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OPTIMIZATION/INTEGRATION OF METALLIC AND NON-METALLIC FOAMS FOR STRUCTURE, THERMAL DISIPATION, MINE BLAST PROTECTION, AND BUOYANCY FOR AMPHIBIOUS MILITARY VEHICLES.

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ABSTRACT

For this particular effort, the U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC) Center for Systems Integration (CSI) was tasked to develop a buoyancy/survivability kit that would serve multiple functions. The underbody kit would meet or surpass current required protection levels. Plus the kit was to ensure that the LAV-25A2 (Light Armored Vehicle) continues to meet the swim requirement. However, the overarching objective is to meet the survivability, ground mobility, and water mobility requirements. Combining the accomplishments in the TARDEC & PM-LAV (Program Manager for the Light Armored Vehicle) survivability program in 2013-2014 with the TARDEC & PM-LAV buoyancy/survivability kit developed in 2015-2016, the overall weight is decreased, water mobility is improved, and survivability is significantly improved.

This is a unique challenge as a combination of buoyancy, mine blast, and structural requirement on a ground military vehicle is novel idea. The current underbody D-kit weighs 3,700lbs and results in a loss of ground clearance that adversely impacts the ground mobility capability. TARDECs survivability program conducted for the Program Manager for the Light Armored Vehicle (PM-LAV) in 2014 estimated that to add survivability upgrades it would add an additional 460 lbs. Furthermore, planned LAV Programs would add an additional 1,600 lbs. This is a weight growth of 5,760 lbs and would severely impact the water and land mobility of LAV-25A2.

This paper will present how U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC) developed innovative solutions to enable the LAV-25A2 to significantly improve survivability, meet current swim requirements, and have enough weight reserve that a ride height suspension and new engine could be added without impacting the other two requirements.

INTRODUCTION:

This paper will discuss how TARDEC leveraged the modeling and simulation (M&S) done during the PM-LAV – TARDEC survivability program in 2013-2014 for the Light Armored Vehicle (LAV) Family of Vehicles (FOV). This M&S data was used to evaluate how the kit weight would be impacted by the ride height of the vehicle. The innovations in the survivability program will also be discussed as to how they were able to keep the weight low. The PM also wanted the option to replace the current D-kit with the TARDEC solution, so cost would have to be kept to approximately what the government paid for the D-kit. So any innovation would have to be economical. Market research into commercial industry and into Navy applications were explored to identify technology that could be used or adapted to meet the needs of the Marine.

Regarding water mobility, TARDEC conducted modeling and simulation analysis regarding the vehicle stability to right itself in the water and the amount of free-board. Water mobility analyzes were done comparing the LAV-25A2 baseline, PM LAV MOB Program planned upgrade with the TARDEC Buoyancy/Survivability kit for higher ride height, and the LAV-25A2 with a TARDEC buoyancy/survivability kit designed for the lower ride height.

The differentials that are on the outside the vehicle use convective heat transfer to keep the differentials cool. If an underbody kit is applied to the bottom of a vehicle, the convective heat transfer is significantly impacted and any airflow is significantly choked off by the underbody kit. Because the kit will be using foam, a very insulative material, the cooling of the differentials will become even a greater challenge than typical underbody kits. Since PM-LAV was able to field a successful underbody kit that did not cause the LAV-25A2 to overheat in the extreme environment of Afghanistan or Iraq, it would be used as a baseline. The new buoyancy/survivability kit design would have to provide the same level of thermal dissipation as the original kit. Once again modeling and simulation was conducted to identify the heat dissipation and hot spots on the kit and provide information to the engineers for material selections and to develop solutions.

Integration was also addressed on the program and the vehicle has a spall liner bonded inside the LAV-25A2. The maximum temperature that the adhesive can withstand is 300 degrees F for a 1 hour duration. This makes traditional gas metal arc (GMA) welding difficult since the heat from GMA welding would typically cause the plate to go beyond that temperature. TARDEC conducted research into bonding options and discovered that stud welding equipment would produce welds at a much lower temperature than GMA welding. A study was conduct on the temperature that results from stud welding different diameter studs to armor plate and plain carbon steel. Testing was also conducted to test the bending and sear strength of the stud weld. A technical paper titled "Low temperature welding to Steel with Adhesives, Thermoplastics, or Composites was recently written by TARDEC.

LIGHT ARMORED VEHICLE (LAV):

The Light Armored Vehicle (LAV) Family of Vehicles (FOV) entered into service in 1983. It has performed significant missions on land and a couple in the water. The Invasion of Panama was one such example where the LAV used its water mobility to escape detection. It also used its water mobility in Iraq when water crossings were more expeditious than land trails/roads [1]. But its land mobility is exceptional. The top speed on improved road is 62 mph while it's off road capability matches the capability of a High Mobility Multipurpose Wheeled Vehicle (HMMWV). A recent article in the LAV Support Quarterly stated "The Invasion of Iraq saw separate advances take place on both side of the Euphrates River prior to the assault on Baghdad. A crucial part of this one-two punch was the 1st Marine Division. In just over three weeks the 1st Marines carried out the longest sequence of attacks since the Corps' inception, and as a whole, the Marine Expeditionary Force rapidly advanced more than 800 km from Kuwait to Bagdad.

In a campaign characterized by blazing fast road marches, numerous strategic feints and sudden maneuvers, the LAV's high road speed, reliability and supportability proved to be major assets" [2]. The goal of this program is to enable the LAV to maintain its effectiveness on the battlefield while enhancing it swim and survivability capability.

LEVERAGING PRIOR TARDEC SURVIVABILITY PROGRAMS:

To keep the research and development (R&D) program cost to a minimum TARDEC leveraged upon it efforts from the prior survivability programs that were recently conducted in the past couple of years.

In 2012, TARDEC's CSI Mechanical Development Team designed and produced a TDP for a new Amphibious Combat Vehicle Hull that held 20 occupants. The structure had several new concepts and innovations never developed previously. Interior innovation included a new flooring design. Also, the TARDEC ACV design utilized air pockets with the potential of filling the air pockets with bladders. The concept would work but the desire was to have a solution that would not loose buoyancy or minimal amount of buoyancy even if severely damaged. Due to funding and time constraints during the ACV program, the impact of using foam on the survivability performance could not be evaluated at that time.

The TARDEC – PM-LAV Survivability Program in 2013-2014 showed how new technology could be integrated to enhance survivability performance to the LAV as well as other military vehicles as well. Furthermore, PM-LAV requested TARDEC to develop solutions that can be competed to industry. We had one additional goal. The survivability upgrade is planned to happen in 2017 but could slip to 2019 and maybe even later. Make the solution such that the best and most current solution is at the time of procurement, which can be 2017, 2019, or later.

We developed an interface control document for the entire survivability package that provides the space claim for the survivability upgrades, hull structural deflection zones, human factors requirements, operational/motion requirements, materials, corrosion, and storage requirements [3,4,5]. This technical data package was then combined with the survivability requirements to form the interface control documentation. Even though the government does not own the technical data package (TDP), PM-LAV was provided an interface control document that can be competed to any authorized US military vendor now or years from now. In addition, this was projected to save the PM over half the initial cost estimate for the program if it could be competed to all vendors.

The PM LAV MOB Program mobility upgrade program was an effort to take a fielded adjustable ride height suspension and integrate that into the LAV-25A2. The program also had an engine upgrade and other upgrades as well. This is a simplistic summary of the program.

