The Future Combat System: Minimizing Risk While Maximizing Capability

USAWC Strategy Research Project

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ABSTRACT

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PREFACE

I am sincerely grateful to the staffs of the Security Studies Program at the Massachusetts Institute of Technology and the Army War College at Carlisle, Pennsylvania. The Senior Service College Fellowship Program and the support of these two organizations provided an outstanding opportunity for individual research on a topic of personal interest.

In particular, I would like to thank Dr. Owen Cote, Associate Director of the MIT Security Studies Program, for his invaluable assistance, advice, and encouragement during this project. I would also like to thank Colonel Joe Cerami, Chairman, Department of National Security and Strategy at the Army War College for his advice on this paper and his mentorship throughout the academic year.

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"SNAFU, that's it!" said Senator John Warner (R-Va.), pointing to the Army's new Chief of Staff, GEN Eric Shinseki, during the Joint Chief's testimony before the Senate Armed Services Committee in late 1999. The Committee Chairman used the acronym to describe the Army's performance during the 78-day campaign in Kosovo - strong words given the vulgar character of the acronym and the fact that it was used by a long-time friend and supporter of the military. World War II soldiers used the acronym, meaning "Situation Normal, All Fouled Up" (a benign translation), to describe a disorganized environment that plagued an Army manned largely by conscripts and commanded by inexperienced young officers. Warner's application of the term to a modern, professional Army boasting recent successes in Iraq, Haiti, and Bosnia represented a profound indictment of the Army's ability to adapt to a new and dynamic post-Cold War environment. Despite these accomplishments, the Army had developed a reputation as the "can't do force" among members of Congress[1] and, while there were certainly extenuating circumstances, the Army clearly stood on the sidelines during the Kosovo conflict. Indeed, General Shinseki had his work cut out for him.

Fortunately, the visionary Chief had already recognized the need for change. Only weeks earlier, the general announced a plan intended to transform the Army into a lighter, more agile force - suggesting its heavy forces are too heavy and its light forces are not lethal enough. He unveiled his plan before Army and industry leaders at the October 1999 Annual Meeting of the Association of the United States Army (AUSA) in Washington, D.C.. The plan posits a fundamental transformation; from an Army organized around heavy armored divisions to one that will increasingly rely on medium-weight units that are equally lethal but more readily deployable. The first step in the process is the ongoing Medium Weight Brigade concept that involves equipping two light brigades with light armored vehicles - creating a highly lethal and rapidly deployable force. The transition will culminate in 10-12 years with the fielding of the "Objective Force" that has been the recent focus of the Army's science and technology efforts. This paper focuses on the technologies associated with equipping an Objective Force that must be capable of defeating asymmetric and traditional opponents anywhere on the spectrum of operations, from humanitarian assistance to high-intensity combat, and rapid transition between mission requirements without loss of momentum.[2]

While many agree that change is warranted, the plan includes revolutionary components, such as the conversion to an all-wheeled force that are certain to produce friction in the tradition-bound Army. GEN Shinseki prepped the AUSA crowd with the following: "Can we, in time, go to an all-wheel vehicle fleet, where even the follow-on to today's armored vehicles can come in at 50 percent to 70 percent less tonnage? I think the answer is yes, and we're going to ask the question and then go where the answers are."[3] While there may be answers out there, many come with a significant caveat - the technical risk that must be addressed before such a force is possible. I believe these risks, while formidable, can be managed by employing a practical acquisition strategy that focuses on parallel development of multiple, competing technologies.

Methodology and Scope

The Army wants leap-ahead results and not incremental improvements - and it wants them soon. Because of the ambitious timeline and technical uncertainties, the Army's plan is to rapidly identify the most promising technologies and then invest significant resources into them in hopes of obtaining leap-ahead results. The approach seems rational in that it promises to provide decision makers the requisite knowledge on each of the technologies that will enable timely decisions, focused developmental efforts, and reduced propensity for cost increases and schedule slippage. Unfortunately, many experts doubt whether industry will be able to deliver these leap-ahead capabilities within the stated timelines. Consequently, instead of asking which technologies to invest in, the more relevant question may be which acquisition strategy will best manage uncertainty while maximizing the benefits of technological innovation.

To address that question, this paper first attempts to validate the need by examining the background of the issue, the threat, and Army requirements. Next it presents design tradeoffs associated with armored vehicles and examines some of the key technologies that promise significant advances in lethality, survivability, and mobility. The purpose here is to illustrate the high degree of programmatic technical risk in an effort to lay the groundwork for an alternative acquisition strategy.

The Army's plan is to search for technologies that will provide answers, within about 3 years, that they will use to design the Objective Force 8-10 years down the road.[4] That is, the Army will give industry until 2003 to optimize their top contenders and present them to selection boards. The Army will evaluate the candidates against established selection criteria and then select the best and most promising for advanced development and production. I posit an alternative acquisition approach - one that delays the production decision and allocates comparatively more resources to basic research over time rather than risking premature selection of chancy technologies and proceeding with full scale production. The belief is that this strategy will maximize technological benefit through competition over a longer period of time. Furthermore, since production is delayed until the need is demonstrated, there will be less risk of premature obsolescence. The main drawback of this strategy is the risk of not having a fielded system when needed in the event of a sudden escalation of the threat, but this concern is rendered nearly immaterial by virtue of the U.S.'s unmatched conventional ground warfare capability. It does however, underscore the requirement for significant conventional heavy forces.

The issue draws attention to one certainty - the presence of tremendous uncertainty - a condition that nearly always accompanies technological innovation. These uncertainties are nearly impossible to prevent but they can be managed during the acquisition process. Dr. Harvey Sapolsky[5] presents an argument by James D. Thompson that there are essentially three types of uncertainly associated with innovation: 1) Generalized – the means-ends issue of which business to be in. 2) Contingency – the need to have other organizations cooperate to succeed. 3) Linking Internal Units – the problem of making an efficient production process within the organization.[6] Of the three, it appears in this case that the most complicated uncertainly will be the second type – the need to obtain cooperation both within and external to the Army. Intuitively, one would expect technological risk to be the most significant dynamic in this case, but overcoming technological risk is relatively easy when compared to gaining widespread political support within a large, diverse, and traditional organization. On the other hand, we should not discount the technical risks because it will be difficult to obtain widespread program support until the technological risks are addressed to the satisfaction of the powerful constituents within the Army. This paper offers a means to reduce those technical uncertainties - primarily as a means to reduce programmatic risk and ensure superior capabilities in the long run.

