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TRADE STUDY OF A LIGHTWEIGHT, MULTI-MATERIAL MILITARY VEHICLE STRUCTURE

Richard J. Gerth, Ph.D.
National Automotive Center
US Army TARDEC
Warren, MI

ABSTRACT

Vehicle light weighting is a priority for the U.S. Army. Due to increased survivability requirements, additional protection measures have been added to vehicles resulting in decreased fuel economy, decreased reliability and associated vehicle availability. The automotive industry response to new CAFE requirements as well as market pressures has not only created new light-weight materials and associated manufacturing technologies, but also a supply chain capable of meeting the military' needs. This paper describes a project that is designed to test this hypothesis through the design, manufacture, and evaluation of a functional tactical demonstration vehicle with an affordable, weight optimized, multi-material substructure. The project is jointly funded by the National Automotive Center (NAC) of the United States Army, the Marine Corp, the Michigan Economic Development Corporation (MEDC), and General Dynamics Land Systems (GDLS).

INTRODUCTION

Vehicle lightweighting is a priority for the US. Army. Due to increased survivability requirements, additional protection measures have been added to vehicles resulting in decreased fuel economy, decreased reliability and associated vehicle availability, and in some cases, decreased fording capability (references).

This paper introduces a research demonstration project jointly funded by the National Automotive Center (NAC) of the United States Army, the Michigan Economic Development Corporation (MEDC), and General Dynamics Land Systems (GDLS) to develop an affordable, light weight, multi-material structure for a military vehicle. The paper begins with some background to lightweighting military ground vehicle structures and the motivation for the specific project. Then the Lightweight Vehicle Structure project and its objectives will be introduced. This will be followed by a detailed description of the trade study conducted to determine the most promising structure / material combinations likely to result in an affordable structure that meets the original requirements. Findings and conclusions are presented in the final section.

GROUND VEHICLE LIGHTWEIGHTING STRATEGIES

Lightweighting of ground vehicle structures, including passenger car bodies, follows a logical and predictable path (see Figure 1):

1. Single material component substitution
2. Single material subsystem substitution
3. Multi-material subsystem substitution
4. Multi-material complete structure substitution

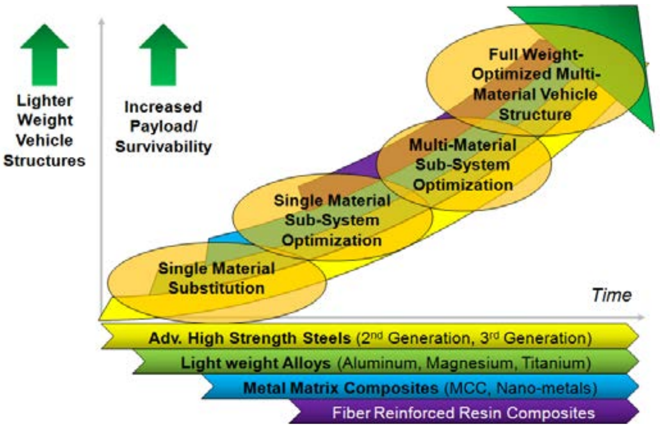

Figure 1. Lightweight Material Adoption Strategy for Structures.

The incumbent material in most cases is advanced high strength steel (AHSS). The alternative lightweight materials are aluminum (Al), magnesium (Mg), titanium (Ti), and fiber reinforced resin composites (FRC). The first step is often a single material component substitution, where a component is manufactured from a lighter material capable of performing as well or better than the original material. Typical examples include advanced high strength steel pillars in cars (ref) and resin composite manifolds on engines (reference). Often these simple material substitutions result in increased costs, simply because the lighter weight materials are often more expensive.

Figure 2. TPI Composite HMMWV [1] and FED Alpha Aluminum Body [2].

However, it has been often noted that the original component designs were part of a subsystem optimized to deal with the material's specific performance and manufacturing limitations. Many alternative material solutions could provide superior performance at the same or lower cost, if the entire subsystem could be redesigned to optimize for the alternative light weight material. This has led to single material dominant sub-systems. The term "single material dominant" is used in contrast to the term "multi-material." While most systems and subsystems consist of multiple materials, they are generally dominant in a single material (90%+), and the other materials play a secondary role in the structure. In contrast, multi-material structures will have a significant portion of a second or more materials (25%+).

