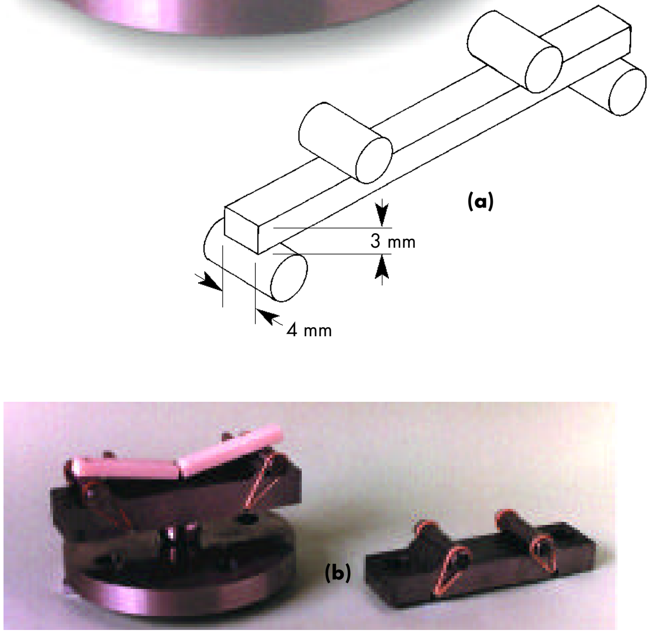


**Figure 1.** Simplified Four-Point Flexural Test (a) and Actual C 1161 Testing Jig (b)

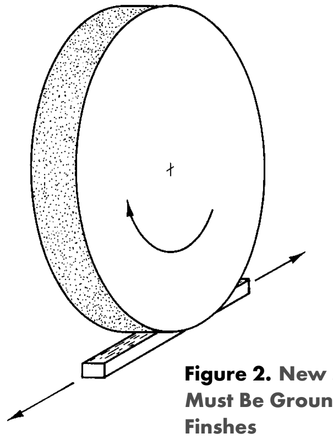


**Figure 2.** New Specimens Must Be Ground to Finer Finshes

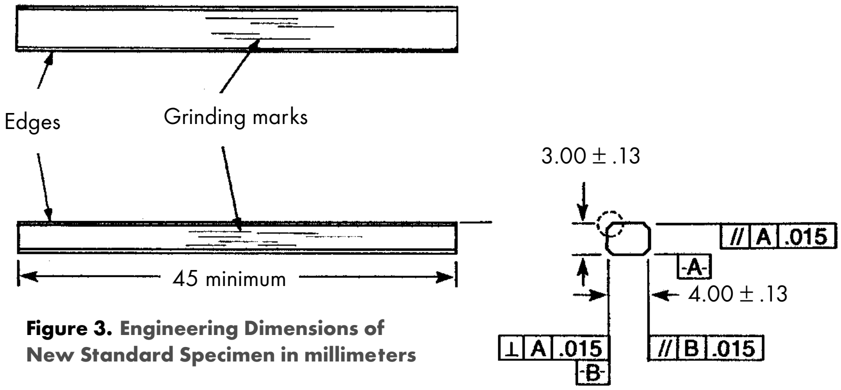


**Figure 3.** Engineering Dimensions of New Standard Specimen in millimeters

# Material EASE

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# Safeguarding America's Critical Technologies (and Avoiding Personal Risk)

## An Introduction to Export Control and Critical Technology Restrictions

All DOD researchers, both those employed by the Federal Government and those from the industrial base, become familiar with the regulations concerning classified documents and technologies early in their career. Use of safes, secure buildings and rooms, proper handling, labeling and storage are all part of the day-to-day world of dealing with classified information. But how much do you know about export control regulations and the control of data and technologies that, while not classified, are still vital to the warfighting superiority of the U.S.?

For instance, suppose an engineer develops an improved processing method for high temperature ceramics that enables near net shape manufacture of complex parts. A paper is prepared which details the production method and various materials used, and is presented at a Materials Research Society (MRS) conference. Forty people are in attendance during this particular session, and the paper is published in the proceedings of the conference. Does this engineer realize that a law may have been broken?

The Department of Defense is congressionally mandated to maintain a list detailing those critical technologies that help maintain the superiority of U.S. armed forces. Technologies on this list are considered for integration into the Department of Commerce's export control lists, such that proliferation may be limited. In the example above, the engineer, in a public forum, presented a processing method that may produce components with performance characteristics which provide a competitive military edge over our adversaries. Since this hypothetical critical information is now available in the conference proceedings, adversary nations could utilize that engineer's work to leap ahead of their current levels of capability. In this fashion, critical technology was allowed to fall into the hands of potential enemies, thus enabling them to stay abreast of our military capabilities

The Defense Department, through the Defense Threat Reduction Agency (DTRA), presently maintains a program called the Militarily Critical Technologies Program (MCTP), whose primary purpose is to prepare the Militarily Critical Technologies List (MCTL). This list, as specified by the 1979 Export Administration Act, is part of the mechanism which seeks to identify technologies critical to U.S. interests. It provides candidate inputs and technical justification for items placed on the Commerce Control List (CCL) and International Traffic in Arms Regulations (ITAR) administered by the Departments of Commerce and State, respectively. The MCTL is also used as a reference tool for evaluating potential technology transfers and for determining whether technical reports and scientific papers are eligible for public release. (For a more detailed history of export controls and the MCTL, see the accompanying sidebar *History of Export Control Regulations*.) The current, public edition of the MCTL is on the Internet (http://www.dtic.mil/mctl) and is continually updated as progress is made on the technologies described in the basic document. For government and contractor personnel with access to the Defense Technical Information Center's STINET, a more complete version of the MCTL is available.

The MCTL provides a codification of what DOD believes to be critical to the military superiority of the U.S. In combination with sound technical judgment, the list may be used to assess whether a proposed transaction permits a technology transfer allowing potential adversaries access to technologies whose specific performance levels are at or above the characteristics identified as militarily critical. The list provides guidance, but is not an export control list in-and-of-itself. The MCTL should be used for initial guidance on the dissemination of critical technologies, and can provide input to export control policy.

### Critical Technologies in Action

Within the Defense community, there are various mechanisms set up to control proliferation of critical technologies. The most obvious are the procedures for dealing with classified materials, but less obvious are those intended to protect what are called critical technologies.

The first and last line of defense for protection of critical technologies is the researcher. Initial decisions about what to publish, what talks to give, and who to talk to, represent the first step in protecting data. The next step is divisional management and/or the Public Affairs Office of specific bases or labs (for government personnel). Contractor personnel follow their own company-specific internal procedures. The decision on whether to allow something to be published or presented in a public forum is ultimately left up to an individual that has the administrative authority to control release of technology. They will often utilize the assistance of senior technical staff in making complex decisions.