As with most highly technical problems, time may be the most effective weapon against risk and uncertainty. Time is often what engineers need most to overcome technological hurdles; otherwise production risks tend toward exorbitance. Rosen[7] presents a discussion by Burton H. Klein[8], who suggests this type of uncertainty can be reduced by buying information on competing developmental alternatives before production. The idea is to invest in competing technologies, usually bringing the systems to prototype stages where they can be tested and compared. Klein suggests deferring production decisions in order to prevent political events or technological developments from making the final product less useful than originally conceived. Three factors make this strategy the preferred solution for the Future Combat System. First, the U.S. Army enjoys a significant military advantage over all potential adversaries well into the foreseeable future. Secondly, the Army is in the process of developing a medium weight brigade concept designed to rapidly deploy highly lethal forces anywhere in the world. Thirdly, the Army desires leap-ahead capabilities; and while some promising candidates exist, they will require a massive investment of time and resources before they can be considered viable. Collectively, these factors both demonstrate the need for and the existence of ample developmental time for the program. With time on our side, the U.S. can avoid rushing the development of remarkable future capabilities.

It is an exceedingly complex problem with far too many issues to examine in a single paper. Two issues beyond the scope of this paper but worth mentioning are the analysis of institutional and organizational impact and the issue of project costs. I will leave these two for more detailed investigation by other researchers, but each warrants the brief comments that follow.

The issue will certainly foster profound cultural change within the Army. In fact, the transformation will almost certainly require organizational evolution and a re-write of warfighting doctrine. As an example, a single system or system of systems that is capable of direct and indirect fire, ground and aerial reconnaissance, breaching operations, and chemical detection may eventually blur the distinctions between the Army branches - especially Infantry, Armor, Field Artillery, and Engineer. As a result, tomorrow's officers and noncommissioned officers may be expected to assimilate and execute a myriad of tasks that previously resided with members of their fellow branches. Could it come to a point where the combat arms will be merged into a single branch and all members undergo identical training? There will no doubt be enormous organizational consequences.

Developmental costs will also represent a significant obstacle for the FCS program and, while fiscal analysis is beyond the scope of this paper, is worth noting that the U.S. Army enjoys a unique advantage by virtue of its global military superiority. The current generation of Abrams tank and Bradley fighting vehicle are arguably the best combat systems on the modern battlefield and there appear to be no peers on the immediate horizon. Some believe the Army should leverage this advantage by delaying further investment in legacy systems to generate funding for the development of new concepts for the Objective Force. Even presidential candidate George W. Bush believes that the military should seize the opportunity to skip a generation of weapons now. He argues that we should not merely improve existing systems, but replace them with a new generation of technology.[9] By foregoing investment in legacy systems, more funding would be available to support basic research and development.

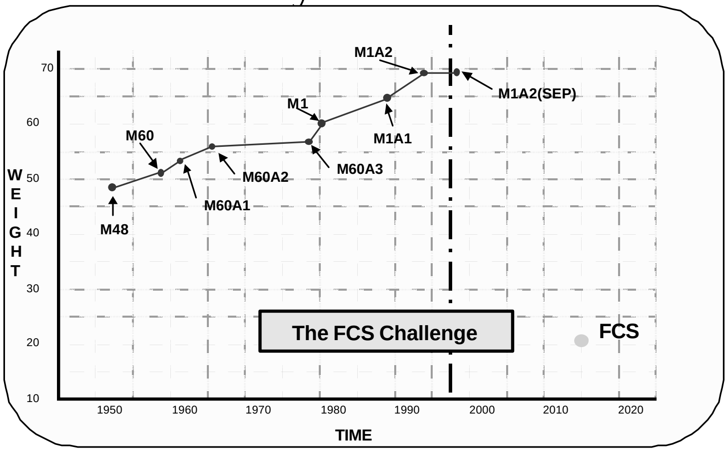
Moreover, the purpose of this paper is not to suggest a design for the Future Combat System (FCS), as any attempt to do so would be presumptuous given the complexities of such a revolutionary concept. Rather, the purpose of this paper is to describe the capabilities and the relative status of some of the critical technologies in an attempt to highlight the significant technological risks associated with the endeavor. We will then recommend an acquisition approach designed to minimize those risks and maximize the capability for the Future Combat System.

The Relevance Debate

At issue is the fact that the M1 main battle tank weights nearly 70 tons and its wingman, the Bradley Fighting Vehicle, weighs in at approximately 35 tons. Neither can be deployed on a C-130 aircraft and must rely on the C-5, C-17, or sealift for transport. Many blame the extensive weight of these and other systems for the perceived failure during the Kosovo operation. Obviously, the Army cannot fight if it cannot deploy and as Figure 1 illustrates, the current challenge is to reverse the trend of increasing armored vehicle weights by producing a combat vehicle less than one third the weight of our most modern main battle tank.

Figure 1

US Army Tank Evolution



Source: Briefing on the Future Combat Vehicle by LTC Marion H. Van Fosson, PM Future Combat Vehicle, 6 Oct 1999.

The Army is considering the development of a revolutionary Future Combat System, which may eventually replace the M1 tank. No one knows precisely what this system will look like but, instead of a single combat vehicle, the concept may involve multiple ground and air platforms (some manned and some robotic) that work in harmony to perform numerous functions. This system is arguably the most critical and controversial component of the transformation, as it must contribute essential improvements to the flexibility, lethality, and survivability of the Objective Force. GEN Shinseki even acknowledged the controversy when he said, “I suspect that moving this quickly will be unnerving to some.”[10] Indeed, his statement perhaps even understates the extent to which the transition will affect the Army. If successful, this endeavor may indeed break the Mother of All Paradigms – the Army’s apparent obsession with heavy armor and the deadly Abrams-Bradley combination.

Troops regard the M1/M2 pair with a reverence born of a track record of undisputed triumph. Consequently, transformation to the extent that their Chief suggests is sure to precipitate extreme cultural changes within the Army and it is not surprising that the plan faces considerable skepticism. The professional Army considers winning wars with overwhelming lethality as mission number one. And in Shinseki’s own words, the Army’s fundamental business is to fight and win our nation’s wars, anywhere on the spectrum of conflict - from peace support operations (PSO) to high-intensity conflict. While few will argue the utility of a lightly armored vehicle in a PSO environment, the notion of employing that same platform on the intense end of the spectrum will send chills up the spines of conventional military professionals.

