ALUMINUM SOLUTIONS FOR MILITARY APPLICATIONS –
BUILDING ON LEARNINGS FROM OTHER INDUSTRIES

Dr. Eric (Rick) Winter, Alcoa Technical Center, Alcoa

[Title Slide]

Good afternoon. First, I want to express my thanks to Suveen Mathaudhu and the other members of the organizing committee for the opportunity to speak to you in such an excellent forum. I'm pleased to be here today to talk to you about the potential for lightweighting military applications using one of my favorite materials – aluminum. However, I have to begin with a bit of a confession: Although my company, Alcoa, has a large and increasing interest in the use of aluminum in military applications and is very active in the market as we speak, I personally have a limited exposure to the industry and the specific details associated with military applications. Thus, if I misapply a term or two, I beg your indulgence, because I do believe that the concepts I will share with you have relevance to the tasks in front of the US military today.

The theme of this conference – the use of lightweight metals technology in Army materiel systems – is one that resonates with me, as I have spent a significant portion of my career looking at systems that could (and should and often did) benefit from lightweighting. Across industries as diverse as automotive, commercial aerospace, consumer packaging and oil & gas exploration there is a common need for lighter, more efficient systems that reduce energy consumption while delivering on the intended mission. It is my contention that there are lessons to be extracted from these other areas which are more than applicable to the US Army; and this is the argument I hope to sway you with over the next half hour or so.

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So, let's start with what matters. It's no secret that the Army (as is the case with most of the US military) has been in transition for the past several years. The necessity of fighting conflicts and projecting US strength at a considerable distance from home has only accentuated the need for a different force than the one we have historically fielded. But what are the essential elements of this new force? What really is important in future Army systems?

From what I have gleaned from my investigations, the essential characteristics of future Army systems seem to fit into four broad themes: These systems must

- Provide decisive advantage in both conventional and unconventional warfare;
- Be rapidly deployable worldwide;
- Be easily sustained – both short and long term; and
- Be modifiable to address new threats, accept new technologies.

Allow me to elaborate a bit on each of these as a means to discuss where I think aluminum may have a role to play.

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Ten years ago, I don't think very many of us could have envisioned the asymmetric type of warfare that we find ourselves fighting today. The threats confronted by the Army today are constantly changing – both in terms of approach and lethality. This requires the systems with which the Army responds to be correspondingly lethal while protecting the warfighters from these ever-evolving threats. While lethality is obviously an essential attribute, it is the protection aspect of this subject which bears more scrutiny with respect to aluminum. Protection can take the form of avoidance through a combination of speed and maneuverability, or it can be the ability to withstand the attack in a manner that shields man and critical equipment from the worst of the damage. In either case, aluminum provides an opportunity to think about these solutions in unique ways, through lightweight, high strength and blast-resistant structures that both enhance avoidance while maintaining shielding.

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Rapid deployment, to me at least, means that your systems get to where they're needed when they're needed, and not a moment later. As outlined in the Future Combat Systems (FCS) initiative, this implies that new Army systems be flexible and agile – an argument for lighter weight systems with equal or greater performance, if ever I've heard one. Additionally, these systems have to be transportable, that is, they must fit the conveyance that exists to get them in theater as fast as possible. These requirements would appear to put a premium on light, strong structures that are efficient in their use of available space. This is a set of attributes is much like the demands placed on other ground transportation structures – a market where aluminum is increasing its usage year-by-year.

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Sustainability is an often used and often misunderstood term. In the current context, I am not referring to the connotation of environmental benefits or "green-ness" – although elements of that sense may still be applicable. Rather, I am asserting that the ability to keep Army systems operating as intended in the field for extended periods is an essential attribute of their service. For example, reducing the amount of energy consumed to accomplish a mission is one element of this mix; the less fuel required by an armored unit, the greater its apparent mobility. Similarly, a robust design and well-thought-out repair procedures can greatly reduce the amount of downtime in theater, enhancing the availability of systems for critical missions and potentially shortening the apparent "tail" required for maintenance of the system. Although these are general attributes that can be met in a variety of ways, there are numerous examples from other industries where the use of aluminum in analogous situations leads to benefits in this regard.