**Table 1. The Three-part Militarily Critical Technology List**

**Weapons Systems Technologies** (WST) provides details of those critical technologies whose performance parameters are at or above the minimum level necessary to ensure continuing superior performance of U.S. military systems. These technologies are selected from the population of technologies that are militarily significant (i.e., they provide measurable advantage to U.S. military systems or enhanced threats posed by potential adversaries).

**Weapons of Mass Destruction** (WMD) [only available in STINET] addresses those technologies required to develop, integrate, or employ biological, chemical, or nuclear weapons and their means of delivery. Technical subsections are included which cover means of delivery, information systems, biological, chemical and nuclear weapons, as well as nuclear weapon effects. Hybrid combinations of advanced and older effective technologies and innovative uses of other technologies that provide threatening weapons capabilities are also included in this section. One of the most critical issues regarding the technologies discussed in Part II is that they become militarily effective even when not developed to their full capability.

**Developing Critical Technologies** (DCT) identifies those critical technologies that provide new or superior performance or maintain superior capability more affordably and support one or more of the Joint Chiefs of Staff (JCS) warfighting objectives outlined in the JCS *Joint Vision 2020*. It also takes cognizance of the Secretary of Defense Quadrennial Defense Review (QDR) and defense plans. The technologies included are candidates for militarily critical technologies, international cooperative programs, and national and international export control. Because of its complexity, it is being issued section by section. Some example sections cover aeronautics, armaments and energetic materials, directed and kinetic energy technologies, lasers, optics, nuclear technology, sensors and signature control technologies. Materials and processing technologies are also covered specifically; examples include armor/antiarmor, electrical, optical, high temperature and high strength structural materials.

**Table 2. Example Material Classes Included in the Weapons Systems Technologies and the Developing Critical Technologies Sections of the MCTL.**

| **Metallics** | **Non-Metallics** |
|---|---|
| Advanced Aluminum and Magnesium Alloys, Tungsten, Copper, Tantalum, Molybdenum and Depleted Uranium (Monolithic) | Ceramic Matrix Composites (CMCs), Polymer Matrix Composites (PMCs), Structural Carbon-Carbon Composites |
| Discontinuously Reinforced Metal Matrix Composites (DRMMCs) | Optical, IR Coatings, Non-linear Optics |
| Advanced Titanium, Titanium Matrix Composites (TMC) and Titanium Aluminide Composites | Various Composites Designed for Kinetic Energy Absorption to Resist Fragmentation or Impede Shock Wave Transmission |
| Gamma Titanium Aluminide | Low Thermal Expansion Structures |
| Advanced Intermetallic Alloys | High-Thermal Conductivity Structures |
| Ultralightweight Metallic Materials and Structures | Silicon Carbide, Titanium Diboride, Boron Carbide, Advanced Monolithic Ceramics |
| Nanocrystalline Materials and Structures | Metallic-Organic Laminates |

For researchers at accredited institutions of higher learning performing fundamental research, there is a blanket exemption from the requirements of export control. According to the amended Code of Federal Regulations (CFR) Title 22, Parts 123 and 125, these institutions do not have to register the export of data or equipment produced solely for, or from, fundamental research. This policy has shifted back and forth from full and open disclosure to restricted release over the past 40 years, and currently there is congressional pressure to limit the exemption as it is currently written. The main exception to the exemption is when an academic researcher initially agrees to information restrictions as a condition of doing the research.

Beyond individual researchers and their departments, DOD has various mechanisms for controlling release of information including service-level offices and specific, joint-service offices set up for selected technology areas. These coordinating offices tend to focus on particularly sensitive technology areas such as low observables (signature reducing technologies) or directed energy (lasers, etc.). If a technology is controlled, there are criminal and civil penalties for their unauthorized dissemination, thus making the offender personally liable for the act. Additionally, companies who develop technologies (whether with government funding or not) are responsible for their control and can also be held criminally and civilly liable for unauthorized technology transfers.

Inappropriate transfer of technology is not limited to papers, journal articles, prepared talks and lectures, but can also include patents and sales of technology. In the case of defense-related patents, the Patent and Trademark Office (PTO) reviews each application for innovative merit; then it is assessed by various recognized experts within DOD. These experts will make recommendations about whether the technology is critical. If it is, then a patent may not be granted, thus keeping the technology out of the public record. When a U.S. company wishes to sell identified critical technology to another U.S. company, multinational company, or foreign company, the sale must be reviewed by DOD. The laws vary, depending on the specifics of each case, but basically the U.S. government has the right to stop a pending sale. Congressional action would be required to override this decision.

The Departments of State and Commerce also maintain lists of countries that are automatically considered off limits for release of critical technologies. There are six countries on this list, including Iraq, Iran, Cuba, North Korea, Libya and the Sudan. While export of critical technologies may be allowed to most other countries, export to the nations on this list is out of the question.

The penalty for unlawful export of items or information controlled under the ITAR is up to 10 years imprisonment, a fine of \$1,000,000, or both (22 U.S.C. 2778). Companies found to export information controlled under the Export Administration Regulations (commonly called the CCL referred to above,) can also be fined up to \$1,000,000, or five times the value of the export, whichever is greater. An individual named in such an action can be imprisoned for up to 10 years, fined up to \$250,000, or both. (50 U.S.C. 2410). Companies cited for export control violations are typically barred from obtaining export licenses for at least three years, and can potentially be barred from doing any business with the government.

The MCTL was developed as a three-part document, Weapons Systems Technologies (WST), Weapons of Mass Destruction (WMD) and Developing Critical Technologies (DCT). Each section addresses a major area of technology vital to the security and warfighting capability of the United States (see Table 1). Areas of greatest concern to the AMPTIAC community like high performance materials, advanced materials processing methods and improved manufacturing techniques are covered in both the WST and the DCT (see Table 2). Please note that Tables 1 and 2 address the broad materials classes that contain some critical technologies. Whether or not a material is deemed critical is entirely dependent upon its performance characteristics. For example Table 2 denotes tungsten as being addressed in the MCTL. However, this material is only deemed critical when it is processed in such a way that it has an elongation greater than 3%, a yield strength greater than 1250 MPa, an ultimate tensile strength greater than 1270 MPa, and a density greater than 17.5 $g/cm^3$. The reader is referred to the MCTL itself to determine the critical performance indicators for other materials of interest.

It should be emphasized that the MCTL is not a control list; it is a list of technologies that are of particular military importance. However, for a number of reasons (e.g., worldwide availability, controllability, etc.), some critical technologies listed on the MCTL are not subject to export controls. For the convenience of the reader, the MCTL lists the control status of the MCTL entries.

As DOD researchers or engineers working with new materials, processing methods, and manufacturing techniques, it is our responsibility to use sound judgment and protect the safety of our uniformed services on the field of battle. The case studies following on the next page will more fully illustrate some of the considerations involved when dealing with critical or potentially critical technologies.