Instead of starting a new M&S analysis, TARDEC leveraged the M&S analyzes previously conducted in past. A vehicle model was raised six inches off the ground and simulated blocks were placed under the wheels and other changes were made to reflect differences in design.

By raising the vehicle 6 additional inches the underbody kit weight could be reduced by over 60%. Additional studies were done to determine if more could be done to reduce weight. After several analyzes it was determined that the kit could weigh 16.5% of the original kit weight by increasing the ride height by 6 additional inches (an 83.5% reduction in weight). A very relevant study of comparing the weight of underbody kit required to meet a survivability requirement level for different ride heights was started for three different threat levels.

BUOYANCY CHALLENGE:

The total weight of the TARDEC underbody armor kit was reduced to approximately 750lbs. This is a substantial weight reduction. However, the kit must float. In addition, it must also provide enough buoyancy to account for the PM LAV MOB Program MOB upgrade weight gain. To achieve a kit that would meet the survivability requirement as well as the water mobility requirement, a total of 2,350 lbs. of buoyancy would have to be added back to the vehicle plus an additional 460 lbs. of buoyancy for the increased weight for survivability upgrades. To achieve threshold buoyancy, all the available volume between the underbody kit and the LAV hull would have to be displaced with a lightweight material that would not allow water to get into the material.

LIGHTWEIGHT MATERIAL:

For this particular effort, materials are being evaluated that can provide buoyancy within a structural shell that will be applied to the bottom of a military amphibious vehicle. As of 2015, we have found that the NAVY and ARMY have both started to use Aluminum Honeycomb and foam filled panels. The Navy and Coast Guard are using them for Bulkheads, Flooring decks, False Decks and other areas that are interior to the ships. The Army has started to use the material for boxes, crates, building walls, floors, roofs, equipment structures, electronic instrument shelters, personnel shacks and more. The Army is also developing "Flexible Honeycomb and composite vehicle armor of hex and foam materials. Specifically, the materials that can be used for this application is as follows:

Honeycomb Material:

- Aluminum Honeycomb
- Plastic Honeycomb
- Stainless Steel Honeycomb
- Nomex with Phenolic coating

Metallic Foams

- Aluminum Foam
- Copper Foam
- Titanium Foam
- Steel Foam

Non-metallic Foams

- Expanded Polyethylene Foam
- Expanded Polypropylene Foam
- Polyurethane Foam
- Vinyl Nitrile Foam
- Expanded Polystyrene Foam
- Styrofoam
- Syntactic Foam
- Nylon Foam
- Water & Tear Resistant EVA Foam

HONEYCOMB & METALLIC FOAM:

Polymer foams have been used in the marine environment for years. There is a growing interest of using metallic foams for marine, automotive or aerospace applications. The benefit of the metallic foam is that they can absorb significantly more energy than polymer foams and they can also provide a structure that is tailored for strength and stiffness. One primary benefit of the metal foam over a honeycomb in survivability or automotive is that the energy absorption can be spherical. Meaning that it performs similar from a frontal impact, side impact, or under the vehicle from a mine blast. Honeycomb needs to be integrated so the loading is applied normal to the honeycomb skin so it buckles properly. "Aluminum foam sandwiches (AFS) [6,7], obtained by combining metal face sheets with a lightweight metal foam core, have peculiar properties (low specific weight, efficient capacity of energy dissipation, high impact strength, acoustical and thermal insulation, high damping), that made them interesting for a number of practical applications, such as the realization of lightweight structure with high mechanical strength and good capacity of energy dissipation under impact. Aluminum sandwich structures are suitable for applications in high speed marine and terrestrial vehicles, as they allow a speed increase with a good passenger comfort thanks to their specific weight and high dampening capacity"[8].

Metal foam can be closed or open celled as needed for the application required. Closed cell is the best for an in water condition and can be machined and not have to worry about any water getting past the very first row of opened pockets. Using Aluminum Foam will give extra protection against mine blast and shrapnel when combined with Armor. .

For this particular case, in order to meet the buoyancy requirement the average density needs to be less than 5 lbs per cubic foot. Based on this metal foams require a very large cell size and concern rises as to the potential for water entrapment. Sealing of the edges would be a requirement and any hole in any part of the sealed edge would be a potential for the entire aluminum foam product to trap water.

NON-METALLIC FOAMS:

A conceptual design was innovated by TARDEC's Center for Systems Integration (CSI) Mechanical Development Team. Specifically this design utilizes aluminum for the structural shell. By meeting the survivability requirement with just the shell, the buoyancy material function was to provide buoyancy while swimming and would not compress under water. The material would also have to meet flammability requirements and temperature extremes of -40F and 160F. The weight of the material needed to be under 5 pounds per cubic foot to provide adequate buoyancy. This excluded metallic foams

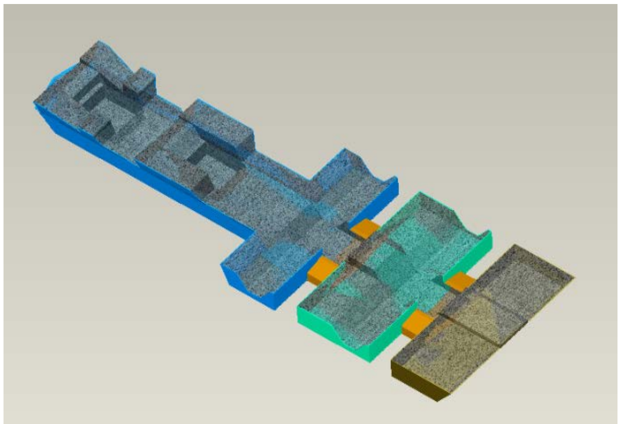

Figure 1: TARDEC Underbody Buoyancy/Survivability Kit

because they were too heavy and so too many syntactic foams. Since this kit would be used as a skid plate, it would sometimes deflect while driving over obstacles. This performance parameter required a material that would deflect and rebound to original shape. This criteria eliminated the use of honeycombs from being used in the design. Cost also drove the selection to Polyethylene, Polypropylene, Polystyrene or X-linked Polyethylene. Polystyrene is used significantly in automotive and in NASCAR industry. It is used for occupant protection and much analysis has been done on this material. NASCAR and NASA have spent considerable effort in dealing with occupant safety in high impact situations. Figure 2 shows a crash in automotive racing. The damage from this crash shows how NASCAR is utilizing energy absorbing foam to help mitigate energy being transferred to the occupant. Dow has conducted studies on their polystryene foam showing its effectiveness over semi-rigid polyurethane foam and polypropylene foam for energy absorption in side auto impacts [9]. Polystyrene foam tested with more consistent and greater energy absorption. The performance of the polystyrene foam to expanded polypropylene foam was more constant from -30°C TO 85°C. Furthermore, Dow has conducted finite element analysis on their foam for particular applications. They have also published the LS-DYNA data for their IMPAXX foam that can be used by analysists for modeling and simulation analysis [10]. Unfortunately this material will wick and will eventually absorb water, even though it is closed cell.

Figure 1: NASCAR Crash [11]

One application that is applicable is the fenders and bumpers used on docks. The foam fenders in particular have matched requirements. They are constantly compressing the fender from the movement of the water and rubbing the surface as the ship moves with the ocean water. The fenders don't wear and the foam does not break down. Figure 3 shows an image of the foam filled fenders protecting navy ships from damage at a US navy ship yard.

Figure 2: Foam Filled Fenders at a Pearl Harbor Navy Station [12]

A close up of an ocean guard netless foam filled marine fender used at the US Naval Ship Yard is shown in figure 4.