History has repeatedly exposed a direct correlation between the weight of a force and its resultant lethality and survivability, with lighter forces being inherently less lethal and more vulnerable. One would therefore expect an intentional forfeiture of mass to be accompanied by a corresponding reduction in lethality and survivability. Given that risk and the string of recent victories to fall back on, many will simply ask, “Why fix something that ain’t broke?”

Recent ineffectual heavy deployments seem to compel the need for improved strategic mobility but others suggest the demand for rapid deployment is overstated and maybe even counterproductive; that were it not for the pressures for rapid deployability, the Army could actually improve the survivability and lethality of its existing combat systems.[11] The Commandant of the U.S. Army War College, MG Robert H. Scales, says the Gulf War stands as an anomaly and that we must guard against relying too heavily on technology. He is troubled by the belief that technology alone will allow Americans to fight simple, decisive campaigns with few casualties and that the U.S. suffers from what he calls a Victory Disease.[12]

Why then, should the Army consume resources and effort to make itself lighter (and in the minds of some critics, less lethal) when we could be improving what we already have? GEN Henry H. Shelton, Chairman of the Joint Chiefs of Staff, offered the following in support of innovation: “We cannot defeat tomorrow’s enemies with yesterday’s weapons; we cannot win tomorrow’s wars with yesterday’s ideas.”[13] This thinking also prevailed at a recent conference at the Naval War College entitled “Strategic Change, Transformation and Military Innovation. To the question, “Why transform the worlds best Army?” Dr. Tom Mahnken simply responded, “Because there are opportunities out there.”[14]

The Threat

The issue is exacerbated by the fact that, unlike the Cold War period, we no longer have a huge monolithic threat to justify innovation and developmental programs. Most security studies experts agree that no peer competitor will emerge before well into the current century and while few will argue the point, others warn against becoming complacent. Dr. Mahnken said it well – "Either you believe we'll remain the sole dominant global power with no peer competitor (in which case perhaps, we all chose the wrong profession) or you believe we'll eventually face a formidable threat. If you believe, like I do, the latter, then now is the time to innovate."[15] Brigadier General (Retired) Huba Was De Czege also warns that shifting power relationships, ad hoc security structures, international crime, terrorism, drug trafficking, and urbanization are catalysts for future conflict that should not be ignored.[16]

Past mistakes further testify to the need for maintaining a technological edge. Some of our greatest civilian and military thinkers have been criticized for lack of foresight and for wasting energy preparing for the last war. One of the most forward-thinking men of his time, H.G. Wells failed to recognize that emerging technologies had profound military applications. He predicted submarines would only suffocate their crews and that airplanes would not fly until 1950. He also failed to recognize the significance of the wireless radio.[17] Certainly no serious student of military history would downplay the significance of these innovations.

As we look to the future, it seems we know less and less about not only whom we will fight, but when, where, and how conflict will occur. Nevertheless, we do know that conflict is occurring more frequently and that our future enemies are likely to develop and employ asymmetric approaches to warfare. What's more, if the '90s are a reliable indicator, we seem to have departed from the traditional approaches to land warfare where, instead of defeat and occupy as we did in WWI and Korea, we now tend to deploy, defeat, and redeploy as quickly as conditions warrant. Beyond lethality and survivability, it seems the secret to remaining relevant for the Army of the future will be improving flexibility and agility.

The Defense Planning Guidance (DPG) requires the United States Military to develop flexible, effective and efficient multi-mission forces capable of projecting overwhelming military power worldwide. The military must be capable of supporting our National Military Strategy and providing our national leaders with an increased range of options for engagement, crisis response, and warfighting. The threats include conventional as well as nuclear, biological, or chemical asymmetric capabilities.[18]

Together, these factors demand that US forces be ready for a broad range of missions virtually anywhere on the planet. While most of the recent contingencies have been low-intensity missions, the Army must remain capable of rapid transition to all-out armored warfare. And while the tank no doubt once held the dominant position on the high-intensity battlefield, the Army's own worst enemy may be its desire to see it remain so. Given the changing global environment, uncertain threats, and new methods of warfare we may have to change how we think about armored warfare, to include traditional roles on the battlefield.

User Requirements

Three characteristics of today's M1/M2 duo emerge as most responsible for their success - lethality, survivability, and mobility. These characteristics not only engender enormous confidence among their own crews, they also have the opposite effect among enemy troops – literally scaring the hell out them and causing them to lose confidence in their own capabilities and equipment. A logical extension then would be that the Army should ensure similar characteristics are factored into the design of any future combat systems. Not surprisingly, the Army considers responsiveness, deployability, agility, versatility, lethality, survivability, and sustainability to be critical factors in achieving dominance throughout the entire spectrum of future conflict.[19]

To achieve that end, the Army and the Defense Advanced Research Projects Agency (DARPA) have joined in partnership to develop a multi-mission system-of-systems concept for the FCS. Their mission is to design, develop, and field a system at an unprecedented pace, with the first unit equipped by 2012.[20] Foremost, the system must be light and rapidly deployable in order to support the Chief's vision. It must be survivable, provide significant combat overmatch against all foreseeable threats and it must significantly reduce the Army's logistics burden (Figure 2).

Figure 2

FCS PROGRAM GOALS

- **C-130 transportable (<20 tons)**
- **33-50% Decrease in logistics sustainment requirements**
- **50% Decrease in fuel consumption**
- **96 hours rapid response**
- **5 days OPTEMPO operation without resupply**
- **100 KPH burst speeds**
- **60 KPH cross country speed-sustained**
- **And should:**
  - **Survive first round engagement**
  - **Maximize commonality**
  - **Have joint & international interoperability**
  - **Embed training & human factors**

Source: Briefing by LTC VanFossun during the FCS Industry Day, 11 January, 2000

The identification of user requirements is one of the most critical steps in the developmental process. It is during this initial process that the user articulates what he expects in terms of capabilities and performance parameters that, in turn, dictate design specifications. The requirements are ordinarily captured in the Mission Needs Statement (MNS) and, in the Army's case, are normally developed by the U.S. Army Training and Doctrine Command (TRADOC). At the time of publishing, the MNS was in its draft form. According to that document, the Mission Need for the Future Combat System is as follows:

> Mission. Army combat forces must be capable of rapid unit deployments both for early entry and follow-on forces. These entire units must be able to immediately deploy with full combat capabilities anywhere on the globe and, without pause or preparation and regardless of the non-permissive, semi-permissive or permissive access conditions, be capable of conducting operations to dominate the threat and win. Overmatch must be achieved through an integrated platform design, systems integration, organizational design, and advances in training and leader development. This domination will be achieved through overmatch in lethality, survivability and standoff capabilities. To that end, these forces must be equipped with the FCS, which will be a family of individual combat systems.