For more information about the Militarily Critical Technologies Program, please consult the MCTL website ... www.dtic.mil/mctl or make inquiries via email at mctl-admin@ida.org.

# Material EASE

**HYPOTHETICAL CASE STUDIES:**
The following hypothetical examples are meant to provide the reader with real-world examples of critical technology questions and issues. These should only be used as guidance in the consideration of critical technology issues and in no way supersede the guidance provided by the MCTL, or the departments of Defense, Commerce or State. In cases where the control status of a technology is not clear, control information can be obtained from the Department of Commerce, Bureau of Industry and Security (formerly the Bureau of Export Administration), by requesting a Commodity Classification. (www.bxa.doc.gov or (202) 482-4811)

## Case 1

*A researcher at an Army lab working with titanium diboride ($TiB_2$), develops an armor sandwich structure of three $TiB_2$ plates between a front and back plate of woven carbon fiber cloth impregnated with epoxy resin. The $TiB_2$ plates are 99% dense. This structure is then mounted to a Nomex honeycomb backing surface and tested in a standard impact regimen with a fragment-simulating projectile at various velocities. The material preparation and specifics on thickness of each plate in the system, as well as test results are detailed in a paper to be presented at an unclassified conference.*

According to the MCTL, (Weapons Systems Technologies {WST}, Section 11.1, Armor and Anti-armor Materials) ceramics with greater than 98% theoretical density, in layered structures specifically intended for absorption of kinetic energy, are militarily critical. Titanium diboride is specifically cited as a material of special interest, as well as the arrangement of layered structures as described above. This paper describes a technology which, though perhaps not classified, definitely falls into the category of militarily critical, and is potentially subject to export control. Dissemination of this information without proper clearance could very well be illegal. Check the MCTL column "Control Regimes" to determine whether the particular material is controlled.

## Case 2

*A scientist at an Air Force lab develops a composite superconductor with a cross sectional area of approximately 35 square micrometers. Its critical temperature ($T_c$), below which the material functions as a superconductor, is 30K with no imposed magnetic field, but will remain superconducting with an imposed magnetic field of up to 1 Tesla. The composite is fabricated in lengths up to 40 meters. The scientist wants to publish the results in a technical journal.*

This example does not fall within the specific parameters outlined in the MCTL (WST, Section 11.2, Electrical Materials). However, sound engineering judgment should be used to ascertain the implications that this innovation has on the science. For instance, does divulging this information enable adversaries to leap ahead of current capabilities? Or does specific information in the intended publication enable further innovation that would place U.S. superiority at risk?

## Case 3

*A university team working on a Navy project develops a foam material that has embedded semiconducting ceramic whiskers. Five millimeters of this foam is found to attenuate 6 dB of a radiant 1.7 MHz noise signal. With additional modifications, the foam can attenuate 20 dB of a 14.8 GHz signal. The team has also developed computer code that enables this material and similar compositions to be modeled and accurately predicts the signal attenuation characteristics. Experimental validation of the results is carried out at a Navy lab. The principle investigator on the project is invited to speak at an international conference in Belgium hosted by NATO.*

This case illustrates one of the more elusive aspects of critical technologies: academic research. The US Government has shifted its policy on academic freedom and release of 6.1 Fundamental Research results to the public. At times university researchers have been restricted, and at other times they have had large amounts of freedom to discuss any Basic Research. The current stance (as of March, 2002) allows a significant level of academic freedom, but there is congressional pressure to limit it. The MCTL specifically calls out performance of signature reducing materials and systems, as well as the associated test procedures, simulation software, and test hardware (WST, Section 16, Signature Control Technologies). The parameters of signal attenuation outlined above fall above the "tripwire" values set forth in this section, thus for non-academic researchers this work would require evaluation by the DOD before it could be disseminated or exported. Academic researchers should address this to their sponsor or other appropriate officials. Low-observable and counter-low-observable (LO/CLO) technologies have their own offices within each service that are responsible for review of potential export issues in this field. Contact information and procedures on this topic can be found in the MCTL, Section 16.

## Case 4

*A defense contractor develops a lightweight, 125-cm mirror, which has potential* *application to an orbital surveillance satellite. A British company expresses interest in adapting the mirror for use in an orbiting astronomical observatory to be launched by France's Arianne.*

The parameters as described are somewhat tricky to evaluate. If a radiation reflectance level were quoted, it could be evaluated against the values in the MCTL, but the size of the mirror and the statement that it is "lightweight" also require attention. The MCTL calls out (in WST, Section 17.2, Optronics) that low area density space optics with apertures greater than 1 meter are critical. This technology should be treated as if it were a critical technology until a review by DOD has been performed. For any technology that is deemed critical and regulated by the CCL, ITAR, or other specific control regime, the company developing the mirror is responsible for controlling the technology, even if there were no government funds used in its development. In cases of unclear or developing technologies, a determination of commodity jurisdiction may be desirable. Information on this procedure may be obtained through the Department of State.

### Case 5

*An Army researcher develops a CAD-based simulation suite that predicts final shapes of ceramic castings. No new materials were developed, nor was the fabrication method altered. A number of multinational ceramic manufacturing companies have heard of the software and are interested in applying it for everything from engine components to biomedical parts.*

While the list of MCT does not specifically name CAD-based simulation software packages, it does address rapid prototyping software. For this case, where the software would be used to significantly reduce manufacturing development efforts, lower costs of manufacturing through reduced waste and rejects, and speed development of novel parts, it could definitely be judged militarily critical. This technology should be evaluated before it is exported.

## History of Export Control Regulations

The concepts of export control and militarily critical technologies have been part of America for most of its history. In 1774, the First Continental Congress declared illegal the importation of British goods as well as the export of goods to Britain. Since that time, the United States has imposed export controls for a variety of reasons through numerous executive and legislative actions. Several laws still in effect today (with modifications) were enacted soon after World War II. For example, the Export Control Act of 1949 gave the U.S. Department of Commerce (DOC) the responsibility of administering and enforcing export controls on dual-use items and, for the first time, defined three reasons for the imposition of these controls: national security, foreign policy, and short supply.

The DOC's Bureau of Industry and Security (formerly the Bureau of Export Administration or BXA) is responsible for issuing Export Administration Regulations (EARs), which define the technical parameters for issuing export licenses. This listing is referred to as the Commerce Control List (CCL) and some may find its length and extensive use of technical terms intimidating. The detailed listing of technical parameters in the CCL establishes precise, objective criteria that should (in most cases) enable one to ascertain the appropriate control status. Broader, more subjective criteria would cause exporters and re-exporters to be more dependent upon DOC interpretations and rulings. Moreover, much of the CCL's detail is derived from multilaterally adopted lists. This specificity serves to enhance the uniformity and effectiveness of international control practices and to promote a "level playing field." The detailed presentation of elements (e.g., licensing and export clearance procedures) enables the exporter to find in one place what he/she must know to comply with pertinent requirements. Of special importance is the detailed listing of License Exception criteria, which enable the exporter to determine quickly, and with confidence, whether he/she needs to obtain an export license. Finally, some of the EAR's detail is specifically aimed at avoiding loopholes and permitting effective enforcement.