Figure 3 Foam Filled Fender [13]

http://www.marinefendersintl.com/portfolio.html

These fenders have the capacity to be compressed up to 65%. The construction of foam filled fenders are typically made with an elastic coating, typically urethane and a nylon or Kevlar fiber with a polyethylene foam core. This performance matches the performance requirement established for this application. The baseline design was then selected to be a non-metallic foam, polyethylene (preferred) or polypropylene.

COLD IMPACT TESTING OF POLYETHYLENE AND POLYPROPYLENE FOAM:

A research review of cold impact testing of polyethylene and polypropylene foam did not provide any information regarding the performance of the different foams and how they perform as the density is increased.

TARDEC conducted an internal test to determine the difference between the material types and the density of the material. The initial test was done at zero degrees Fahrenheit. This study had several samples of the two different types of foam with a density of 1.3 PCF (pounds per cubic feet) to 5 PCF were placed in a freezer for 24 hours. A thermocouple was placed in the foam block to validate that the center did reach the desired temperature. It was interesting to note that the foam reached ambient temperature quickly. In this case, ambient temperature in the walk in freezer was zero degrees Fahrenheit. One sample was removed from the freezer at a time and immediately evaluated to determine their impact properties. It was noted that as the foam density went higher that the materials performance declined. The material had a permanent compression set where the lighter foams rebounded to the original shape. Polyethylene performed better than polypropylene, but it was close.

Figure 4: TARDEC Cold Temperature Chamber

A second test was conducted using the foam blocks to evaluate the impact performance at the cold temperature limits, - 40 degrees Celsius. A couple of foam blocks of each material from 1.3 pcf to 4.2 pcf were put into a cold chamber at TARDEC's Vehicle Armor Lab (figure 5).

Once again the higher the density the more damage to the foam. In fact, the damage was more severe at the colder temperatures for the higher density foam. Also, polypropylene foam experienced more damage than the polyethylene foam. At 1.3 pcf, the polypropylene foam experienced cracking from impact loading. Most importantly is that the 1.3 PCF foam returned to its original shape and did not take on any permanent compression from the impact. The 3.7 PCF polypropylene foam unfortunately did take on a permanent set. Figure 6 shows the Expanded Polyethylene (EPE) foam blocks after cold impact testing and figure 7 shows the Expanded Polypropylene (EPP) foam blocks after cold impact testing.

Figure 5: EPE Foam Blocks after Cold Impact Testing

Figure 6: EPP Foam Blocks After Cold Impact Testing

SPONSON BUOYANCY KIT:

As stated in the buoyancy challenge, all of the available space would be replaced with foam. Figure 1 shows the volumetric space claim of an early prototype underbody kit. The kit weighed approximately 739 lbs and provided 1,320 lbs of net buoyancy. This is below the 1,600 lbs required by PM-LAV and if the survivability upgrades are to be installed into the vehicle, an additional 460lbs of buoyancy might be required. This level of buoyancy would not be enough so other areas of the vehicle were considered for evaluation.

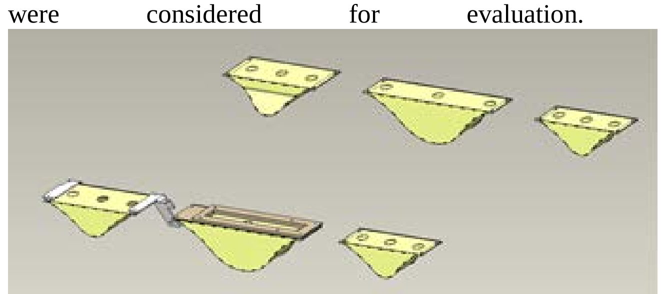

Figure 7: Buoyancy Boxes

The PM-LAV did not allow the use of buoyancy boxes to simply add volume. However, amphibious combat vehicles have put additional volume between the tires and the sponsons. This is one area the does not change the shape or size of the vehicle and would not impact how the marines utilize the LAV-25. The benefit of the buoyancy boxes in this location is that they provide buoyancy near the water line that helps stabilize the vehicle in the water. Figure 8 shows the computer aided design (CAD) model of the buoyancy boxes. The shells were made out of aluminum, but for production it is recommended to be made out of a polymer to further reduce weight and cost. Figure 9 shows the buoyancy boxes with no foam.

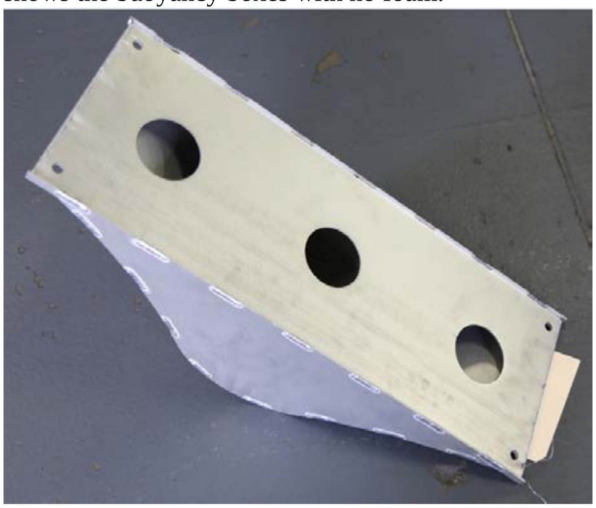

Figure 8: LAV-25A2 Buoyancy Box Shell

The foam selected for the underbody kit could not be used for the buoyancy boxes because it is typically made into sheets or molded. This process is not available for one or two prototypes and welding would damage the foam. Additional research was done to determine other non-metallic foam type materials that were available that could be poured into a cavity. The top candidate is bead foam. Bead foam has potential survivability benefits as that the individual beads collapse. The University of Bayreuth, Germany published an article on bead foam that was released online 7 Nov 2014 in Polymer. That article stated that "bead foams are gaining popularity for structural parts in automotive industry, such as crash absorbers in bumpers, due to their high specific energy absorption at impact [14]. The driving force for the growing use of bead foams is weight-reduction, which correlates directly to saving fuel and material. However, for prototypes and for ease of development, the buoyancy boxes were filled with polyurethane foam. Since the buoyancy boxes are protected by the aluminum shell almost entirely and the only opening is protected by the sponson, the foam should not compress, or it would be minimally compressed. Also, polyurethane foam is used extensively for boating and we had a boat repair shop fill the buoyancy boxes because of their familiarity with this foam. Structural foam like polyurethane foam "helped the Cadillac Seville luxury car enabling IIHS offset barrier test performance improvement to highest rating possible without structural 'tear-ups' or styling changes required in the upper structure. To achieve this 0.65 kilograms of foam was added to the hydro-foamed A-pillar upper"[15]. Figure 10 shows the buoyancy boxes after the foam was installed.

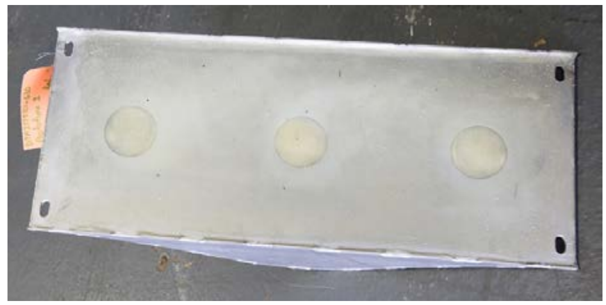

Figure 9: LAV-25A2 Buoyancy Box with Foam

TRIM VANE BUOYANCY KIT:

The trim vane is a composite and can be damaged from impact and the edges are also susceptible to cracking and delamination due to design and utilization issues. Since this part is experiencing damage and it is a high cost replacement item, PM-LAV requested that TARDEC consider what can be done to the trim vane to protect it better. Also if any additional buoyancy can be added, that would be the best place since volume would be added at the water line and buoyancy would be added to the front of the vehicle which would help keep the nose of the vehicle up. Based on prior research, EPE foam was selected to be added inside the trim vane protective cover shell. Fig 11 shows an exploded view of the aluminum shell and the EPE foam plus mounting hardware. The design is to slip over the composite trim vane and be captured on the sides and top with the bracket on the bottom to prevent the kit from sliding or bouncing off the composite trim vane. The composite trim vane is not shown, but looks similar to the foam piece in the picture.