Lightweight vehicle demonstrators have been built before, most notably the composite HWMV by TPI [1] and the aluminum body by Alcoa for the Fuel Efficiency Demonstrator [2] (see Figure 2). These studies were based on a single material dominant solution, i.e., the structures were constructed primarily from a single material. And this has been the natural progression for light weighting, as many lightweighting demonstrators have been created by the material suppliers, such as TPI, a composites manufacturer and Alcoa, an aluminum manufacturer to exhibit the military applicability of their material.

With increased CAFÉ requirements, the commercial automotive industry and its associated supply chain have been working for several years under internal and Department of Energy funding to accelerate the incorporation of lightweight materials. These efforts have recognized that to achieve the weight gains needed to meet CAFÉ a true multi-material structure solution will be needed. Towards this end, many technologies have been developed both in materials and in joining technology to overcome the barrier of joining dissimilar materials. Thus, the Lightweight Vehicle Structure (LWVS) program was initiated at TARDEC by the National Automotive Center to evaluate the state of commercial multi-material technology as to its applicability to lighten military ground vehicle structures.

Single material substitution is already occurring. Single material substitution is when the material used to create a single component is substituted with a lighter material without any loss of part functionality, such as replacing an iron brake drum with a composite one. This approach is relatively straight forward, and allows aspects of the organization to gain experience with the material with minimal impact on the system or subsystem design.

However, this approach is limited. Often material substitution of individual components cannot lead to large weight reductions because of interactions with other components. Hence, the next step is to weight optimize a particular subsystem or sub-assembly with a particular material. This allows an organization to gain additional experience in designing and manufacturing with the particular material.

But any subsystem or system made from a single material cannot be as light weight as a weight optimized system composed of multiple materials. This is the target of the industry – to effectively design, manufacture, and assemble vehicle structures and systems that are as light as possible and able to meet functional and cost requirements.

LIGHTWEIGHT VEHICLE STRUCTURE PROGRAM

A true multi-material structure for a military vehicle has not yet been produced for production. The FCS Aries was a hybrid monocoque / space frame architecture that was predominantly aluminum and composites [3]. It was a multi-material structure which demonstrated the state of the art. The LWVS program is not designed to show the state of the technical art, but rather the state of the commercial art. In other words, it is not a study in how much weight can technically be eliminated through material optimization, but rather how much weight can be eliminated from a current military vehicle using commercially available and affordable technologies. The project tests the hypothesis that multi-material technologies developed for the commercial automotive industry can be adapted for military applications to significantly reduce vehicle weight for an acceptable cost. The ultimate goal of the project, if successful, is to transition the adapted technologies into a current military vehicle through a future upgrade program.

The demonstration platform for the LWVS is the Marine Light Armored Vehicle (LAV). The LWVS program is a multi-year program structured in three phases (see Figure 3):

1. Trade study and technology development (14 months)
2. Detailed design and manufacture (18 months)
3. Testing (12 months).

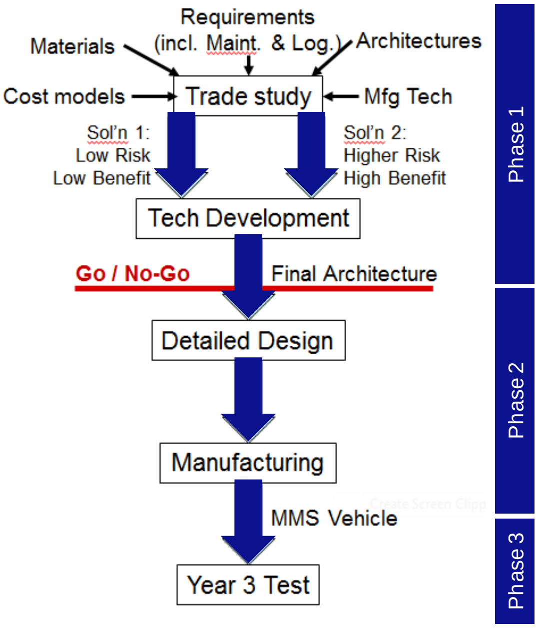

Figure 3. LWVS Phases.

Phase I consisted of a trade study and a technology development task. The concept was that light-weighting trade studies are performed frequently stand efficiently. However, given tradeoffs, uncertainty of the future, and risks involved in a multi-material structure, there would be a great deal of risk in any recommendation resulting from a trade study. Indeed, it was expected there would be low risk, material substitution recommendation, and higher risk, multi-material structure recommendation. The technology development task was a task to focus efforts on overcoming technological barriers or reducing the uncertainty surrounding the high risk option. At the end of phase I a decision would be made. If the technology development task was sufficiently successful, then the high risk option would be selected. If the technology development task was able to sufficiently reduce the uncertainty, then the low risk recommendation would be followed, unless it did not meet the weight reduction goals. In the latter case, the program would cease. If the weight reduction goals were met then the recommended solution would proceed to detailed design, manufacture, and test.