Almost 20 years after enacting the Export Control Act, Congress enacted the Arms Export Control Act (AECA) in 1968. This legislation established the International Traffic in Arms Regulations (ITAR), which the Department of State (DOS) Office of Defense Trade Controls (DTC) administers. The ITAR includes the United States Munitions List (USML), which defines articles and services related principally to national defense and for which licenses are required.

In 1979 Congress enacted the Export Administration Act (EAA), which superseded the 1949 Export Control Act. The EAA required the Department of Defense (DOD) to produce the Militarily Critical Technologies List (MCTL). The language states:

> "The Secretary of Defense bears primary responsibility for developing a list of militarily critical technologies . . . . The Secretary (of Commerce) and the Secretary of Defense shall integrate items on the list of militarily critical technologies into the control list . . . with all deliberate speed. . . . The Secretary of Defense shall establish a procedure for reviewing the goods and technology on the list of military critical technologies on an ongoing basis."

The basic purpose of the MCTL is to define technologies that are critical for continued U.S. military superiority. The list is used primarily to provide technical justification and rationale for new proposals and to ensure the continuation of specific technology controls enforced under U.S. regulations and other multinational agreements. It is also used as a reference tool for evaluating potential technology transfers and for determining whether technical reports and scientific papers are eligible for public release.

The first version of the MCTL was published in 1981. Since then the list has been updated seven times and is currently published as an unclassified document (although some parts are limited distribution). The current edition of the MCTL is on the Internet (http://www.dtic.mil/mctl) and is continually being updated as progress is made on the technologies described in the basic document. Moreover, the Internet has provided the opportunity for more people to comment on proposed changes.

## Mark Your Calendar

*2002 MSS National Symposium on Sensor and Data Fusion*
08/13/02 - 08/15/02
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*Theme:* "Meeting the Counterterrorism Challenge Through Information Fusion"
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Ann Arbor, MI 48113-4008
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# DARPA: A Leader in the MEMS Revolution

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Microelectromechanical Systems (MEMS) is one of the three core enabling technologies supported within the Microsystems Technology Office (MTO) of the Defense Advanced Research Projects Agency (DARPA). Together with photonics and electronics, MEMS forms the foundation for a broad variety of advanced research projects sponsored by MTO as well as other offices within DARPA.

MEMS technology merges computational, communication, and power functions together with sensing, actuation and control to completely change the way people and machines interact with the physical world. Using an ever-expanding set of fabrication processes and materials, MEMS will provide the advantages of small-size, low-power, low-mass, low-cost and high-functionality to integrated electromechanical systems, both on the micro- as well as on the macroscales. Further, demands for increased performance, reliability, robustness, lifetime, maintainability and capability of all types of military equipment can be met by the integration of MEMS into macro devices and systems.

## Introduction

In "Joint Vision 2020", published by the Joint Staff Study Group, "full spectrum dominance" was described as the overarching focus of the vision for the US military in the year 2020. There are two key strategies under this vision: information superiority and technological innovation. MEMS is one of the critical new technologies that has far-reaching impact on information superiority and represents a crucial technological innovation for the future of the US military.

MEMS are revolutionizing defense weapons and information systems, providing the broad applications that modern warfare demands. The infusion of advanced technologies, including MEMS, into military systems is accelerating because of the vital need of the armed forces to keep pace with the exponential growth in information collection and accessibility.

The central mission of DARPA is to pursue radical innovation in support of national security. It is chartered to be at (and driving) the leading edge of critical new technologies that will revolutionize military platforms. In the post-cold-war era, U.S. forces must be able to conduct prompt, sustained, and synchronized operations with our allies in specific situations, and with the freedom to operate in all domains - sea, land, air, and space. MEMS technology has now been demonstrated in all four domains.

In 1992, DARPA identified MEMS as an emerging technology critical to the nation's security needs, and formally established the MEMS program. Numerous projects were launched for a broad range of feasibility studies on fabrication, designs, and performance limits for various applications. Since MEMS has its roots in planar integrated circuit (IC) technology, several key advantages are inherent in MEMS-fabricated devices, similar to those in their IC counterparts. These include batch fabrication, enabling mass production at lower per-unit cost, photolithographic techniques that miniaturize the resulting devices with high degree of feature definition, and integration capability to co-locate various functions on the same substrate.

At the same time, MEMS devices perform functions that are beyond what electronics can offer. The most frequent uses of MEMS are in the creation of microsensors and microactuators, which serve as the interfaces between electronics and the physical, chemical, and biological worlds. These enable highly automated and intelligent machines with superior perception, computation, and execution capabilities. The unique advantages offered by MEMS are highly attractive for modernizing military platforms because at the core of every military operation is the ability to collect, process, verify, communicate, and act on a vast amount of information in a timely manner[1].

In 1999, the pervasiveness and broad applicability of MEMS were fully recognized. As a result, MEMS was transformed from being one of the many DARPA projects into a core enabling technology within MTO, in parallel with electronics and photonics. New programs in various technology focus areas are continuously created that leverage heavily on MEMS as the enabling foundation. The unifying long-term goal of these new programs is to merge information processing with sensing and actuation to realize new systems and strategies, as well as bring collocated perception and control to systems, processes and the environment.

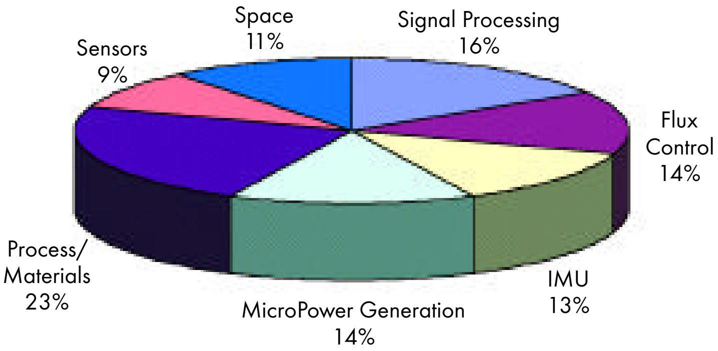


**Figure 1.** The Seven Thrust Areas within the DARPA MEMS Program

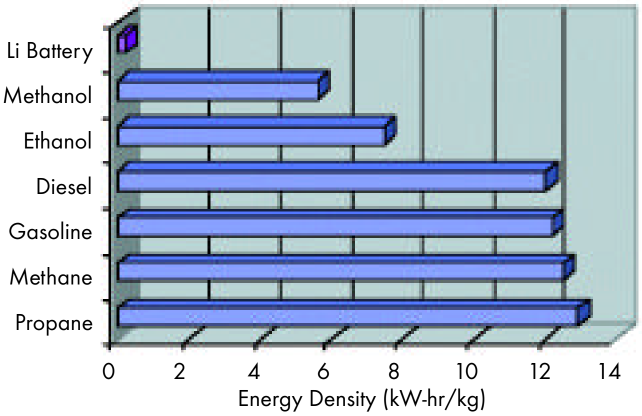


**Figure 2.** Energy Density Comparison

### Current Program Activities

Since the beginning of the DARPA MEMS program, numerous feasibility studies in applying MEMS to military platforms have been demonstrated. These platforms span the four domains of military operations: sea, land, air, and space. Currently, the program is categorized into seven major thrust areas to address this broad range of platform applications: process/materials, sensors, space, signal processing, flux control, Inertial Measurement Unit (IMU), and micropower generation (Figure 1).