Source: Mission Needs Statement (Working Draft) for Future Combat System (FCS) Capability

The language is broad but this statement is significant for its reference to unit deployments with full combat capabilities, implied forced entry, overmatch capability, and a family of combat systems. It also articulates the objective of providing a lethal, survivable, and sustainable FCS-equipped land force, capable of rapid deployment and immediate employment as a unit upon arrival to defeat any threat well into the 21st century.[21] These functional characteristics are important in that they represent the user's performance expectations but they are profound for what they exclude - the ability of existing combat systems to meet the stated requirement. Today's heavy forces are incapable of deploying as units with full combat capability and because of the need for substantial port and airfield infrastructure, are ill-suited for forced entry. Similarly, the requirements for overmatch and survivability beg a force that is more robust than extant light forces. So, assuming the performance requirements can be justified, the Army appears to have demonstrated a need.

Design Tradeoffs

The armor/anti-armor field has been a continuous horserace between penetration levels and armor protection levels with neither side holding the lead for very long.[22] Each incremental improvement in either the penetration capabilities of the projectile or protection levels of the armor caused an increase in resultant vehicle weight. New and better armament systems (read heavier) lead to subsequent or parallel improvements in armor (also heavier), which begs an even bigger cannon (heavier yet), better armor (heavier still), and so on. Mobility requirements also demand bigger engines, beefier drivetrains, and heavier suspension systems to accommodate the incremental weight - an endless succession that has resulted in the 70 ton behemoths we have on the battlefield today.

Figure 3
FCS Functions

Source: Briefing by LTC VanFossun during the FCS Industry Day, 11 January, 2000

With this precedent, it seems nearly inconceivable that a vehicle less than one-third the weight of an Abrams could rival a modern main battle tank. To get there from here the Army is changing the way it thinks about armored warfare. TRADOC's answer to the problem is the development of a system of systems – not a single vehicle with a solitary role but suite of networked platforms that perform numerous functions in symphony (Figure 3).

System of Systems

The FCS force will be structured to exploit information dominance through a collection of fighting ensembles. This team achieves battlespace situational understanding by employing a common relevant operating picture. The result will be a synergistic interdependence in which the product of every sensor is tied to every shooter. The FCS force will consist of a combination of manned and unmanned air and ground elements. Each element depends on the other for protection as well as lethality. The net effect is an Abrams-like capability in a much lighter, more lethal and survivable platform. Its ability to engage targets is no longer constrained by the range of its own direct or indirect fire weapons. Its ability to sense the battlefield, process that information while understanding friendly and enemy situations, decide the best method of engagement, and act decisively within the enemy's decision cycle are key to its success.

Source: Mission Needs Statement (Working Draft) for Future Combat System (FCS) Capability

This system of systems approach is likely to involve numerous components that act in harmony to perform the required functions. The system will in all probability include ground and air components, with some of them manned and others being robotically controlled. For the purpose of this discussion, we will limit focus on an examination of the primary weapons platform and will not address peripheral airborne or robotic components. What follows therefore, is a brief examination of the more relevant technologies affecting lethality, survivability, and mobility of the manned weapons platform.

Lethality

The fundamental mission of the main battle tank (MBT) is to close with and destroy the enemy. Its purpose is to protect its crew so they can safely serve the main gun[23] and live to fight another day. Conventionally speaking, there are primarily two technologies commonly employed on today's combat vehicles – kinetic energy and chemical energy weapons. Both are being considered for the FCS.

Modern tanks destroy enemy tanks by using large cannons designed to deliver a tremendous amount of kinetic energy (measured in mega-joules) against their targets. Conventional tank cannon are, in the simplest terms, single-stroke, single-piston heat engines that can weigh up to three tons and be as long as 25 feet. The guns are fueled by solid propellants that produce pressures in excess of 100,000 pounds per square inch to propel projectiles, with diameters of up to 5½ inches, at incredible velocities. The bore surfaces must endure extremely high pressures, temperatures, and friction while guiding and launching projectiles at targets thousands of meters away, and they must do this for thousands of rounds. The breach mechanism must open quickly for loading yet seal propellant gases that will exert over three million pounds of force in an effort to escape.[24] In essence, a kinetic energy round depends on its speed and mass to pierce its target. In order to maximize speed and velocity, KE projectiles must be manufactured from the densest materials possible and have as small a cross section as possible. The result is an arrow or dart-like projectile of tungsten or depleted uranium with length-to-diameter ratios of approximately 20:1. This type of penetrator is referred to as an armor piercing, fin-stabilized, discarding sabot or APFSDS.[25]

With conventional kinetic energy technologies, there are only two ways to boost the muzzle energy of the projectile - either increase the mass of the projectile or increase its velocity and regrettably, both lead to larger and heavier guns. The former necessitates an increase in gun caliber, which means a larger breach and a heavier cannon. Assuming no change in projectile mass, the latter means higher chamber pressures and a larger gun to contain them.

Using solid propellant technology, the 120mm cannon on the U.S. M1 tank delivers approximately 9 megajoules (MJ) of muzzle energy[26] and is capable of destroying nearly any target on the modern battlefield. No doubt it is sufficiently lethal today, but studies conducted in Switzerland and elsewhere indicate that successful frontal attacks against future improved armors will require guns that fire APFSDS projectiles with muzzle energies of about 18MJ. As a result, the U.S., France, Germany, and the UK have done some work on larger guns and agreed on 140mm as the standard caliber. Their work demonstrated that guns of such caliber are fully capable of achieving 18MJ of muzzle energy, but the prospect did not prove popular because of the added size and weight of the gun and ammunition.[27]

The laws of physics coupled with the sub-20 ton goal for the FCS platform essentially eliminate conventional cannon as a viable 18MJ armament candidate so the challenge will be to find a lighter, more efficient alternative. Other options include chemical energy (CE) weapons and leap-ahead kinetic energy (KE) weapons that promise hypervelocity projectiles (>2,500m/s)[28] by deriving energy from either electrical energy or a combination of electrical energy and conventional propellants.