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Finally, I noted earlier that the modern military is a constantly evolving entity. As new adversaries and threats appear, commensurate responses are required to keep up with the stated mission. In this context, in order for a system to be truly sustainable, it must be able to adapt to the ever changing landscape around it. Modularity of design helps: The ability to swap out sub-systems and quickly reconfigure for new requirements prolongs the utility of the overall system and makes it more amenable to new technologies. In a similar fashion, although aluminum as a material has been in commercial applications for well over one hundred years, the ability to continue to modify compositions and mechanical and thermal manufacturing processes enables us to offer advanced solutions well into the future.

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In fact, the history of the aluminum industry has been a more or less continuous process of application development dating back to the start of the twentieth century. The simultaneous discovery of the electrolytic reduction process by Charles Martin Hall in the US and Paul Heroult in France in the 1880s took what had been a precious metal akin to gold or silver in value and put it within reach of common applications. Many of the technical innovations we take for granted today (for example, widespread electrical distribution and commercial air transportation) were founded upon the development of distinct aluminum alloys or alloy families. This rich history of application development provides both insight into how aluminum development was spurred by the end use as well as an invaluable source of example problems from which solutions might be unearthed for present and future systems – a concept we will consider in a few moments.

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First, however, it is instructive to examine how a specific market development advanced the state of aluminum alloys. In the case of commercial aerospace, the development of increasingly sophisticated aircraft was directly linked to the corresponding enhancements in the associated materials of construction, as can be seen in this figure. What is also worthy of note is the material specialization that has occurred over time. As the demands for lighter weight and greater efficiency and fuel savings increased, the developers of aerospace alloy systems responded with further differentiation on the basis of material properties corresponding to the specific needs of the application – be it upper or lower wing skin, fuselage skin or underlying skeletal structure. This approach points out an underlying truth, which should be applicable to any material selection problem: It is essential to take a holistic view of the problem to be solved, rather than start from the material performance perspective. Beginning with a good understanding of the overall system mission expectations and translating those into attributes that can be mapped to specific structural performance targets will create a much richer field of potential solutions to the problem. At the risk of being branded as a heretic (since I am employed by a material supplier), I contend that it's most important to maintain this solutions-orientation above all else, for it's the answer to the problem that matters, not the specific material that is chosen.

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So, setting aside my heresy for the moment, how does one go about applying aluminum effectively to the development of new Army systems and materiel? I submit that the general approach is relatively straightforward, and probably well known to most of you in the audience by now. It starts with a well-defined set of attributes for the system in question. The degree to which the entire picture is available to the material developer is the extent to which it will be possible to innovate.

With the picture in place, it is essential for the materials community to take a holistic view of the problem, incorporating not only material choices, but also manufacturing process modifications and new design options into the thought process. Only in this way will we be able to create the widest possible space for innovative solutions to emerge.

One of my opening statements in this talk – and a theme to which I've returned more than once thus far – is that there are a number of parallels that can be drawn from other industries to potential military applications. Borrowing from our previous CEO, Alain Belda, I've referred to this on the slide as "stealing shamelessly". Let me be abundantly clear at this point: I am not advocating any sort of unethical behavior. Please do not construe what I'm saying as a recommendation to violate intellectual property or overtly plagiarize an idea. Rather, I am invoking that most sincere form of flattery – imitation. If someone has gone to the trouble of developing an elegant solution to a problem, and one can see parallels to a problem at hand, why shouldn't the solution be modified to fit?

The final point on this slide speaks to how we go about the process of innovating. (As an aside, I want to publicly acknowledge my colleague, Ralph Sawtell, who I credit/blame for this terminology.) When confronted with the need for a new material solution for a problem, our first thought will always be to <u>adopt</u> an alloy from another application. In essence, we are practicing what I just preached – stealing shamelessly from ourselves. If it's not possible to simply "reuse" a known solution, the next level of intensity is to <u>adapt</u> a known solution to the new problem. This may entail modifications to the thermomechanical processing of the alloy, or perhaps a very limited set of "tweaks" to the alloy itself in order to the requirements of the problem, but the overall goal is to build on as much of the previous effort as we can.