The process/materials thrust area aims to explore innovating and enabling technologies and methodologies which support new MEMS devices. The IMU thrust continues to explore MEMS alternatives in acceleration and rotation sensing. Successful demonstration in this area has contributed to establishing DARPA's Inertial Navigation Systems (INS) program within the Special Projects Office (SPO), which leverages MEMS-fabricated, ultra-miniaturized IMUs.

One of the projects within the Flux Control area is the development of miniature safe/arm-and-fuze devices for 6.25-inch-diameter anti-torpedo torpedoes. Two successful sea run demonstrations have led to the decision by the Navy to invest in follow-on development and future fleet deployment.

A pair of "pico-satellites," each measuring only 2.5 cm by 7.5 cm by 10 cm and weighing 0.3 kg, was launched and operated in low-earth orbit in early 2000, demonstrating the ability of the on-board MEMS devices to survive the launch and to function in the hostile space environment. It points to the potential of a new paradigm of space-based defense augmentation. This first pair of pico-satellites demonstrated the first-phase feasibility of low-cost, launch-on-demand, space-qualified, cooperative constellations for space-based military operations.

New types of microsensors are developed to perform sensing functions that have never been realized. An example is the "Polychromator" project[2], which uses micromirror strips to differentiate and analyze photon emission signatures and identify chemical species remotely. Successful demonstrations within the MicroPower Generation and Signal Processing thrusts have led to two new programs: the MicroPower Generation (MPG) and the NanoMechanical Array Signal Processors (NMASP). These two programs, and the Chip-Scale Atomic Clocks (CSAC) effort, are described next.

### New Focus Areas

#### *MicroPower Generation (MPG)*

The aim of the MPG program[3] is to generate power at the microscale to enable standalone microsensors and microactuators with wireless communication functions. This will enable new strategies for weapons systems, processes, and battlefield environments. The advantages of these microsensors and actuator systems are severely limited by the associated bulky power supplies, typically batteries. Hydrocarbon fuels offer attractive alternatives as power sources due to their superior energy densities. For example, the energy densities of propane, methane, gasoline, and diesel are at least 50 to 100 times higher than the best lithium-ion batteries (Figure 2).

With a modest energy conversion efficiency of 10% from chemical energy to electricity, the resulting power generator will still be five-to-ten times smaller than a comparable battery. Specific demonstration goals of the MPG program include:

- Feasibility and practical limits in converting chemical energy into electrical energy on the microscale;
- Significant advantage (>10X) in energy density over state-of-the-art batteries;
- Capabilities in fuel processing, energy conversion to electricity, thermal and exhaust management;
- Integration of various power-generation components with microsensors and microactuators; and

- Standalone remotely distributed microsensors and actuators with built-in power supply and wireless communication.

The development of micropower sources will enable ultra miniaturization and functionality of new standalone systems. The use of MEMS technology has already demonstrated reductions in size, mass and power, as well as performance enhancements, new sensing concepts and new functionality in weapon systems and platforms. Micropower sources will be the key components in ultimate miniaturization and integration of standalone, self-contained, wireless microsensors and microactuators that can be deployed remotely in clusters to drastically enhance superiority of weapon systems and field awareness.

Microfabrication techniques used to create micropower generators include deep reactive-ion etching (DRIE), laser milling, wafer bonding, stereolithography, thin-film deposition, and heterogeneous integration. Novel materials suitable for combustion and fuel cells include alumina, SiC, Si, Pt, PdH, polymer membranes, etc. Micropower generation techniques include thermo-electric converters, microscale combustion engines, fuel cells and fuel reformers.

The key research focus is on innovative MEMS solutions that allow system optimization on several major factors affecting the overall efficiency and utility of the final MPG devices. Examples of optimization factors include (1) the power requirement of the associated sensor, actuator, and/or electronic circuits, which typically range from tens of microwatts for sensor operations to less than a few hundred milliwatts for wireless data transmission; (2) thermal management if conversion of thermal energy is involved; (3) intake and exhaust managements if fluid or solid transports are required; (4) material compatibility and robustness if high-temperature and high-contact mechanical loads and/or mechanical outputs are parts of the design; and (5) energy storage and power distribution methodologies if there is a mismatch between the rates of energy conversion and energy consumption. Success of the MPG program will revolutionize energy storage and generation for micro- and hand-held devices.

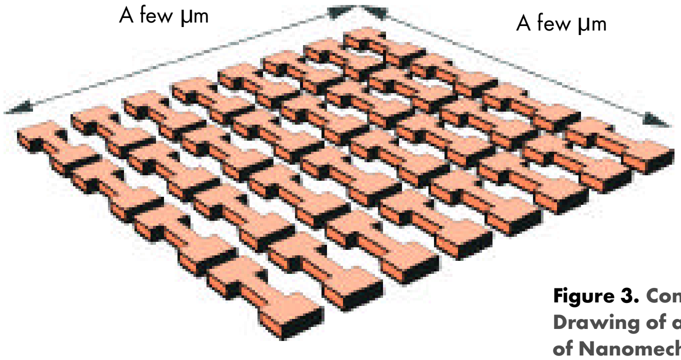


**Figure 3.** Conceptual Drawing of an Array of Nanomechanical Resonators.

### *NanoMechanical Array Signal Processors (NMASP)*

The NMASP program[4] aims at creating arrays of precision, nanomechanical structures (Figure 3) for RF-signal processing that will achieve:

- >100X reduction in size (from 80 $cm^2$ to 0.8 $cm^2$ or smaller),
- >100X reduction in power consumption (from 300 mW to less than 3 mW during receive, and from 30 mW to <0.3 mW during standby, compared to current cell phones), and
- >10X improvement in RF performance (spectral efficiency and bandwidth).

The development of nanomechanical array signal processors will enable ultra miniaturized (wristwatch or hearing aid in size) and ultra low power UHF communicators/GPS receivers which will greatly improve the mobility and location identification of individual warfighters. They can also be used for miniaturization and integration of stand-alone, self-contained, wireless microsensors and microactuators that can be deployed remotely in clusters to drastically enhance superiority of weapon systems and field awareness. Other potential uses for military applications include an ultra portable spectrum analyzer, Fourier signal-transformer, programmable equalizer, frequency converter, parametric amplifier, and other UHF signal processing equipment.