WATER MOBILITY ANALYSIS:

The initial primary goal of the program was to provide the required buoyancy such that it off-set the weight gain from the mobility upgrade so the vehicle swimming capability would be brought back to LAV-A2 capability. To achieve this buoyancy requirement additional buoyancy kits were added to the design. Figure 1 shows all of the buoyancy kits designed by TARDEC's CSI Mechanical Development Team that were added to achieve 1,772 lbs of additional buoyancy.

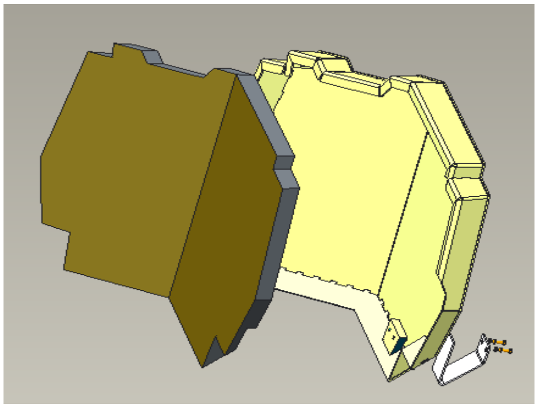

Figure 10: CAD model of Front Trim Vane Buoyancy kit.

TARDECs Thermal and Fluid Flow Analytics Team Analyzed the TARDEC underbody kit with the MOB upgrade weight to the baseline LAV-A2 and the LAV-A2 with the MOB Kit. This analysis was based upon VIPER Data conducted by TARDEC on the LAV-25A2 and the center of gravity and center of buoyancy provided by PM LAV MOB Program regarding the LAV-25A2 MOB upgrade model.

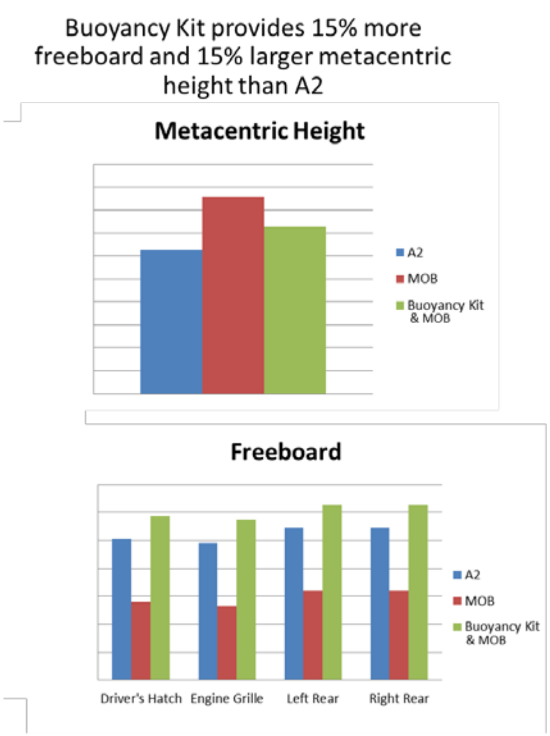

Figure 11: TARDEC Mine Blast/Buoyancy/Skid Plate Kit Concept Freeboard & Metacentric Height

The data for the Buoyancy kit was based on CAD data provided by TARDEC Center for Systems Integration Mechanical Development Team and the PM LAV MOB Program data of the MOP upgrade. A hydrostatic analysis was performed for the following configurations of the LAV: A2, with MOB, and MOB plus the CSI buoyancy kit concept. This analysis was performed using the Orca3D naval architecture software. Figure 12 shows that the freeboard and the metacentric height is 15% better than the baseline vehicle (LAV-A2).

One of the issues of adding buoyancy is the issue that if the center of gravity of the vehicle and metacentric height approach each other, the vehicle will become less stable. TARDECs Thermal and Fluid Flow Analytics Team performed the vehicle stability analysis on the TARDEC underbody kit solution and determined that the MOB upgrade with the TARDEC solution would be more stable in the water (Fig 13). This is because the stability is measured by the area under the curve. So for an approach angle of 15 degrees going into the water, the LAV with the MOB upgrade with the TARDEC buoyancy kit is about 50% better at righting itself than the baseline LAV-25A2.

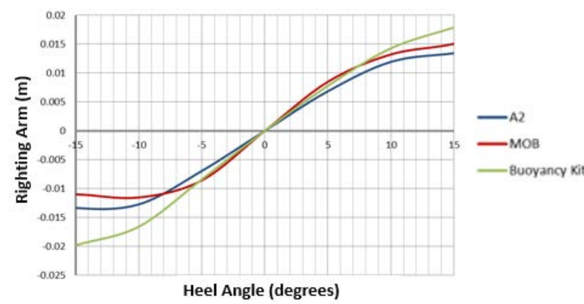

Figure 12: TARDEC Mine Blast/Buoyancy/Skid Plate Kit Concept Stability Curves

REMAINING CHALLENGES:

Two remaining challenges are integration and heat dissipation. Integration was tackled next in the program. The original D-kit used NPT threaded fasteners and bolted a bracket to it. The NPT threaded adapters are items 58 and 59. These are used to convert from National Pipe Thread Taper (NPT) to Unified Course Thread (UNC) threads so the kit can be bolted onto the vehicle. The design is very solid from the standpoint of survivability as the fasteners should not become projectiles in the event of a mine blast.

The PM did not want to modify the hull for bolting the kit onto the vehicle. It was also desired not to weld on the vehicle unless required. It was preferred to use the same or similar drain holes for mounting the kit. The second issue would be draining the vehicle. The kit fielded to theater did not provide a pass through for draining the vehicle. So when the bolts were unfastened, the liquid inside the vehicle would run onto the underbody kit and collect in the V and run-off. Furthermore, the maintainer had to reach between the armor kit and the bottom of the vehicle and unbolt each mounting fastener one at a time. Since you are removing the mounting fasteners that bolted the kit to the hull, the maintainer has to be careful not to remove more than one of the bolts or the kit can shift and if too many bolts are removed it could drop.

An innovative solution was developed that enables the TARDEC LAV-25 Buoyancy/Survivability kit to bolt the kit onto the LAV-25 lower hull using the existing drain plugs and enabling the drain plugs to continue to be used for draining the vehicle, and meet survivability and automotive durability requirements as well as keeping the hull sealed from water intrusion. Fig 14 shows a cross section of the fastening method developed for the kit. The kit uses an adapter like the original D-kit. However, instead of bolting though the center of the adapter, the outside is threaded and a special hat shape nut is used to bolt the bracket onto the vehicle while having the same wrench size for ease of installation. The hat shaped bolt has internal threads that are used for a plug to seal the vehicle. This enables the bolts to be removed without unbolting the kit from the vehicle.