Only when we are confronted with no readily available or modifiable material solution will we actually resort to developing the solution from scratch, because this approach will take the most time, the most money, and – in the final analysis – may not allow us to meet the target window of the need. While on the surface, this may seem to be a rather lazy way to go about solving materials problems … I prefer to think of it as an efficient use of available resources.

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Perhaps the best way to demonstrate the approach is to provide a few practical examples. In so doing, I hope to also reinforce the idea that the parallels found between different industries and applications can and should find their way into the military realm as well.

The first example, shown in this slide, is the full-blown development path. In this case, airbus came to Alcoa in 1999 with a well-articulated need for a higher strength thick plate and/or forged product that could be used in wing applications. The incumbent aluminum alloy, 7050, was a good solution for other aspects of the structure, but it would not provide the characteristics necessary to achieve the desired weight targets in the new A380 aircraft. We embarked on an alloy and temper development program that, roughly three years later, yielded the alloy known today as 7085, along with the different tempers that provided the appropriate strength and toughness combinations for the A380 wing applications. In addition, extensive manufacturing process development led to the ability to make both thick plate and forged products with consistent properties throughout the material. The result: Significant amounts of 7085 fly on every A380 in both product forms, including one of the largest die forgings in the world.

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Now, once the heavy lifting of material development has been done once, it is always available for further use in other applications. In the aforementioned case, the development of 7085-T65X, with its consistent properties throughout the material, opened the possibility of large, near net shape forgings being used in other aerospace structures. One of the first to take advantage of the previous work was the F35 Joint Strike Fighter, whose main bulkheads were engineered in 7085. Thus, the alloy and process development work done in support of Airbus found a second life – in a military application, I should add – as an important part of the JSF core structure.

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Taking the concept one step further, it is often possible to provide completely new applications of a conventional material solution with only minor modifications to the original material and manufacturing processes. As an example of this, let me consider for the moment the subject of tooling for injection-molded plastic components. Two significant factors determine the yield from the injection molding process: the cycle time to create, cool and extract the part from the die, and the integrity or quality of the die itself. (Obviously there are other factors at play here, but these two will suffice to describe the problem for our purposes.) Cycle time is controlled by a number of parameters, but one of the most important ones is how quickly and reliably one can heat and then cool the die. This also – indirectly – has a bearing on the quality and life of the tool itself.

Traditionally, injection molding dies have been made from various grades of steel, with inserts of other materials such as copper, bronze and aluminum occasionally used to address specific issues in the tool. These dies involve a great deal of fabrication to create the part cavity or cavities as well as cooling channels, ejector pin ways, and a host of other details that make up a functioning molding die. The machining of these features must be done in a manner that not only creates the correct initial geometry, but also maintains that geometry throughout the useful life of the tool.

With the development of the 7085 alloy and associated manufacturing processes, it was recognized that there now existed a thick forged or plate product with very consistent properties that might be able to handle the operating environment posed by plastic injection molding. Moreover, the ability to create the entire die (or at least a significant part of it) from aluminum meant that the process could take advantage of aluminum’s much higher thermal conductivity in the heat management during the molding cycle – a development that resulted in shorter molding cycle times due to the better heat extraction in the part. And, as an added benefit, the tools were quite a bit lighter, making them easier to install and remove from the molder.

After getting a deeper understanding of the specific details of the molding process, it was determined that some minor modifications to the alloy and processing would create an ideal material for the application. The result: QC10, a thick forged product well suited for use a tool stock for the injection molding industry. Initial applications with an automotive components fabricator have more than proven out the value proposition of the initial premise.

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Another example of adaptation comes from an industry that is … unfortunately … very much in the public eye right now – oil and gas exploration, specifically deep water drilling. As I'm sure most of you are painfully aware, the quest for new oil and gas reserves has driven us to look in places we would not have been able to go until relatively recently. One such location is the apparent reserves located deep beneath the oceans – often in water depths of greater than a mile. As has been demonstrated in the crisis in the Gulf of Mexico, these reserves require extraordinary efforts and technology to get to them.