Phase I of the program was recently completed, and the results of the trade study are presented below.

TRADE STUDY

The purpose of the LWVS program is to demonstrate that it is commercially justifiable to develop, design, manufacture, and field a lighter weight structure in a military vehicle. Thus, hull sections (upper and lower), ramps and hatches, turret, etc. were all structures that could be considered for light weighting. It is acknowledged that ramps and hatches are primarily a single material substitution effort. Therefore, the primary focus was on the hull and turret structures. For cost and risk reduction purposes, the lower hull was never under consideration as it interfaced to too many subsystems, such as drive train and amphibious power units, and had more stringent ballistic requirements.

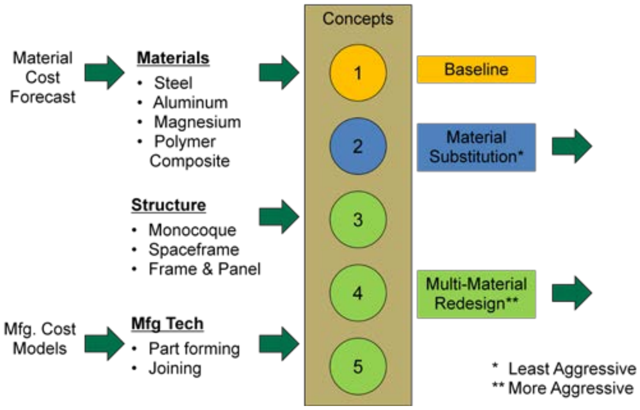

Figure 4. Trade Study Inputs and Outputs.

Further, the program is not focused upon armor development or material development. Thus, only commercially available materials are generally considered: advanced high strength steel (AHSS), aluminum (Al), magnesium (Mg), and functional resin composites (FRC). Architectures could be of any type ranging from monocoque to spaceframe, and everything in between. Lastly, it was anticipated that there would be significant manufacturing barriers that would need to be overcome in either material forming or joining. The barriers would have to be overcome either by introducing a part supplier capable or manufacturing the requisite component and selling it to the defense prime, or by identifying the appropriate manufacturing process and investing in the process for the prime to produce the requisite components.

The technical challenges and costs associated with all these factors were considered in the trade study (see Figure 4). Various combinations of these factors would yield a set of specific concepts, which were compared to the current design (steel monocoque). The results of the trade study were expected to be two competing concepts: a straight forward material substitution approach, similar to what has already been done in the past; and a more aggressive multi-material redesign.

As with any trade study certain assumptions and forecasts were made regarding future material costs and availability, as well as an assessment of manufacturing technologies required. All concepts were evaluated as to their sensitivity to the forecast assumptions.

Since one of the hypotheses of the program was that CAFE had driven the automotive industry and its associated supply chain to address many of the multi-material joining challenges, a “Technology Day” was hosted by the defense prime where 12 companies and research labs were invited to present their recent developments for vehicle lightweighting. Two of the 12 companies were later included in the technology development task specifically to address multi-material joining technologies.

Table 1. LWVS Concepts

Concept	Structure	Architecture	Material(s)
1	Upper Hull	monocoque	steel
2	Upper Hull	spaceframe	steel
3	Turret	monocoque	steel
4	Turret	spaceframe	steel
5	Upper Hull	monocoque	composite / steel
6	Upper Hull	monocoque	composite / steel
7	Upper Hull	monocoque	aluminum
8	Upper Hull	monocoque	magnesium
9	Upper Hull	monocoque	titanium
10	Turret	monocoque	composite / steel
11	Turret	spaceframe	composite / steel

Table 2. Trade Study Criteria, Weights, Definitions, and Units.