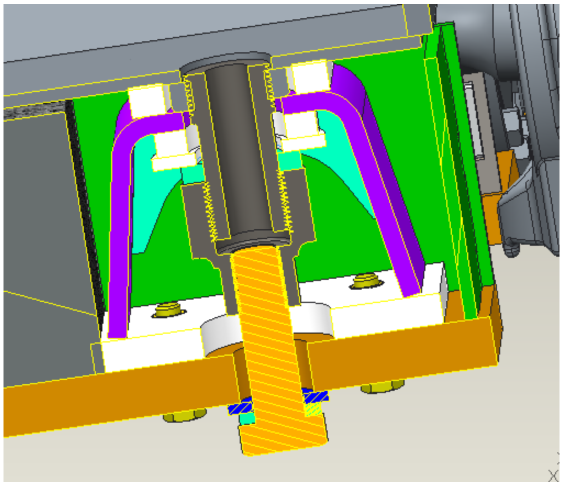

Figure 13: Innovative Drain Plug/Mounting Fastener

STUD WELDING:

Another integration issue was how to mount the buoyancy boxes to the LAV-25A2. The vehicle did not have any existing attachment points and the composite inside the vehicle was glued to the hull and it could not be removed without ruining the armor. PM-LAV did a study that determined the adhesive is damaged if traditional GMA welding is done on the steel it is bonded too. The study concluded that if the composite adhesive is exposed to a temperature of 300 degrees Fahrenheit or higher for one hour or more, the adhesive will fail and the composite will most likely be damaged. However, the testing did show that it might be possible to weld to the vehicle with robotic welding and cooling aids. The risk level was moderate to high so TARDEC was authorized to evaluate other alternatives by the PM. TARDEC conducted literary research to determine other viable options. The best one was stud welding. A preliminary test was conducted on a ¼ thk plain carbon steel plate to gauge if the stud welding process would be an option. The stud welding process used a Nelson Nelweld® N1500i™ was used for this test.

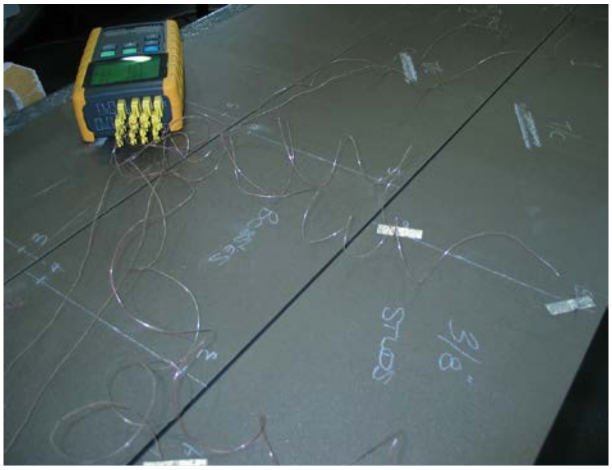

Figure 14: OMEGA RDXL12SD Recorder and Test Plates

Welds were done from ¼ inch diameter studs to 3/8 diameter studs. After each weld the plate was turned over and the temperature was measured by the Omegascope thermal infrared (IR) gun. It did take about 5 seconds to get the plate turned over. The hottest temperature recorded was 150 degrees

Fahrenheit.

Figure 15: Stud Welding Setup with View of Foam Under Weld Blanket

This was way below our requirement, but the initial temperature of the plate was hard to evaluate and the plate cooled quickly. Within about 7 seconds the plate was cool enough to touch from the backside. To conduct a more thorough analysis, it was decided to cut larger plates and mark representative locations for the studs on the plate. Both sides of the plate was marked and thermocouples were put on the back side of the steel plate being welded. To trap the heat in like the composite would do, the steel plates were put on a welding blanket that was covering a 6 inch thick piece of foam (fig 16). The welding took about ½ a second with the stud welding equipment. To record the temperatures datalogging equipment was set to record all 12 channels simultaneously with recordings being measured every second. Figure 15 shows the OMEGA RDXL12SD 12 Channel Temperature Recorder on an Omegascope Model OS530 Series thermal gun with an optional K type probe. Eight thermocouples were initially hooked up to the OMEGA temperature recorder with an additional four added later. The figure also shows the three test plates that were used for stud weld testing.

Stud used	Max Temp	Average Max Temp	Max time above 300F	Ave max time above
	°F	°F	Seconds	Seconds
1/4 Stainless Steel Stud Nelson Part Number 12A867	262	208.75	0	0
5/16 Stainless Steel Stud Nelson Part Number 12A877	348	259.375	4	0.625
3/8 Stainless Steel Stud Nelson Part Number 12A887	387	292	4	1

Figure 16: Stud welding temperatures for different studs

A total of eight studs were welded onto each test plate and simultaneous recordings were taken for all eight stud locations with a temperature reading taken every second. A table summarizing the average data is shown in Figure 17. This shows that the ¼ stainless steel stud was able to be welded without going over 300 degrees Fahrenheit and should be safe for welding. The 5/16 is most likely acceptable with additional information regarding the max temperature of the epoxy or composite. Only one temperature reading was over 300 degrees Fahrenheit and it appeared that the stud welder took longer than normal to weld that particular stud. The analysis done at TARDEC on stud welding is in the technical paper Low Temperature Welding to Steel with Adhesives, Thermoplastics, or Composites [16].

Figure 17: Stud Welding 1/4 stainless steel studs onto the LAV-25A2

Templates were made and the studs were welded onto the vehicle on May 2016. Pictures showing the studs being welded to the LAV-25A2 is shown in figure 18. The image on the upper right of the figure shows what a stud looks like after welding. Stud testing was also done on the bend testing of the studs. All studs tested satisfactorily completed bend testing. Additional destructive testing was also conducted on the studs to determine the maximal torsional load the bolts would be able to take before failing. On average the bolts were able to take three times their specified torsional loading before failure.

THERMAL ANALYSIS:

The final challenge was to keep the differentials as cool as or cooler than the LAV-25A2 with the D-kit. The problem is that we are adding an insulative material that is going to reduce the conductive and radiative heat transfer. Fortunately, the original D kit did have very large brackets that were restrictive to

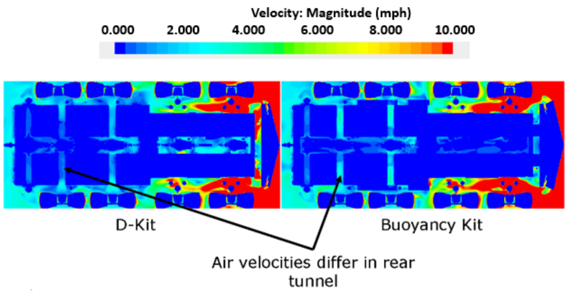

Figure 18: Air Velocity Images for the Buoyancy Kit and the D-Kit

the airflow and did not allow airflow into the rear differential area.

The technical manual for the D-kit required the differentials to be inspected during operational checks and also whenever necessary. An infrared gun was used to check the differentials and number 3 was the differential inspected to measure the temperature of the differentials. It was noted that information from the field provided by individuals familiar with the fielding of the D kit noted that Differential 3 and 4 tended to get the hottest in the field, although all could get hot depending on driving conditions and condition of the differentials and oil quality and level in the differentials.