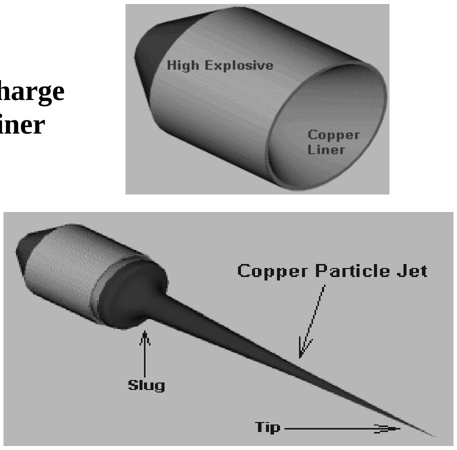
Chemical Energy Weapons

Combat system designers often turn to anti-tank guided missiles (ATGMs) as an efficient alternative to the tank cannon. ATGMs employ chemical energy as opposed to kinetic energy and because the missile is self-propelled, they permit a lightweight launcher instead of a heavy cannon, thereby reducing the weight burden on the platform. CE weapons are efficient in perforating armor because they convert the chemical energy of high explosives into mechanical energy in the form of a very fast jet to attack the target. The high explosive is usually shaped around a conical cavity that is lined with metal. When the ‘shaped charge’ (Figure 4) explodes, the metallic cone collapses under tremendous pressures that compress the copper liner into a narrow, extremely fast, jet of copper particles and gas. At the time of the explosion, particles at the tip of the jet assume a higher velocity than those at the rear, resulting in a velocity gradient and an ever-elongating jet. The tip of a typical jet travels at speeds approaching 10,000 m/sec while the rear, or slug, travels at much slower velocities (approximately 1,000 m/sec).[29]

When a shaped charge jet strikes a target of armor plate, pressures on the order of hundreds of kilobars are produced at the point of impact. The pressure produces stresses far above the yield strength of steel, so the target material flows like a fluid out of the path of the jet. This phenomenon is called hydrodynamic penetration and the depth of penetration is a function of the length of the jet, density and hardness of the target material, and the density and quality of the jet. As a rule, the longer the jet, the greater the penetration, which is true until the jet begins to break up or particulate as a result of the velocity gradient. Optimal performance is obtained by detonating the shaped charge at some distance from the target, typically 6 to 8 diameters of the cone. Effectiveness is also a function of jet precision or straightness, which, to be discussed later, can be disrupted by certain active armors.[30]

Figure 4

Shaped Charge Technology



The shaped charge with copper liner

Jet formation and elongation upon detonation

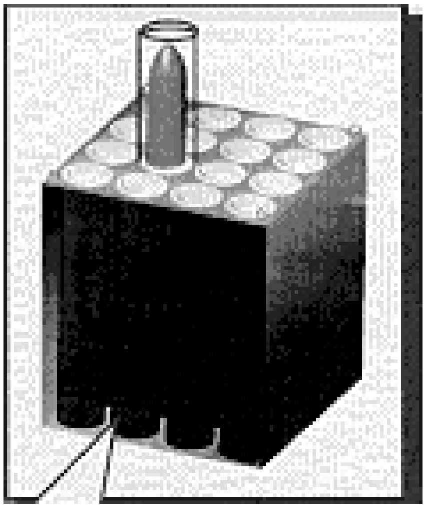
Source: Rank Enterprises, Inc., Website http:www.fortunecity.com/skyscraper/siliconex/575/body_reactive.html, accessed 25 Oct 99.

Typical large ATGMs can penetrate hundreds of millimeters of rolled homogeneous armor (RHA) and effective ranges of 4,000-5,000 meters are not uncommon. Integrated guidance systems now offer a “fire and forget” capability that eliminates the disadvantage of gunner exposure while he optically guides the missile to the target. Another advantage with this technology is that warhead and missile improvements can be developed and integrated independently with no need for major changes on the platform itself.

Cost and stowed-kill capability rank among the most significant disadvantages of ATGMs. This technology is comparatively mature and costs will continue to come down, but it is unlikely they’ll ever be as cheap as KE rounds. Stowed-kill capability represents the number of potential enemy targets that can be destroyed with a basic load on a given weapon platform. For example, the Abrams basic load includes a maximum of 40 main gun rounds - or a stowed-kill of 40 (assuming a probability of kill of 1.0 per round). Because of the larger missile components, ATGMs require more stowage space than KE rounds so stowed kill capabilities are usually lower on missile platforms. The M2 Bradley, for example, will only stow 5-7 rounds plus two in the launcher for a total stowed-kill of 7-9.

Recent CE weapons developments may offset the cost and stowed-kill disadvantages and may be a viable candidate for application on the FCS. Called "Missile in a Box", the idea is to package multiple missiles in a single box to increase stowed-kill capability and reduce costs per round. As the conceptual diagram in Figure 5 illustrates, the stowed kill would be relatively high (16) and offers the advantage of not having to individually load each missile into the launcher such as is the case with the Bradley Fighting Vehicle. It also offers the advantage of enhancing survivability because it is a non-line-of-sight weapon that permits the crew to employ the system from a fully covered and concealed position. By packaging multiple missiles in a single container, crew-handling requirements and reload time can be greatly reduced.