The drill rigs capable of prospecting in water depths of more than a mile are relatively few – and very expensive to build, own and operate. Ultra-deep water rigs are capable of handling the long strings of riser and drill pipes necessary to bridge the gap to the ocean floor and drill into the seabed to create the well, although even they are somewhat limited in the amount of mass they can move, leading the industry to explore what other materials and systems might be employed to do the job being done by steel pipes today. In this respect, oil and gas exploration is not unlike the aerospace and military industries, with aluminum, titanium and composite materials all in the discussion.

At a macro level, the problem to be solved in oil and gas offshore exploration can be expressed as the following: How does one create the lightest weight solution for deep water drilling that meets all of the structural requirements of a riser system or a drill string, so that prospecting at the required depths is possible without having to build a new fleet of ever-larger drill ships? This, as recent history shows us, is an immensely complex and delicate task, and there are a number of factors to be considered. If, however, we restrict ourselves to the mechanical problem of how to minimize the weight that the drill ship must support while drilling the well, there is a manageable materials selection task to handle.

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This is the opportunity presented by the deep water riser system, and is the final example of adaptation that I will discuss here. Since risers are assembled from sections, with each section having (in a simplistic sense) a body and two end flanges, if one could determine how to make a riser section from aluminum and solve the associated joining problems, it would be possible to replace some elements of the riser string with aluminum, thereby lightening the load on the drill ship above. The aforementioned 7085 alloy, while initially configured for an aerospace application, has an appealing combination of strength and toughness for use in a relatively high load environment like a drilling riser, but it suffered from one small problem – it was not configured to create tubes as formulated. The end flanges could readily be made from forgings, but the body needed to be a seamless tube – an application tailor=made for the extrusion process. So, to make a long story slightly shorter, the answer to the problem was to slightly modify the alloy and thermal practice, prove it out on the ability to manufacture large diameter, relatively thick-walled extruded tubes, combine said tubes with forged end flanges through various joining processes, and demonstrate that the resulting section could survive the operating environment of an undersea drilling operation. That is exactly what has been done to date, and is being proved out as we speak. (Fortunately, none of this was a part of the Deepwater Horizon misadventure.)

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Thus far, I've discussed why the use of aluminum makes sense for military systems, and how one can go about finding examples from other industries that point to possible solutions in military applications. At this point, it may make sense to present a specific case of how this works, and to do so, I will borrow from my own past and discuss the wonderful world of ground transportation – specifically, automotive structures.

The drivers of competition in the automotive industry are well known, and have been the subject of countless analyses over the years. While the relative emphasis among them may shift with time, the general set is always the big four: Performance, Safety, Sustainability and Affordability. Not too surprisingly, these product categories map well into the demands on Army systems, as shown in this slide.

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Ten years ago, one of my mentors (and a former boss), Dr. Peter Bridenbaugh, presented a talk at an Army conference in which he outlined the history of lightweight automotive structures development. He particularly emphasized the work between Audi AG and Alcoa that resulted in what we know today as the Audi A8 and its ASF space frame structure. This structure, comprised of aluminum sheet, castings and extrusions joined together through welding and mechanical fastening, represented a radical departure from the traditional practice of spot welded sheet metal body structures. In his talk, Dr. Bridenbaugh postulated that the very ideas that drove the development teams at Audi and Alcoa to the aluminum space frame architecture could and should be applied to thinking about the next generation of Army systems, that is, FCS.

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Since then, much has changed in the world, but the concept of lightweight aluminum design in automotive structures has continued to advance. In addition to Audi, a number of other manufacturers such as Ferrari, Jaguar, BMW, Ford and General Motors have introduced vehicles using partial or completely aluminum body structures. Others have incorporated aluminum into sub-systems such as engine cradles, crash management systems, doors and lift gates. In every case, these manufacturers were seeking to reverse elements of what Audi originally termed the automotive weight spiral.