Criteria	Weight	Definition	Units
Weight Savings	20.5	Weight saved from baseline	lbs
Production Cost	20.5	Avg. Unit Prod Cost of structure (200/year x 5 years)	Low < 25% Increase Med < 75% increase Hi > 75% increase
Repackaging Burden	12.3	Number of components adversely affected	Low < 10 Med < 100 HI > 100
Growth Capability	12.3	Upgrade flexibility at the vehicle level	1 = worse than base 3 = same as base 5 = better than base
Durability	6.4	Resistance to environment / obstacle impact	1 = worse than base 3 = same as base 5 = better than base
Retrofit Cost	6.1	Installation cost	Low < $50k Med < $100K Hi > $100k
TRL	6.1	Technical Risk Level	1-9
Repairability	4.6	How easy to repair battle damage	1 = worse than base 3 = same as base 5 = better than base
Human Factor	3	Heat/vibration/noise and vehicle egress	1 = worse than base 3 = same as base 5 = better than base
Life Cycle cost	1.6	Predicted "down the road" cost of concept. Excludes production cost	1 = worse than base 3 = same as base 5 = better than base
Reliability	1.6	Mean time between operational failures	1 = worse than base 3 = same as base 5 = better than base
Maintainability	1.6	Req'd preventive maintenance checks & services	1 = worse than base 3 = same as base 5 = better than base
Economic Impact (2)	3.2	Impact to Michigan economy	1 = Low 3 = Med 5 = Hi

A constraints placed early upon the team was that any new design would have to accommodate the existing add-on armor kits. This meant the external shape of the hull could not change. This constraint severely limited what was possible to even consider for the lightweighting the existing hull.

Evaluation

Eleven concepts were developed (see Table 1) and evaluated on the set of criteria presented in Table 1. Ballistic and functional performance were evaluated based on simulating a set of load cases presented in Table 3. Performance was not an evaluation criterion. Rather it was a requirement that all alternatives meet the performance of the current structures. Thus performance was used to determine the amount of material required for a given concept. This lead directly to the weight and cost estimates. The ballistic performance requirements were the primary drivers of weight.

Table 3. Standard Hull Load Cases.

Load Case #	Nomenclature	Description
1	Lateral Inertial Load	1.5 G Inertial Load
2	Longitudinal Inertial Load	2.0 G Inertial Load
3	Vertical Inertial Load	2.0 G Inertial Load
4	1.0 G Racking Load	1.0 G Diagonally Supported Vertical Inertial Load
5	Lifting Load	1.5 G Inertial Load
6	Roof Stowage w/ Vertical Inertial Load	1,000 lb Roof Stowage w/ 4G Inertial Load
7	Ballistic Pressure	1 psi Surface Pressure Load
8	Vehicle Torsional Stiffness 1	Enforced Longitudinal Angular Displacement at Axel Centers
9	Vehicle Torsional Stiffness 2	Enforced Longitudinal Angular Displacement at Suspension Attachments
10	Vehicle Bending Stiffness	Enforced Bending along Vehicles Longitudinal Axis
11	Fixed-Fixed Normal Modes Response	Modal Response, all axles fixed

Table 4. Standard LWVS Turret Design Load Cases.

Case	Description	Load	Stress Criteria	Deflection Criteria
1	Vertical Acceleration	4G Vertical	FS >= 1.5 wrt yield	<= 0.09 in
2	Lateral Acceleration	1.5G Lateral w/ 1G Vertical	FS >= 1.5 wrt yield	<= 0.03 in
3	Longitudinal Acceleration	2.0G Longitudinal w/ 1G Vertical	FS >= 1.5 wrt yield	<= 0.03 in
4	Lifting	2.3G Vertical Lift	FS >= 1.5 wrt yield	<= 0.69 in
5	Frequency Response	1 to 1000 Hz		
6	Main Gun Single Fire	9000 lbf	FS >= 1.5 wrt yield	
7	Main Gun Repeat Fire	9000 lbf @ 3.33 Hz	FS >= 1.5 wrt yield	
8	Ballistic Pressure	1 psi over surfaces	FS >= 1.5 wrt yield	<= 0.47 in

Table 5. Complete Trade Study Table (B= Better, L=Low, M=Medium, H=High, S=Same)

Concept	1	2	3	4	5	6	10	11
Weight Savings	539	339	295	500	810	<810	384	339
Production Cost	L	M	L	M	M	M	M	M
Repackaging Burden	L	M	L	L	L	L	L	L
Growth Capability	S	B	S	B	S	B	S	B
Durability	S	S	S	S	S	S	S	S
Retrofit Cost	H	H	M	M	H	H	M	M
TRL	7	6	6	6	5	5	5	5
Repairability	S	S	S	S	S	S	S	S
Human Factor	3	2.5	3	5	3.5		3	5
Life Cycle cost	S	S	S	S	S	S	S	S
Reliability	S	S	S	S	S	S	S	S
Maintainability	S	S	S	S	S	S	S	S
Economic Impact (2)	L	L	L	M	M	M	M	M

TECHNICAL EVALUATION

The technical evaluation phase was to narrow down the candidate turret configurations to a single configuration that would be acceptable to submit phase 2 and phase 3 of the program. The four candidate configurations were combinations of metal versus composite (see Figure 4) – metal materials and monocoque versus spaceframe construction. Only the monocoque metal solution would be able to utilize the existing appliqué armor. The other three concepts would all require new armor to be developed and procured for additional cost.