Figure 5
Missile in a Box



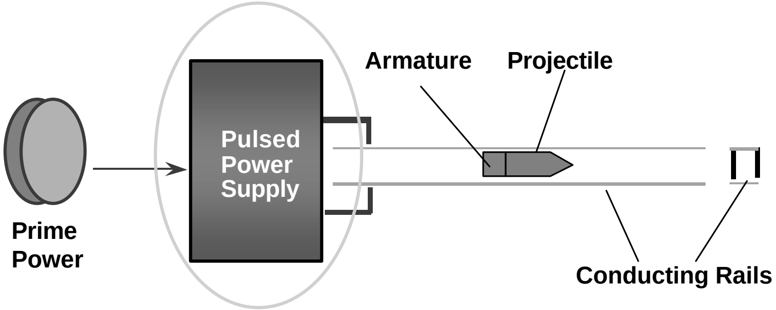
Source: Briefing by LTC VanFossun during the FCS Industry Day, 11 January, 2000

ENHANCED LETHALITY WITH KINETIC ENERGY

The Army and industry have been investigating novel concepts for defeating advanced targets such as reactive armor or active protection systems by launching KE projectiles at hypervelocity. The most promising concepts involve launching projectiles using electrical energy either exclusively, such as with Electromagnetic (EM) guns, or in conjunction with the chemical energy created by conventional propellants - a process called electro-thermal-chemical (ETC). EM launch is an approach that uses electromagnetic energy to launch the projectile, while ETC yields significant performance improvements of conventional guns by using electrical energy to control the release of chemical energy from propellants. While both offer tremendous potential for lethality improvements, much developmental effort is needed before they will reach technological maturity. ETC is the more mature of the two and may be applicable to future combat platforms with tests already having been completed on the 120mm tank cannon.[31] Nonetheless, there are significant hurdles to overcome before the concept can be reliably applied to light armored vehicles.

Figure 6

Concept Sketch - Electromagnetic Gun



Source: Briefing by LTC VanFossun during the FCS Industry Day, 11 January, 2000

Electromagnetic Gun

Electromagnetic gun technology is not nearly as new as its leap-ahead performance potential would suggest. As far back as 1987, FMC Corporation conducted a design study for DARPA of an armored vehicle with a 15MJ electromagnetic gun and concluded that a prototype could be developed by as early as 1991. A DARPA-sponsored study reached a similar conclusion a year later - expecting to demonstrate components of an 11MJ tank destroyer by 1992. At about the same time, UK experts were similarly optimistic - with Royal Armament Research and Development Establishment proposing a tech demo of an EM gun on a Chieftain chassis by 1987. For as old as the technology is, it is interesting to note that not a single vehicle armed with an EM gun has been developed.[32]

The EM gun is commonly referred to as the rail gun because an electric impulse is passed through two parallel rails between which the projectile is sandwiched (Figure 6). With conventional propellants, projectile velocity is limited by the speed of the chemical propagation within the chamber (the speed of sound). The EM gun, on the other hand, uses electrical energy to create a magnetic field to propel the projectile at velocities with a *theoretical limit* (my emphasis) of the speed of light. To illustrate the potential for improvement, conventional 120mm tank main guns obtain muzzle velocities of no more than 1,800-2,000 m/sec. Rail guns on the other hand, are realistically expected to launch hypervelocity projectiles at up to 4,000-8,000 km/sec and produce 30-60MJ of muzzle energy.[33] The Defence Evaluation and Research Agency (DERA) in the UK has already launched realistic 90mm APFSDS projectiles at velocities of up to 1,730m/s and proof shots up to 2,340m/s. US engineers have launched projectiles at rail launch facilities at up to 4,000m/s, albeit with less realistic projectiles. DERA projectiles hit targets at battlefield ranges of up to 2,000m, while those launched in US facilities flew only a few meters in laboratory conditions.[34]

EM systems offer a number of advantages. Because they are powered by electric energy, they can be "tuned" to optimize performance against specific targets by simply varying the amount of current supplied to the rails. Hypervelocity projectiles appear to be more effective against some armors but less so against others. Although contrary to the familiar principle that lethality increases with the velocity of the projectile, effectiveness actually peaks at different velocities depending on the type of projectile and the target. Against homogeneous steel armors, the effectiveness of long rod penetrators decreases after about 2,200m/s. Against armor targets incorporating ceramics, the optimum velocity is in the region of 2,600m/s. Finally, velocities as high as 3,000m/s may be required for maximum effectiveness against reactive armor.[35] Hence, it is advantageous to be able to adjust projectile velocity before launch. Projectile homogeneity also affects performance against certain advanced armors. Effectiveness against explosive reactive armor increases if the projectiles are segmented while homogeneous penetrators are more effective against some of the complex composite armors.[36]

Electrical energy is much simpler to transport, handle, store, and control than conventional propellants so its contribution to simplified logistics seems to tip the scale in favor of the EM gun.[37] Note, however, that while electric energy ranks among the EM gun's advantages, practical application is problematic and will be discussed later.

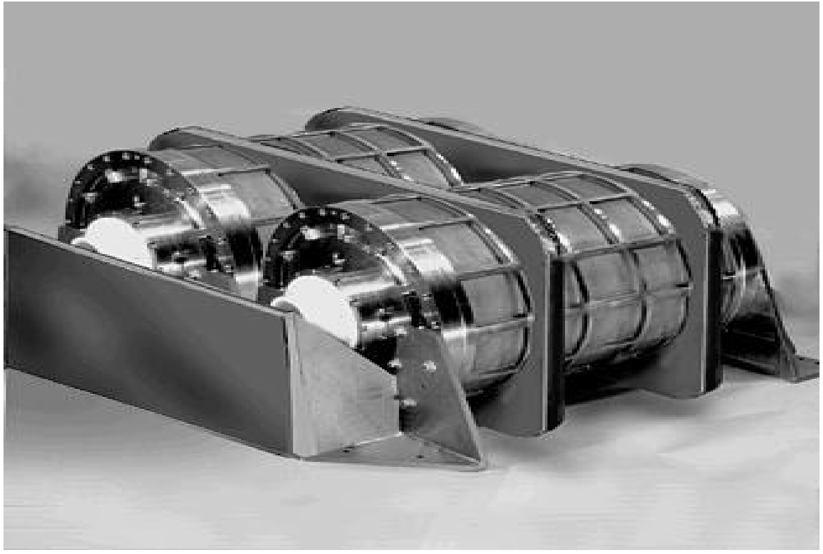
The impressive results to date have been achieved with laboratory EM launchers and not with fieldable EM tank guns and viable EM guns will not be feasible until engineers overcome significant technological hurdles. The most pressing challenge for the EM technology is developing mechanisms to produce the pulsed electrical power for the system. EM railguns operate on essentially the same principle as electric motors. That is, a high current is supplied to highly conductive rails, which creates a strong magnetic field (on the order of 20-40 Tezla[38]) generated by the resultant electric arc across the rails. About ten years ago, laboratory results produced muzzle energies of 9MJ with velocities of 2,500-4,000 m/sec, but the device needed to power the system weighed 20 tons[39] - the entire weight budget for the FCS. Encouraging progress has been made since then but current power systems are still about the size of a standard office desk and weigh between 1-2 tons - still too large and heavy for the FCS.[40]