In essence, as the demand increases for performance, comfort and safety, the auto maker traditionally responds with upgraded systems – more powerful engines, heavier suspensions and brakes, more electronics and amenities and so on. This creates the need for heavier structures to carry the increased mass of the enhanced systems, which causes degradation in performance. The degraded performance must be offset by further increases in propulsion systems, etc., and the cycle goes on.

However, as Audi argued in their original work on the subject, the way to disrupt this spiral and essentially reverse its course, is to break the apparent link between enhanced structural performance and increased mass. This is precisely what Audi achieved in the A8, with a 40%

reduction in the mass of the body-in-white, and it has been understood and is increasingly being applied in the automotive industry today.

As societal pressures for fewer greenhouse gas emissions and greater fuel efficiency increase, the auto industry finds itself on the forefront of finding intelligent solutions for personal transportation. Regardless of whether future generations of vehicles are powered by conventional internal combustion engines or alternate propulsion systems – the necessity for lightweighting will only grow, which is driving every car maker to rethink fundamental assumptions about weight and materials choices.

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As you might surmise, automobile manufacturers aren't the only ones contending with a weight spiral. In every transportation industry, there is an analogous set of conditions– each with its own unique set drivers, but all arriving at the same place. The basic technologies and approaches developed for automotive applications – different aluminum alloys, product forms, fabrication and joining methods – have been used in trucks, buses, and … in the past few years … to military vehicles.

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Starting with essential a clean sheet of paper, the Joint Light Tactical Vehicle (JLTV) incorporates some of the best ideas aluminum has to offer – many of them lifted from markets far afield from typical military solutions. The JLTV makes extensive use of aluminum in its structure, and traces its technological lineage back – at least in part – to the automotive space frame work mentioned earlier. It also borrows from prior technology developments in aerospace – alloys and tempers as well as selected manufacturing processes.

In its development, JLTV embodies the basic principles I described earlier: Adoption in the selection of certain alloys; adaptation of other alloy / processing applications as well as selected structural sub-systems; and development of the overall concept to meet the new and/or unique mission requirements of this vehicle. (Development is unavoidable, because, in truth, while one can borrow heavily from things such as automobiles, trucks and buses, none of those vehicles has to run quite the gauntlet that a HMMWV does while in theater.) It serves as an excellent example of what can be done to use aluminum effectively, if one is willing to take cues and learn from other industrial applications.

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Those of you following closely might be wondering by now why I have not made much – if any – mention of invention, the fourth element in our approach to application of aluminum. It's definitely not because of any deep-seated opposition to it on my part; rather, I think it's an essential element of R&D. I simply don't think one should count on invention for the very next systems solution.

In my exposure to aerospace and a limited number of military development programs, I have noted and become a big fan of the concept of technology readiness levels (TRL). Clearly, invention is embodied in TRL 1-3 activities, and not yet ready for its "prime time" debut. Nevertheless, I would be remiss if I left you with the impression that all there is to aluminum is the reuse of existing solutions; there are some intriguing new possibilities in the early stages of development, and it is worthwhile to keep them in mind.

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I will only begin to scratch the surface of all that is or may be possible with aluminum in the future, but let me at least whet your appetite.

Today's commercial aerospace community finds itself divided into two camps – those who favor polymer-based, fiber reinforced composites, and those who like monolithic aluminum. For the record, as an aluminum guy, let me start by acknowledging my inherent bias: aluminum keeps a roof over my head and food on the table. All biases aside – there's a lot of life left in the aluminum solutions space.

In addition to classic aluminum alloy development, which creates new alloys and tempers on a regular basis, there are a number of researchers investigating nano-scale additions, which are reported to provide new or unique strengthening mechanisms in aluminum. As one of my more erudite metallurgical colleagues noted, all strengthening in aluminum is triggered at a nano-scale, so this should hardly be considered "new". Nevertheless, the ongoing developments in the area bear some scrutiny.