TARDEC's Thermal and Fluid Flow Analytics Team conducted an analysis to determine the temperature difference of the D-kit to the TARDEC buoyancy/survivability kit for the LAV-25A2. The purpose of the analysis was to compare the thermal performance of the 3rd and 4th differentials for the following:

- LAV-25A2 + D-kit
- LAV-25A2 + Buoyancy/Survivability kit

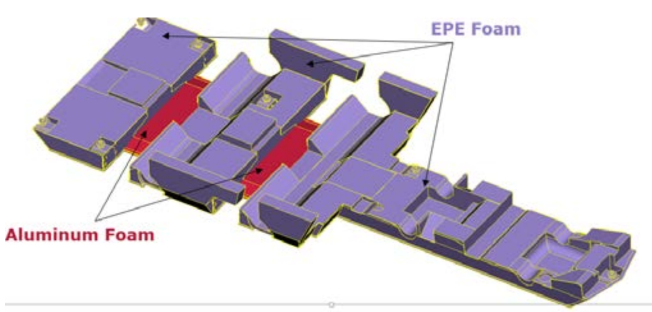

Figure 19: EPE Foam and Aluminum Foam Locations for the TARDEC Buoyancy/Survivability Kit

Figure 20 shows the location of the EPE foam and its shape and the location of the aluminum foam. The predicted surface temperatures were compared for each case under the same conditions so that relative performance can be determined. The general assumptions of the study are as follows:

- Steady State
- Ambient Temperature 130°F
- Vehicle (air) Speed: 5, 10, 20, 35 mph
- Drive: 4x8 (3rd and 4th axles)
- Differential Heat Load: Varies with Speed, Same for Each Differential
    - Chosen to achieve a D-Kit differential surface temperature of ~ 265 °F

The model parameters are as follows:

- Heat rejected through conduction, convection, and radiation
- Buoyancy Kit Material: EPE Foam
    - Density: 32 kg/m^3
    - Specific Heat: 1,300 J/kg-K
    - Thermal Conductivity: 0.03 W/m-K
- Buoyancy Kit Material: Aluminum Foam
    - Density: 350 kg/ m^3
    - Specific Heat: 920J/kg-K
    - Thermal Conductivity: 35 W/m-K
- Aluminum Shell/Underbody
    - Density: 2,652 kg/ m^3
    - Specific Heat: 884 J/kg-K
    - Thermal Conductivity: 201 W/m-K
- Surface Emissivity: 0.8 (for all surfaces)

Figure 21 shows the results from the analytical analysis. One of the reasons for the D-kit running hotter than the Buoyancy kit at higher speeds is that a bracket on the D-kit blocks the air behind differential number three. Also, the air flows over the plates for the D kit and is not forced into the differential area. This is the case only for high speeds at 35 mph or faster. For speeds lower than 35 mph the TARDEC buoyancy kit is running hotter than or as hot as the D-kit. The table in Fig 21 shows that the buoyancy kit is running up to 35 degrees hotter than the D-kit. Since the differentials were overheating in Iraq, this is an unacceptable result and the differentials would have to be cooled by something.

Temperature, °F (Diff. 3 / Diff. 4)		Vehicle Speed, mph			
		5	10	20	35
	D-Kit	265 / 260	265 / 265	235 / 265	220 / 265
	Buoyancy Kit	300 / 295	290 / 280	240 / 245	220 / 230
	Delta	+35 / +35	+25 / +15	+5 / -20	0 / -25

Figure 20: Temperature of the Differentials for the Initial Buoyancy Kit Prototype and D-Kit

The typical options are to put a fan to cool the differentials. This becomes difficult because the fan would be outside the vehicle and would be under the vehicle that could be submerged. The other issue is that the fan could become clogged with dirt, mud, and debris from cross-country terrain or dirt trails. Another option is to put an oil cooler for the differential and allow the oil to be pumped and cooled. This had the added benefit of easily checking the differential fluids. The drawback is the additional lines would be more prone to leaking. The last option considered was to use a passive cooling system. Since the underbody plate was aluminum the thought was that heat could be transferred from the tunnel area to the thick underbody plate that would serve as a huge heat sink. If this could be done correctly, the solution would have no moving parts and the design could provide other benefits as well.

TARDEC Center for Systems Integration's Mechanical Development Team developed a Pro-E CAD model concept shown in figure 22 that shows a conceptual design that would go around the differentials and get as close to the heat source to help draw the heat away from the differentials. The heat from the differentials is going to rise to the top of the tunnel. Also the tunnel design for the LAV, lends itself to trapping the heat in the tunnel. So the kit was designed so that it would get as close to the top of the differential tunnel so more heat can be pulled out of the tunnel area letting the heat from the differentials be more effectively transferred to

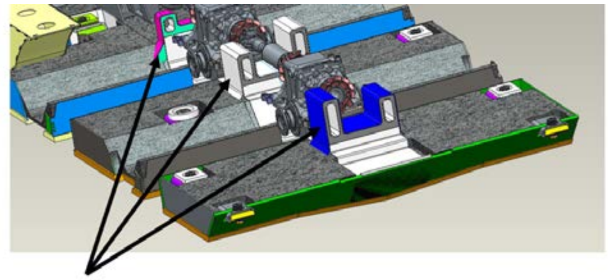

Figure 21: TARDEC Buoyancy Kit with Aluminum Heat Sink and fans

the underbody kit. The design used ¼ thick aluminum plates that were welded to a cross channel that had a 1/8 aluminum skin welded to the sides and cooling tubes that were extended to and welded to the side plates. These were then welded to the underbody plate.

In addition, the area between the cooling housings and under the differentials were also lined with 1/8 thick aluminum. Additional channels with heat sink mounting plates were riveted to the aluminum that was on top of the foam.

A study was then conducted to compare the thermal performance of four differentials for the LAV-25A2 with no underbody kit (baseline), LAV-25A2 with the D-kit, another one with the LAV-25 A2 with Buoyancy Kit and Heat Sinks only and the last study was for the LAV-25A2 with the Buoyancy Kit with Heat Sink and Rotating Fans on the drive shaft. The calculated average temperatures of each differential was compared for each case under the same conditions. The general assumptions that were made are as follows:

- Steady State
- Ambient Temperature: 130°F
- Vehicle (air) speed: 5 MPH
- Differential Heat Load: 180 W (each)
    - Value was chosen to achieve a D-kit differential temperature of ~290 °F
- Heat rejected through conduction, convection, and radiation
- Buoyancy Kit Material: EPE Foam
    - Density: 32 kg/m^3
    - Specific Heat: 1,300 J/kg-K
    - Thermal Conductivity: 0.03 W/m-K
- Buoyancy Kit Material: Aluminum Foam
    - Density: 350 kg/ m^3
    - Specific Heat: 920J/kg-K
    - Thermal Conductivity: 35 W/m-K

- Aluminum Shell/Underbody
    - o Density: 2,652 kg/ m^3
    - o Specific Heat: 884 J/kg-K
    - o Thermal Conductivity: 201 W/m-K
- Surface Emissivity: 0.8 (for all surfaces)

		Baseline	D-Kit	Buoyancy Kit with stationary fans	Buoyancy Kit with rotating fans	Delta
Temperature °F	D1	213	282	296	292	-4
	D2	217	260	275	265	-10
	D3	218	291	227	241	+14
	D4	229	293	224	218	-6

Figure 22: Comparative Temperature for the Differentials for the Four Configurations

The results in Figure 23 show excellent results for the rear and marginal results for the front two differentials. It is interesting to note that Differential number 4 was cooler for the TARDEC Buoyancy/Survivability kit than the baseline LAV-25A2 with no kit. It was initially thought that the fans would have the most impact, but they had marginal improvement and in some cases they actually made the differentials hotter. Figure 24 pictorially shows the temperature of the differentials.