Beyond the production of electrical energy, the storage of electrical energy also remains a considerable problem. Efforts in the early 90s focused on capacitors for storage with optimistic projections leading to predictions that the energy density of capacitors would reach 63MJ/m^3. An EM gun that would generate only 9MJ of muzzle energy would have required a capacitor bank of about 32MJ and it would occupy about 0.5m^3 – a practical goal for tank installations. Unfortunately, the best that has been achieved thus far is capacitors with an energy density of 2.5MJ/m^3. If such a capacitor were used in the 9MJ muzzle energy case, it would require a volume of 12.8m^3 – equivalent to the total hull space of the Russian T-72. With even the latest estimates of energy densities of 7MJ/m^3, the 32MJ bank would still occupy as much space as the power pack in a modern battle tank.[41]

The U.S. Army Research Laboratory is now working on rotating machines, called compensated pulsed alternators, or compulsators, to provide higher energy densities than capacitors (Figure 7). This technology has been under development since the early 1980s at the University of Texas at Austin. Compulsators are considered capable of storing as much as 135MJ/m^3 but they must rotate at tremendous speeds if their size and weight are to be minimized. Despite mechanical problems this creates, UT efforts appear very promising. That notwithstanding, application of this technology to a 15-20 vehicle remains a distant goal.[42]

Figure 7

Compulsator Power Supply



Source: Briefing by LTC VanFossun during the FCS Industry Day, 11 January, 2000

Aside from energy storage, EM rail guns face other design challenges. Fieldable EM guns must be much lighter than the massive launchers used under laboratory conditions. Unlike their simple conventional gun counterparts, rail launchers are complex mechanisms that must contain 3-4 million amps of electrical energy within light but adequately stiff and strong structures and so far, attempts have failed. There is also the challenge of integrating the EM gun system into the vehicle, to include the myriad electrical power transmission components such as cables, busbars, connectors, and rotary junctions capable of transmitting mega-amp currents. Finally, human factors such as the potentially adverse effects of the magnetic fields on the vehicle crew must be addressed. The magnetic fields will have to be attenuated to safe levels, which is tantamount to creating a magnetic enclosure around the crew compartment; but any openings, which will be difficult to avoid, will greatly reduce the effectiveness.[43]

Electro-Thermal Chemical Gun

Encouraging results have also been obtained with ETC guns, which employ a chemically energetic liquid instead of conventional solid propellant. Unlike conventional propellants, where detonation pressures quickly diminish as the projectile moves down the barrel, the ETC process regulates the pressure at near its maximum as the projectile departs the combustion chamber. The technology is recognized by many as showing promise of infinitely variable lethality with the added advantage of requiring significantly less electrical energy in comparison to the EM gun.[44]

Again, this technology is not new. The Soreq Nuclear Research Center in Israel has pursued it since 1986 where it progressed by 1993 to field tests with a 105mm ETC gun. Germany has done ETC since 1986, which evolved into a Franco-German bilateral program in 1991.[45] Premature attempts to convert 120mm solid propellant tank guns into ETC were made in the U.S. as long ago as 1989.

Over the course of their development, ETC guns have been radically transformed. It began with attempts to attenuate the high-temperature effects of electrical discharges on projectiles by inserting a fluid between them from which propulsion pressures were generated. Because the fluid was inert, all of the propulsion energy was electrical and early guns were therefore electrothermal (ET). Work continued in Germany until, in 1995, they launched a 2kg projectile at 2,400m/s from a 105mm ET gun. Despite the impressive results, these guns consume at least as much electrical energy as EM guns and possibly more due to the inherent requirement to convert electrical into kinetic energy. As a result, ET guns require the same electrical storage systems as EM guns and are not yet a feasible proposition for lightly armored vehicles.[46]

By replacing the inert fluid with an energetic fluid, or slurry, a chemical reaction occurs in the chamber, which upon ignition contributes energy to the propulsion of the projectile while drastically reducing the amount of electrical energy required. As work continued, the amount of electrical energy decreased to as little as 6% of the total propulsion energy and while this led to significant improvements, engineers began to see more promise in solid propellants than energetic fluids.[47]

Pioneered by Soreq, solid propellant ETC has been pursued in the U.S. since the early 1990s and more recently in France and Germany. Initially, ETC guns increased muzzle energies by adding an electrically generated plasma jet to the combustion process, yielding muzzle velocities of 2,000-2,500m/s. Unfortunately, chamber design pressures limited the amount of electrical energy that could be inserted into the chamber during initial combustion and injecting it at a later stage proved inefficient.[48] Yet again, considerable amounts of electrical energy were required to obtain high velocities.

The latest designs use electrical energy in the form of a powerful plasma igniter. With this method, the chemical process can be controlled and chamber pressures regulated with much less electrical energy – as little as 0.5MJ and currents between 10 and 30kA (vice 3000-4000kA). This breakthrough makes ETC much more feasible for installation on armored vehicles and it offers several advantages over conventional, solid propellant guns. The plasma igniter makes higher propellant loading densities possible, implying more energy for projectile propulsion. The intense jet also allows lower vulnerability propellants to be used, which means a safer environment for the crews.

Although there are advantages, several issues must be addressed, not the least of which is systems integration. With three components (projectile, propellant, electrical energy) the technology requires considerable developmental work before full integration will be possible. Furthermore, the higher chamber pressures will require a sizeable cannon that may consume more of the weight budget than is acceptable.[49]

SURVIVABILITY

Because of the extraordinary lethality of modern anti-tank weapons, many regard crew survivability as the most significant challenge for designers of light combat systems. Armored vehicles have become increasingly vulnerable to a wide range of threats, ranging from small arms to shaped charge warheads, long rod penetrators, top-attack munitions, mines, and chemical weapons.