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There are also a number of novel aluminum manufacturing processes in the early stages of development and/or commercialization that merit some mention here. As an example, Novelis has brought to market their Fusion process, which enables the creation of a three layer aluminum ingot through a simultaneous vertical-drop ingot casting operation. The result is a sheet product with different surface and interior alloys and characteristics.

Also in the works, although at an earlier phase of development, are ingot casting processes that can create multi-layer and continuous gradient aluminum ingot, with the capability of generating just about any combination of aluminum material characteristics through the thickness of the material. Such materials, which could be highly tailored to the application requirements, could then be processed through conventional rolling, forging and forming operations.

Yet another emerging processing idea with the promise to yield unique aluminum materials is an approach to go from molten aluminum to directly to a sheet structure at solidification rates that are orders of magnitude faster than existing processes. Such an approach holds the potential to generate microstructures that are unknown in today's sheet materials.

All of these processes, plus the ongoing alloy and temper development, suggest many more options for the future's users of aluminum.

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Now, let me return to the composites versus aluminum aerospace debate I mentioned earlier. I want to challenge an inherent assumption of the debate: Why does it have to be "either or"?

There's been a great deal of work, some stretching back two decades or more, into the use of laminates made of aluminum layers interleaved with fiber-bearing polymer-based layers. Some of these materials have already achieved a certain level of commercial success – GLARE and

ARALL applications in Airbus come immediately to mind. More recent developments – by Alcoa and others – point to systems of alloys and laminate layers that should advance damage tolerance and durability aspects of these materials even further, thus capturing some of the strongest elements of each of the constituent materials. It seems to me, that such material systems could have a role in Army applications, even if not in today's solutions.

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And, last but not least, let me briefly consider the concept of aluminum foam. With densities of 20% to 33% of monolithic aluminum and strengths comparable to certain high-end wood-based products, aluminum foam can be moisture-resistant and fire-resistant while providing a stiff structural core for a host of applications. Originally developed as a unique building and construction type of material, aluminum foam has also demonstrated an ability to dissipate shock and pressure waves, leading me to wonder what its potential might be in armor systems.

In each of these, I have barely begun to articulate the potential of the invention, and as I said at the start of this slide, I have probably made some glaring omissions of aluminum-based research with merits for military use. However, I hope I leave you with the sense that there is a lot of impressive work going on that will set the stage for use of aluminum as a serious structural material well into the future.

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As I conclude this talk, let me take us back to where we began: the basic premise that aluminum has something to offer in lightweighting US Army materiel and systems of the future.

I think we all agree that the demands on Army systems – both today and in the future – are significant and requirement a major paradigm shift if they are to be met. Virtually every element of the new Army systems will benefit from lightweighting, and there will be a host of ways to provide it. Aluminum can – and will – be a part of the solution, but only if applied properly. This requires a judicious matching of the needs of the solution to the specific characteristics of the material.

Aluminum's development as a material is highly correlated to the development of its applications. This suggests that breakthroughs in its use in military systems will come as the nature of the application is understood. There are a number of parallels that can be drawn between the needs of military systems and the aluminum solutions created in other industries. By recognizing these parallels it will be possible to accelerate the creation of aluminum-based solutions of the Army.

Key to this approach is a clear mapping of military system needs. This facilitates an easier translation of solutions from other industries. If this can be married to the technique of adopting existing ideas wherever possible, adapting existing solutions when necessary, developing new solutions based on the core of an earlier solution and inventing as a last resort, the result should be an efficient process to find solutions to Army systems problems.

And even though I place "invention" as a last resort, there is a lot of fertile ground for completely new solutions to be created. Aluminum and its attendant processes may be perceived as a mature material, but it is by no means over-the-hill!

It remains my strong belief that creative minds, possessed of sufficient background and information, can generate the solutions required to keep the US Army's systems competitive with the task in front of them. It will take innovation and skill combined with a close interaction among systems suppliers, materials suppliers and the customer – in this case, the US Army – in order to make this happen. I have no doubt about aluminum's ability to play a major role in these solutions, and I welcome the opportunity to engage with the military community in the pursuit of this goal. To borrow from an old advertising tag line of Alcoa's: We can't wait!

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Thank you for your attention.