Core NMASP technologies can also be used for mass spectrometer, calorimeter, bolometer†, and high-resolution IR imager applications. All of these NMASP applications will be characterized by significant power reduction and/or ultra miniaturization while meeting or exceeding the performance levels of the state-of-practice approaches. The program includes three technical tasks:

- Exploit and adapt emerging technology in nanofabrication to create nanoresonators by chemical and physical transfer of materials on nanoscale patterns.
- Use parallel processing of nanopatterning to create uniform arrays of nanoresonators.
- Integrate nanopatterning with Complementary Metal-Oxide-Silicon (CMOS) circuits to create chip-level integration.

The key technical focus of the NMASP program is optimized combinations of innovative solutions in micro- or nanofabrication, materials processing, device design, transduction mechanisms and interconnects. These and other relevant engineering approaches directly address the performance issues in high-Q‡ UHF mechanical resonator arrays for radio frequency (RF) transceiver and signal processor applications. The issues include: (1) temperature stability, tunability, signal-to-noise (S/N) ratio, and environmental sensitivity of individual resonators; (2) uniformity, repeatability, and variability within the arrays; (3) cross-talk, coupling, and isolation among the resonators; (4) clear potentials for chip-level integration with Si, Si-Ge, SiC, III-V, or other appropriate circuit technologies; and (5) compatibility with

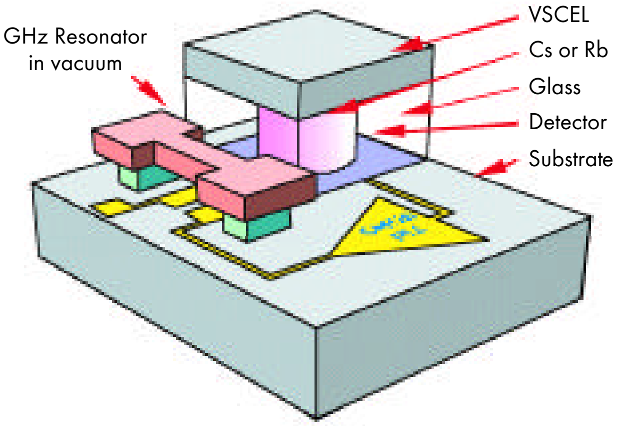


**Figure 4.** **Conceptual Drawing of a Chip-Scale Atomic Clock**

on-die or second-level hermetic packaging.

Fabrication, materials choices, device design, and other engineering approaches are tightly coupled in influencing the performance of the mechanical resonator arrays. For example, by using a structural material with very high stiffness, one can design a resonator with dimensions that are not necessarily all in the sub-micron regime to achieve resonance in the UHF range. Another coupling and engineering tradeoff may be manifested in the balance of employing precision machining to create the resonators and the use of innovative electronic interface and compensation techniques to achieve controls in the desired frequencies within the array. Also, in the dimensions of interest, surface-to-volume ratios of the UHF mechanical resonators are likely to be very high compared to lower-frequency resonant structures, and thus surface effects and sensitivity to mass loading, among others, may need to be considered.

These considerations are expected to bear important implications in the requirements for some form of isolation, surface treatment, on-die and/or second-level packaging, or possibly other innovative approaches. Combinations of these will be needed to achieve stability, useful S/N ratio, Q, and other performance parameters of interest relevant to RF transceiver and UHF signal processing applications. When successful, the NMASP program is expected to drastically impact frequency-domain analog signal processing in general, and particularly wireless UHF communication.

### *Chip-Scale Atomic Clocks (CSAC)*

The goal of the CSAC program[5] is to create ultra-miniaturized, low-power, atomic time and frequency reference units that will achieve, relative to present approaches:

- >200X reduction in size (from 230 cm$^3$ to less than 1 cm$^3$),
- >300X reduction in power consumption (from 10 W to less than 30 mW), and
- Matching performance ($\pm 1\text{x}10^{-11}$ accuracy, which corresponds to less than 1µs/day deviation).

The development of a chip-scale atomic clock will enable ultra-miniaturized (wristwatch in size) and ultra low power time and frequency references for high-security UHF communication and jam-resistant GPS receivers. The use of these ultra-miniature time reference units can greatly improve the mobility and robustness of any military system or platform with sophisticated UHF communication and/or navigation requirements.

The ultra-stable frequency reference from an atomic source will drastically improve channel selectivity and density for all military communications. It will also enable ultra-fast frequency hopping in synchronized spread-spectrum communication for improved security and jam resistance and strong encryption in data communication.

When used in military GPS receivers, it will greatly improve the jamming margin in a high-jamming environment, reacquisition capability, and position identification accuracy. In surveillance applications, chip-scale atomic clocks can be used to improve resolution in Doppler radars and to enhance accurate location identification of radio emitters. Other important uses include missile and munitions guidance, robust electronic and information defense networks, and high-confidence identification of friends and foes. All of these applications will be characterized by significant power reduction and/or ultra-miniaturization while meeting or exceeding the performance levels of current state-of-practice approaches.

The key focus of this program is to optimize combinations of innovative solutions for micro- or nanofabrication, materials processing, device design, transduction mechanisms, interconnects, and other relevant engineering approaches that directly address the performance issues in atomic frequency and time referencing. The most essential research elements include confinement and stabilization of cesium, rubidium, or other suitable species, excitation and detection of the hyperfine-transition resonance of the chosen species, and phase-locking or direct coupling with micromechanical resonators.

Research issues include, among others: (1) temperature stability, magnetic shielding, hermetic encapsulation, and means to maintain atomic ground-state coherence within the confinement cell; (2) integration with vertical cavity surface emitting laser (VCSEL) or other photon and/or microwave sources and photo detector with the confinement cell; and (3) integration, phase locking, and/or direct coupling with micromechanical resonators (Figure 4).

Phased technology development approaches are planned. The first phase focuses on establishing theoretical limits of chip-scale atomic clocks and demonstrating practical design and fabrication feasibilities. Several alternative design and fabrication techniques will be explored, and the most promising ones will be downselected. Phase 2 aims at demonstrating individual components of ultra-miniaturized atomic confinement cells, GHz nanoresonators, atomic-resonance-coupled resonators, and phase-locked and interface circuits. Each component will be based on robust design for temperature stability and magnetic shielding. Phase 3 will be the final chip-level integration, focusing on demonstrating operational chip-scale atomic clock and integration with CMOS circuits (Si, Si-Ge, or III-V electronics).

Throughout the entire three phases, potential DOD users will be engaged to identify operational requirements and to set the stage for transition to military systems. Potential implementation opportunities include placing CSACs in high-security UHF communication and jam-resistant GPS receivers.