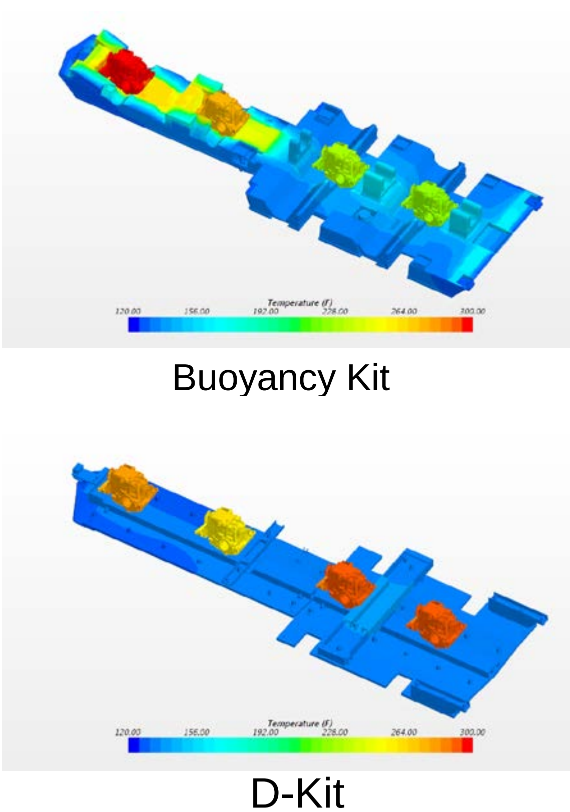

Figure 23: Pictorial Representation of Thermal Comparative Analysis

Looking back at figure 22, the heat sinks are all after the transmission and surround differential 3 and 4. There are no heat sinks in the tunnel for differential 1 or 2. This clearly indicates that the fans can be removed from the design and a heat sink needs to be added between differential 1 and 2 if possible and better if closer to differential number 1.

HEAT SINK SURVIVABLITY ANALYSIS:

It was thought that by adding the channels and welding to the underbody kit that the kit would perform better in a mine blast. To evaluate the performance of the kit, a simple bubble pressure analysis was conducted to determine the effectiveness of the channels and heat sinks. An FEA analysis was done to compare the amount of deflection that would result for the two conditions. Figure 25 shows that the design with the heat sinks and channels has about a 10% improvement over the design with no channels or heatsinks.

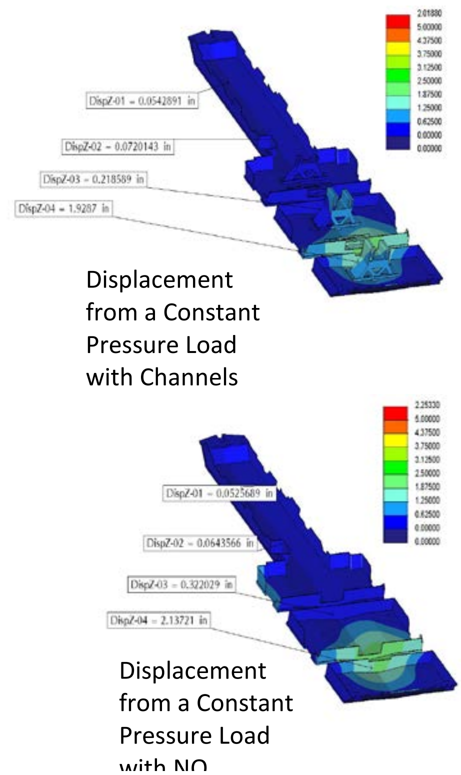

Figure 24: Comparative Displacement Plots for a Radial Pressure Loading

In the 2015 GVSETS paper [17], a study was conducted for a given pressure load on a 1 inch thick steel plate with a shallow V that is off-set from a vehicle hull. The plate experienced 0.648 inches of deflection in the FEA analysis. An effort was conducted to provide a lightweight solution that would have minimal deflection. Since we can get plate in 2-3 inch thicknesses, TARDEC analyzed a lower hull shape with sides and pocketing. Pro-E size and shape of the pockets. By doing this the idea is to determine how much weight can be removed from the kit.

Two limits were that the plate must be ½ inch thick minimum and could be as thick as 2.375 inches. Figure 29 shows how a substantial reduction in deflection can result from this process. The egg-crate aluminum structure had only .11 inches of deflection while the plate structure had .648 inches of deflection.

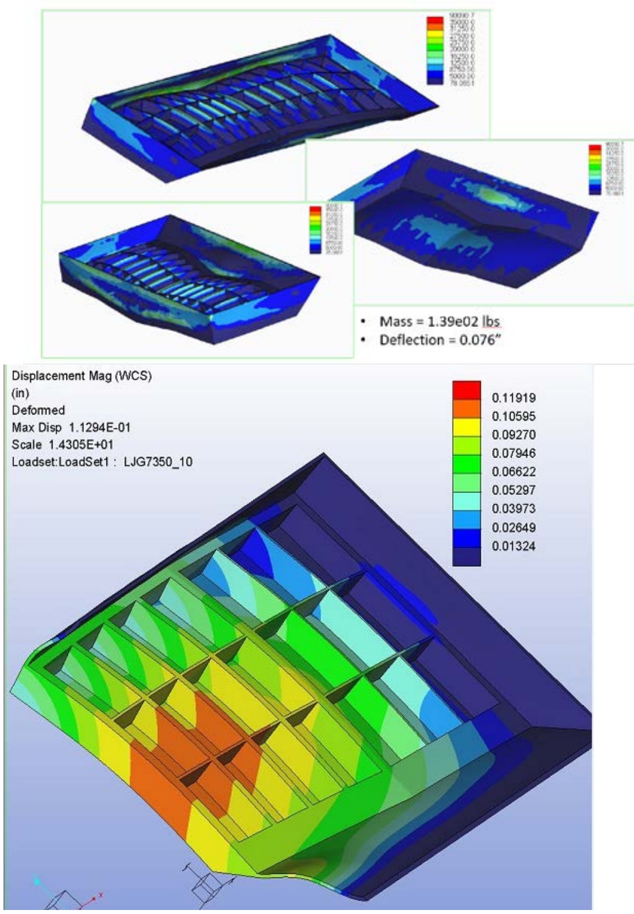

Figure 25: Static Deflection of Egg-Crate Structure from a Pressure Bubble.

Comparing the current flat plate design even with the channels welded and tab and slot through the structure, the deflection is significantly more than the eggcrate structure and it would be possible to maintain a similar weight. For a vehicle like the LAV that have a low ground clearance to maintain a low profile to avoid detection in combat, reducing deflection becomes a critical element in the survival of the Marines. Thus additional survivability capabilities might be possible by egg-crating the buoyancy/survivability kit without a weight or ground clearance impact.

SURVIVABILITY INNOVATION:

TARDEC Center for Systems Integration Mechanical Development Team has designed and modeled a Free Falling Heel Support Seat Base Side Mounted Foot and Leg Energy Absorbing Mechanism. It is a new concept breakthrough that has the potential to vastly improve the survivability of vehicles with regard to lower leg injury [18]. This footrest would have to be mounted on the side of the seat to provide maximum benefit. This way the legs and occupant go down at the same time. Also, when the seat base gets flipped up so the occupants have better egress out of the vehicle the footrests also go with the seat pan. The footrests were placed in the LAV-25 such that the occupant's leg would be in the best appropriate angle.