The technical evaluation focused on specific technologies applicable to each concept, including:

- Composite Material Investigation & Characterization
- Joining Technologies
    - Explosive Bonded Transition Joint
    - Laser Deposition Welding
    - Aluminum Cast over Steel
    - Composite Joint Design
- Detailed FE Modeling

Composite Turret Investigation

The composite material investigation focused around the applicability of low cost carbon fiber material. This was of particular interest given the recent DOE investments in the development of low cost carbon fiber. In anticipation that future fiber costs would be driven downwards successful completion of the DOE projects, as well as from automotive investments in broader carbon fiber use, currently available low cost carbon fibers from Zoltex and AKSACA were evaluated for their performance applicability (see Table 5).

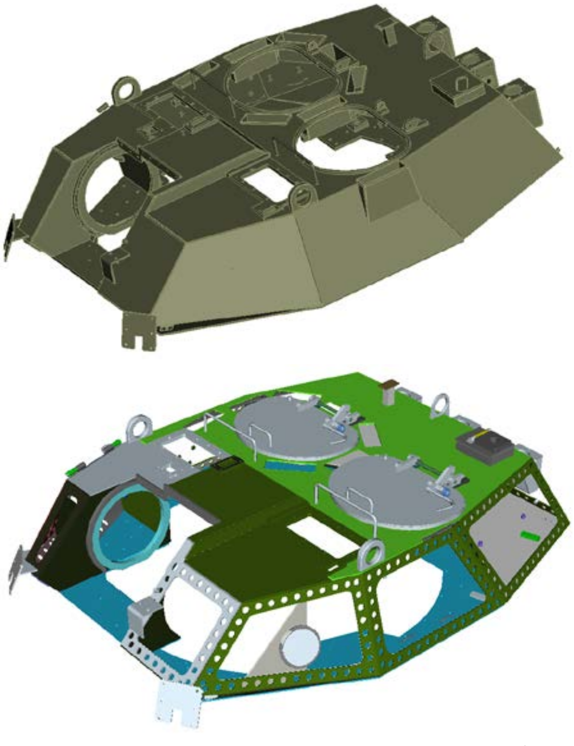

Figure 5. Example (a) Monocoque versus (b) Spaceframe Multi-Material Turret Designs.

These high quality fibers generally sell for $13-14 / lb and are used by the wind energy, pressure vessel, infrastructure, transportation, sporting goods, offshore and marine industries. Having different tow sizes available simplifies layup optimization. Designs were conducted with 55% fiber content. Testing did not show significant variation in material properties, particularly strength. Since the current design is governed by stiffness requirements, the nominal strength variation did not alter the design or predicted weight savings.

Table 6. Properties for Zoltex and AKSACA Low Cost Carbon Fiber.

Material	Tensile Strength (ksi)	Tensile Modulus (Msi)	Strain (%)	Density (lb/in3)	Yield (ft/lb)
Panex 35	600	35	1.5	0.065	400
A-38 (3K, 6K)	552	34.8	1.6	0.064	7440, 3720
A-42 (12K, 24K)	610	34.8	1.8	0.064	1860, 930
A-49 (12K, 24K)	711	34.8	2	0.065	1860, 930

The major risks and unknowns associated with the turret design involved the Integration of large metal components, such as the roof, trunnion, and mounting ring with the composite structure. Primary joining technologies considered are high strain adhesives and mechanical joints, such as bolts. These various materials are expected to add approximately 20-35 lbs to the structure. Galvanic corrosion between the carbon composite and the steel components will be mitigated by using fiberglass as an isolating material. This is a low risk solution that has been shown to work in other applications. The greatest unknown at the moment is the effect of differential thermal expansion. This requires significant analysis into determining the detailed joint design and appropriate high strain adhesive for each joint.

Additional design details for the joints, spaceframe structure, fiber thicknesses, and so on were developed under this program, and will be described in further detail in a forthcoming article.