## A Bright Future for MEMS

In the future, DARPA will continue to establish MEMS-enabled programs with focused objectives. MEMS will be successful in all applications where size, weight, power, and cost must decrease concurrently with increases in functionality. MEMS devices will be widely used in both the military and commercial arenas. Applications will range from fighter aircraft to automobiles and from munitions to printers. While MEMS devices per se will account for only a relatively small fraction of the cost, size and weight of these systems, they will be critical to system operation, reliability and affordability. MEMS devices, and the products they enable, increasingly will be the performance-defining factor for both defense and commercial systems.

## References and Notes

[1] W.C. Tang and A.P. Lee, “Military Applications of Microsystems”, The Industrial Physicist, the American Institute of Physics, Feb. 2001, pp. 26–29.

[2] G.B. Hacker, et al, “The polychromator: a programmable MEMS diffraction grating for synthetic spectra,” Tech. Dig. Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 4–8, 2000, pp. 89–92.

[3] Broad Agency Announcement 01-09 “MicroPower Generation,” Commerce Business Daily, October 3, 2000, Issue No. PSA-2698.

[4] Broad Agency Announcement 01-10 “NanoMechanical Array Signal Processors,” Commerce Business Daily, December 11, 2000, Issue No. PSA-2744.

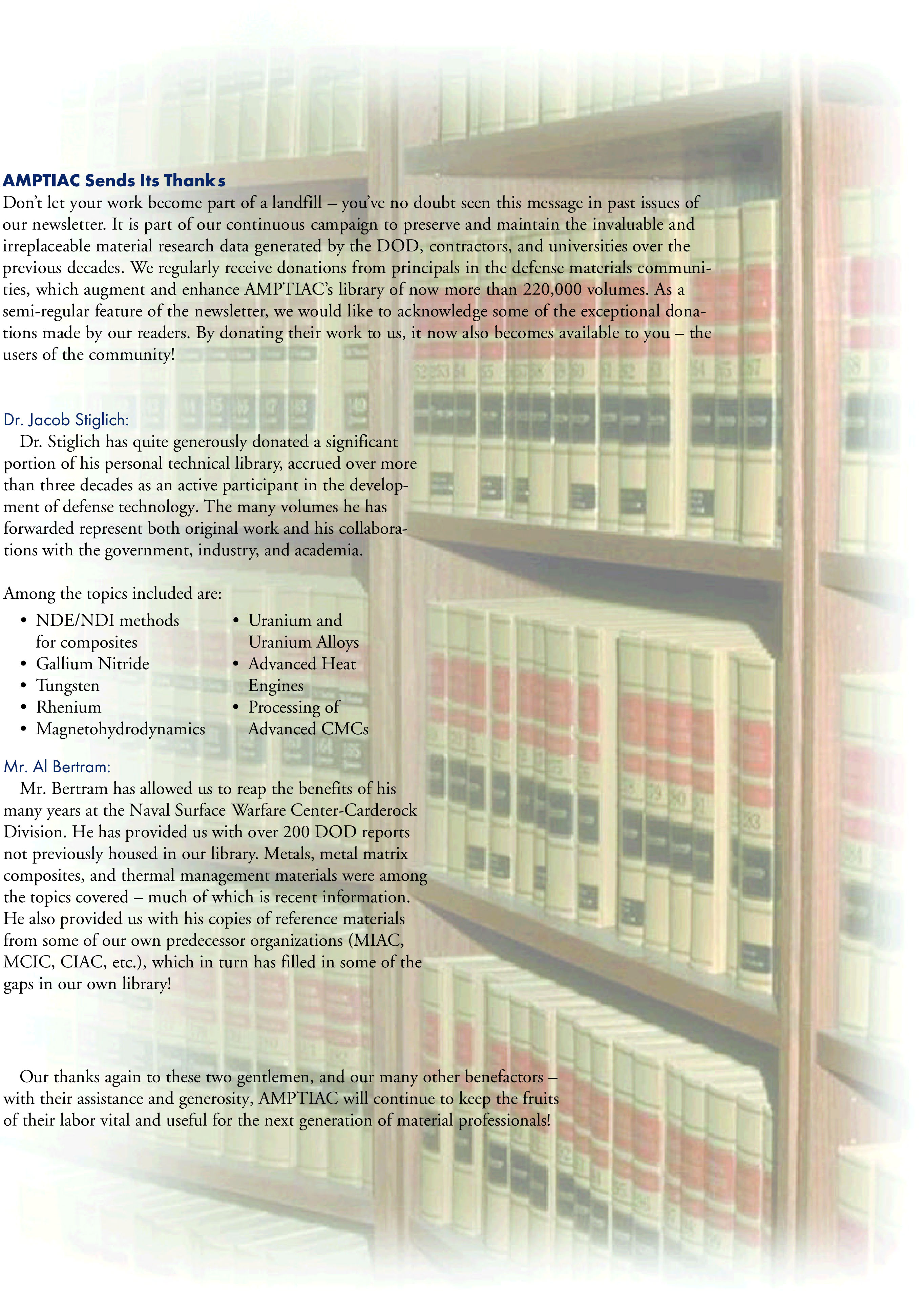
[5] Broad Agency Announcement 01-32 “Chip-Scale Atomic Clock,” Commerce Business Daily, July 6, 2001; Issue No.: PSA-2887.

† *Bolometers measure power output of transmitters in the ultra-high frequency (UHF) and super-high frequency (SHF) ranges, where the more conventional measurements of amperage, voltage, and resistance are difficult or impossible to reliably attain.*

‡ *Q is a parameter which is an indication of power output efficiency.*

## Presentation of the John W. Lincoln Award

Dr. James C. Newman, Jr., Professor, Department of Aerospace Engineering, Mississippi State University and recently retired from NASA Langley Research Center, Hampton, Virginia, was presented the 2001 John W. Lincoln Award. It was given in recognition of his outstanding work over many years in advancing the technology of fatigue and fracture mechanics and applying it to aircraft structural integrity. The Award was presented at the 2001 Aircraft Structural Integrity Program (ASIP) Conference in Williamsburg, Virginia on 11 December 2001. The Award, which consists of a gold medal and a certificate of recognition, was named in honor of Dr. John W. (Jack) Lincoln of the USAF Aeronautical Systems Center, Wright-Patterson Air Force Base, Ohio. Dr. Lincoln was a pioneer and major contributor to the development and application of durability and damage tolerance design to insure the safety and longevity of both military and commercial aircraft. The Award has been presented previously to Dr. Lincoln (1996), to Mr. Charles Tiffany (1997), to Mr. Thomas Swift (1998), to Professor Jaap Schijve (1999) and to Professor Alten F. Grandt Jr. (2000). A plaque with the names of the recipients is on display at Wright-Patterson Air Force Base, Ohio.