A very exhaustive study was conducted by engineers and scientists from BMW Group in Munich Germany (Innovationszentrum, Ergonomie and Komfort department) and Department of Biomechanics in Sports at the Technische University Munich, Germany. Their Journal "A Literature Review on Optimum and Preferred Joint Angles in Automotive Sitting Posture" [19] breaks down the optimum angle ranges for the various joints of the human body for the driver's station. In this study the mean value for recommendations are as follows:

Ankle angle: 98.26 °
Knee angle: 124° ± 7.8°
Hip Angle: 9.8°
Shoulder Angle: 28.26° ±10°
Elbow Angle 121.12° ±7.8°

Although there are many more seating positions in vehicles, the driver's is the most confining. So these values should hold similar results to other seating locations such as for scouts or troops.

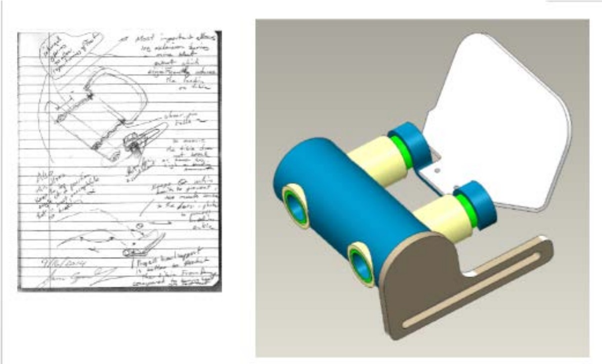

Figure 26: TARDEC Heel Support Innovation

Further investigations into the studies indicate that the overall mean value may not be the best angle and it may be an angle that is not optimal or comfortable. Research conducted by Kyung and Nussbaum [20] indicated that there are two ranges for the optimum angle for many of the joints. The actual range for the knee in this study was 95 – 105 degrees (sedan) and 135-138 degrees (SUV) for the left knee.

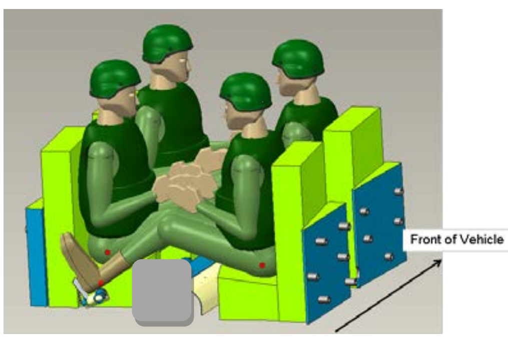

Figure 27: Isometric View of The Free Falling Heel Support Seat Base Side Mounted Foot and Leg Energy Absorbing Mechanism Installed in a Vehicle (initial concept).

Figure 28 shows how the seating would be for occupants in the rear of a military vehicle that is transporting troops or scouts. This design allows for the angle to be in the correct position and to be moved out of the way when the seat pan is moved up.

Unique to this design is the ability to allow the foot to slide out to prevent an excessive compressive loading to the leg but yet be properly supported so the soldier is comfortable. To allow for the soldier to be comfortable and yet prevent an excessive loading on the leg to break it, the back of the heel is supported by the larger blue cylinder. The corner where the back of the heel and the sole of the boot meet is supported by the yellow tubes. The endplate provides support for the sole of the foot.

The maximum compressive force that can be put one a single leg is 8 kilo-newton's [21] before injury results. Analysis on this concept has shown significant improvements over an energy absorbing pad or typical foot rests. Figure 1 shows the initial concept for integration.

SURVIVABILITY & BUOYANCY:

The foam also provided additional mine blast energy absorption, but it was marginal because of the low density. A study of different density could easily be conducted to determine if the foam could play a more significant role in reducing the energy transferred to the vehicle. A full mine blast study was conducted on the LAV-25 for all seating positions. Based on that study, survivability can be improved interior survivability upgrades, buoyancy/survivability kit and the PM LAV MOB Program MOB kit. Unfortunately, the design is about 300 lbs. overweight for water mobility with the MOB kit and survivability enhancements. Fortunately, additional analysis was conducted without the MOB upgrade and at the baseline ride height. At this location the new TARDEC kit would still improve survivability with the upgrades.

The new TARDEC kit designed for lower ride height will weigh approximately 1,450 lbs., but will add 2,700 lbs. of buoyancy. Figure 29 shows that the new design will provide 40% more freeboard than the A2 without compromising stability. The vehicle stability is proportional to the area under the stability curve. The TARDEC Buoyancy/Survivability kit shows similar stability at low heel angles and increases stability at high heel angles.

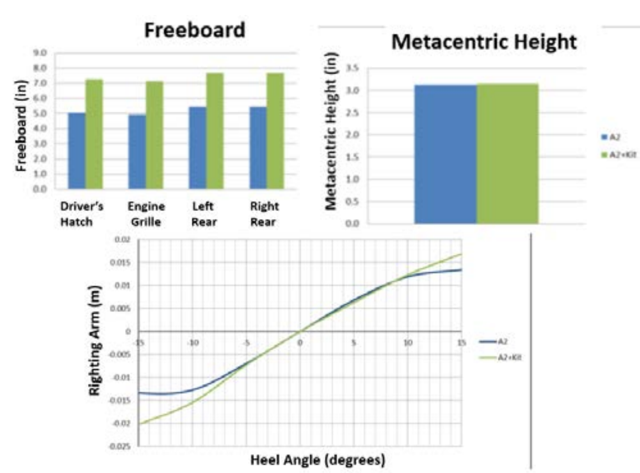

Figure 29: Water Mobility Analysis of Low Ride Height Survivability/Buoyancy Kit

CONCLUSION:

In working on both the LAV buoyancy and survivability kit and the TARDEC Amphibious Combat Vehicle Hull Survivability Demonstrator, both programs had significant concerns about water filling any pockets of air. The other concern was that if the air pockets are filled with material, this will reduce the space the underbody kit or hull has to deform and result in more energy being transferred to the hull structure. What the research has shown to this point is that material can be added between the underbody kit and the hull without adversely impacting survivability. In the contrary, some slight improvement in energy dissipation resulted in the use of foam, but it was limited to the low energy absorption of the material selected.

Clearly the foam adds significantly more buoyancy, but concern was raised that adding buoyancy to the bottom of the vehicle will cause the vehicle to become less stable in the water. This is true, but the buoyancy foam was offset by the weight of the heavy underbody plate. A positive was that for the buoyancy only kit applied to the LAV that the underbody plate had to get thicker to increase the metacentric height and improve water stability which also improved the survivability by having a thicker underbody plate. The sponson buoyancy boxes and the trim vane buoyancy kit provided buoyancy at the waterline which helped in stabilizing the vehicle in the water.

The use of stud welding worked extremely well and was utilized safely to weld studs to the LAV-25 hull with composites bonded inside the vehicle. Integrating composites has been a significant challenge because a lot of them have materials that have temperature limits around 250 to 300 degrees F. A primary concern is that if a vehicle uses composites that added welds later on to integrate new hardware or technology would be not possible or extremely difficult and costly. The ability to weld an as is composite panel without damaging the materials is a significant advancement in being able to integrate composites into a vehicle.

The issue of trapping the heat around the differentials and then insulating the differentials with foam was thought to be the defining issue of the program and it was truly the most challenging. By actually allowing a small pocket of airflow and allowing the heat to be transferred to the main underbody plate and used as a huge heat sink is a concept that can be advantageous to many current and future programs.

The optimization/integration of non-metallic foams, metallic foams with conventional underbody kit shapes enabled designs to meet requirements that are lighter, buoyant, and more survivable than previous designs and are economically feasible.

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