Metallic Turret Investigations

Both monocoque and spaceframe metallic turrets involved the use of steel and aluminum. Thus, the technology development phase examined a number of forming and joining technologies, both available from commercial suppliers, as well as those still in industrial research and development. The technologies investigated were:

- Forming
    - Large aluminum casting
    - Aluminum extrusions
    - Sheet stamping
- Joining
    - Bi-metallic strips
    - Laser Deposition Welding
    - Aluminum cast over steel

The large aluminum casting is in the R&D stage, and based on initial results was very promising. This manufacturing process would be the preferred method going forward for the metallic spaceframe. If this method proves unsuitable for some reason, then aluminum extrusions could be used. Stamping was ruled out simply because the tooling cost was too great over the approximately 550 total units that would be produced.

Bi-metallic strips created from explosive bonding is a method used by naval ship builders to joint steel plates to aluminum hulls and supports. Investigations into specific joint designs and tests conducted during the technology investigation phase showed these to be a satisfactory process: no failures in the joints were created and weldability was not an issue. Laser deposition welding is a novel use of additive manufacturing processes to create a mechanical joint between a steel and aluminum plate. While initial investigations resulted in strengths roughly half those of riveted joints, the team believes this can be overcome through improved joint design. While this technology shows promise, its cost, design limitations, and performance are yet to be determined. It is still in the R&D phase and not commercially viable.

Lastly the aluminum cast over steel is a commercially available process. It was successfully applied to the lifting eye and showed improved strength and corrosion performance. Further, the lack of bolts, washers, etc. resulted in a more crew-friendly assembly with fewer protrusions and secondary projectiles.

Results

The results of the technology development stage were very successful and resulted in improved weight and cost estimates for each concept. Table 7 shows the nominal and upper / lower limit for the amount of weight saved, concept procurement, and new armor. These numbers are used to determine the cost per pound of weight saved.

Table 7, Cost per Pound of Weight Saved for each Turret Concept.

Concept		Weight savings	Unit Procurement	Armor	Total	$/lb saved
Monocoque Metal	Nominal	270	$ 62,000	$ -	$ 62,000	$ 230
	Upper limit	257	$ 65,100	$ -	$ 65,100	$ 254
Spaceframe metal	Nominal	240	$ 72,000	$ 28,500	$ 100,500	$ 419
	Upper limit	204	$ 79,200	$ 34,200	$ 113,400	$ 556
Monocoque Comp.	Nominal	384	$ 83,000	$ 28,500	$ 111,500	$ 290
	Upper limit	353	$ 93,375	$ 34,200	$ 127,575	$ 361
Spaceframe Comp.	Nominal	339	$ 77,000	$ 28,500	$ 105,500	$ 311
	Upper limit	305	$ 86,625	$ 34,200	$ 120,825	$ 396

Both the monocoque and the spaceframe composite solutions have essentially the same cost per pound weight saved. While the monocoque is nominally 7% less costly on a per pound saved basis, the uncertainty is about 20%. The uncertainty is not only driven by the uncertainty of the material and design, but also by the uncertainty around any new armor that would have to be developed.

The metallic space frame is the most expensive on a per pound saved basis and has the greatest uncertainty in that metric. This is because it is a new technology which brings the cost on par with the composite solutions. But more critically, the weight savings are significantly lower therefore increasing the cost on a per pound weight savings.

Given the low risk of the monocoque metal alternative, it was decided that further development of that design and technology was not needed. In other words, confidence was high that any upgrade program that called out such a weight savings could be successful without any further R&D investments. Thus, it was decided to take the composite turret designs into detailed design and manufacture. The specific architecture had not been decided upon at the time of this publication.

DISCUSSION AND CONCLUSIONS

The Lightweight Vehicle Structure program has already shown that a lighter weight, multi-material substructure (refer back to Figure 1) is currently possible. The aluminum-steel monocoque turret provides the same or better performance while reducing by approximately 270 lbs (30%). The major difference between this program and other previous weight savings programs is that rather than creating a structure from a single material, this project utilizes the most cost effective material that meets the need for each component.

The next phase of the project is to determine whether resin composite materials are competitive from a cost and performance point of view to be utilized by a defense prime to meet lightweighting needs of a military vehicle. This will not only be a function of production cost and product performance, but also of testing cost. It is anticipated that testing costs could be a significant barrier to adoption by increasing the upgrade cost beyond what makes sense. Therefore, the next phases of this project will also address question of how to reduce the test and evaluation cost of a hypothetical upgrade program involving a composite turret to the point that testing costs are equivalent to those for a monocoque metallic turret.

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