## AMPTIAC Sends Its Thanks

Don't let your work become part of a landfill – you've no doubt seen this message in past issues of our newsletter. It is part of our continuous campaign to preserve and maintain the invaluable and irreplaceable material research data generated by the DOD, contractors, and universities over the previous decades. We regularly receive donations from principals in the defense materials communities, which augment and enhance AMPTIAC's library of now more than 220,000 volumes. As a semi-regular feature of the newsletter, we would like to acknowledge some of the exceptional donations made by our readers. By donating their work to us, it now also becomes available to you – the users of the community!

### Dr. Jacob Stiglich:

Dr. Stiglich has quite generously donated a significant portion of his personal technical library, accrued over more than three decades as an active participant in the development of defense technology. The many volumes he has forwarded represent both original work and his collaborations with the government, industry, and academia.

Among the topics included are:

- NDE/NDI methods for composites
- Gallium Nitride
- Tungsten
- Rhenium
- Magnetohydrodynamics
- Uranium and Uranium Alloys
- Advanced Heat Engines
- Processing of Advanced CMCs

### Mr. Al Bertram:

Mr. Bertram has allowed us to reap the benefits of his many years at the Naval Surface Warfare Center-Carderock Division. He has provided us with over 200 DOD reports not previously housed in our library. Metals, metal matrix composites, and thermal management materials were among the topics covered – much of which is recent information. He also provided us with his copies of reference materials from some of our own predecessor organizations (MIAC, MCIC, CIAC, etc.), which in turn has filled in some of the gaps in our own library!

Our thanks again to these two gentlemen, and our many other benefactors – with their assistance and generosity, AMPTIAC will continue to keep the fruits of their labor vital and useful for the next generation of material professionals!

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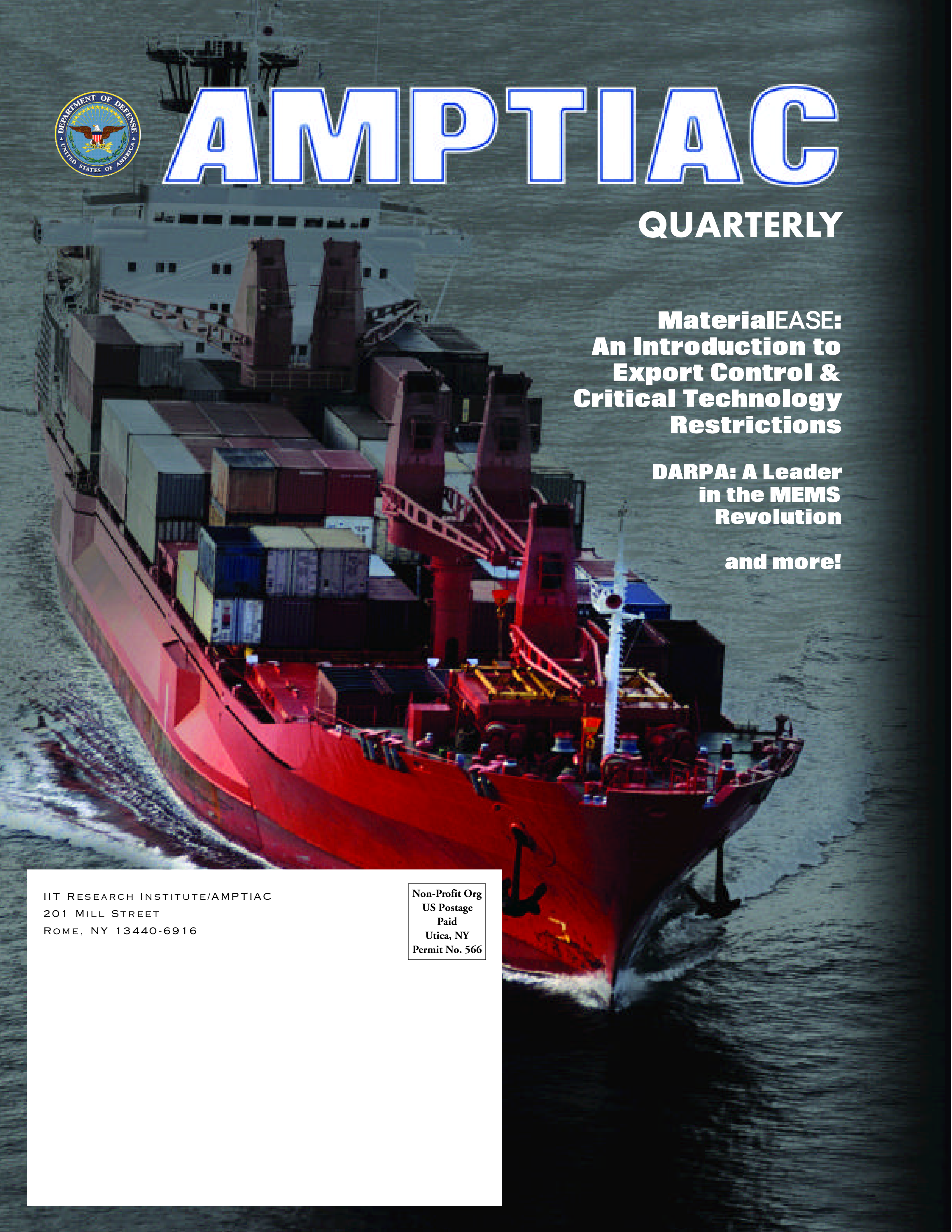
### Where Have All the Tech Directors Gone?

As mentioned in the Editor's introduction on Page 2, AMPTIAC has come a long way since our beginnings in 1996. During those early days, we were charged with integrating four pre-existing DOD sponsored Information Analysis Centers (HTMIAC, CIAC, MIAC, and MMCIAC), and the next year added the mission areas of a fifth center (PLASTEC). Along with these mergers came the acquisition of a tremendous amount of technical reports - nearly 3 1/2 tractor-trailers full!

To ensure continuity of service and customer focus, we initially established five individual technical directors to help oversee and guide our transition-related activities. These technical directors were each responsible for a technical focus area to ensure balanced and comprehensive coverage in the traditional structural materials categories including metals, ceramics, composites, and polymers, but also other nonstructural materials including electronic and optical materials, as well as the whole area of lubricants and fluids.

Since AMPTIAC is now a mature and integrated Information Analysis Center, our original management and technical support structure is no longer needed. To provide better service to our customer base and to ease access to the tremendous amount of technical information available, we are broadening the responsibilities of our technical inquiry services manager, Mr. David Brumbaugh, to be the single point of contact for all customer inquiries. AMPTIAC is responsible for acquiring, analyzing, archiving, and disseminating technical information that covers nearly all classes of materials. We have more than 220,000 technical reports that cover the waterfront of materials technologies, including in-service performance. Our technical staff is second to none in that their core competency is to locate materials-related technical information and assist customers with design, materials selection, failure analysis, and the like. If you need assistance or would like some additional information on AMPTIAC products and services, please contact David at 315-339-7113 or email him at dbrumbaugh@iitri.org.



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