Table 1

Component Weights (lbs)

	LAV	AGS	M2A2	M1A2
Hull	8,680	9,200	32,960	38,880
Suspension	6,060	7,420	12,120	24,350
Power Plant	3,970	6,500	6,970	10,660
Aux. Auto	1,800	1,980	2,170	3,960
Wpn Station	3,500	9,810	7,520	43,900
Fire Control	Included in WS	700	1,370	3,770
Ammunition	1,190	1,990	2,570	3,590
OVE	890	920	2,160	3,070
Fuel	510	1,080	1,320	3,580
Crew	2,180	760	2,200	840
Total	28,780	40,360	71,360	136,600
Tons	14.4	20.2	35.7	68.3

SOURCE: U.S. ARMY TACOM/TARDEC BRIEFING ON THE 20-TON WHEELED HYBRID WEAPONS CONCEPT

Furthermore, weight, mobility, and fuel consumption constraints no longer allow engineers to improve protection by simply inserting more heavy, homogeneous armor between the crew and the projectile. And since long rod penetrators and ATGMs can destroy even the most modern and heavily armored main battle tanks, it will take a leap of faith to expect a 20-ton chassis to survive a direct hit. In fact, the Army no longer expects the FCS to survive a direct hit, which is to say the Army is changing the way it thinks about survivability.

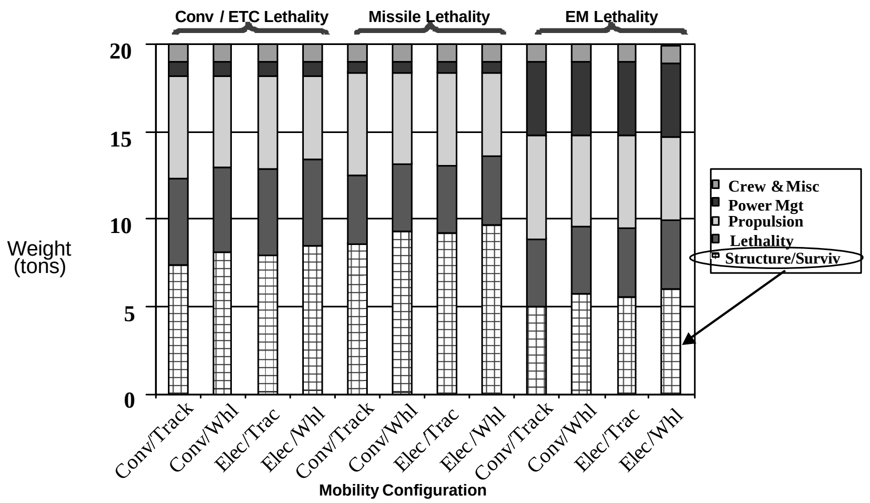
Armored vehicle design has always included tradeoffs. The survivability package must compete with all of the other subsystem components for its share of the total design weight, so any incremental increase in the weight of one subsystem compels a commensurate reduction among the remaining components. With the obvious need for a complete system that incorporates survivability, armament, propulsion, and drive train components, the test will be to develop an effective survivability package within available weight constraints.

Table 1 highlights the magnitude of the issue by presenting weight data for some conventional combat vehicles. On even the lightest vehicles, structural components consume a significant portion of the total design weight. For example, the hull, suspension, and propulsion components on the LAV weigh 11,830 pounds, or 41 percent of the total system weight. The same components consume 62 percent of the available weight on the Armored Gun System (AGS), 76 percent on the M2A2, and 57 percent on the M1A2 main battle tank. The three lighter vehicles are designed for all-around protection against heavy machine guns and will not survive engagements from even hand held high explosive weapons such as the RPG7. Of the four, only the M1A2 is able to survive first round frontal impacts against tank main gun rounds and ATGMs. Unfortunately, this protection comes at a cost of approximately 39 tons – nearly twice the weight goal of the FCS.

With the 20-ton constraint, it appears crews will no longer be able to simply rely on the physical structure of their vehicles for protection. Survival will increasingly depend on how well they can avoid potential threats and, if engaged, whether the system can degrade the inbound threat before it impacts the hull. `The Army calls it “Full-Spectrum Active Protection” - encompassing detection, hit avoidance, penetration avoidance, and kill avoidance.

In early 1999, the Commanding General of the U.S. Army Training and Doctrine Command, the Deputy Assistant Secretary of the Army for Acquisition, Logistics, and Technology, and the Deputy Chief of Staff of the Army for Operations and Plans tasked the Army Science Board (ASB) to conduct a study to investigate the potential for advanced technology to meet ground combat vehicle protection requirements anticipated for 2025. Their report, entitled “Full Spectrum Protection for 2025-Era Ground Combat Vehicles” was released in July 1999. As illustrated in Figure 8, the board determined that it would be reasonable to allocate approximately 5-9 tons for survivability and structure on a 20-ton platform, depending on the choice of the weapons system.[50]

Figure 8
20-Ton Vehicle Weight Distribution Tradeoffs



Source: Army Science Board, FY99 Summer Study "Full Spectrum Protection for 2025-Era Ground Combat Vehicles", Final Report, 17 Aug 99

The sobering reality is that even the most advanced conventional armor systems will come nowhere near providing the desired levels of all-around crew protection within those weight constraints. In the course of its study, the Army Science Board examined survivability options for a notional 20-ton vehicle using current technologies. It determined that to provide minimal frontal protection against large caliber KE penetrators for only a small area in front of the crew compartment and protection against lesser threats on the balance of the vehicle, current technologies would exceed the weight allocation by a factor of 4 or more. The ASB could meet protection goals using the best technologies it could predict for the 2005-2010 timeframe, but it would not protect the usual 60-degree frontal arc. Only an area of about 10 square feet in front of the crew would be protected against all threats and the balance of the vehicle, with the exception of the rear, would protect against lesser threats.[51]

As KE projectiles become more and more lethal, FCS engineers will also have to consider the harsh realities of impact physics. "Kinetic" is derived from the Greek word "kinema," which means "motion," and kinetic energy is represented by the following equation:

$$\text{Kinetic Energy} = KE = \tfrac{1}{2}MV^2$$

Where: M = the mass of the projectile in kilograms

V = the velocity of the projectile in meters per second

Among the most significant concerns for FCS engineers will be the task of containing the kinetic energy delivered by advanced penetrators. Hypervelocity projectiles present an intimidating problem and, since we expect 18MJ penetrators in the near future, it is important that we understand the difficulties associated with defeating them. Because kinetic energy is proportional to the square of velocity, major increases in penetrator velocity result in frightening amplifications of impact energy. For example, the impact energy delivered by a direct hit from an 18MJ penetrator is roughly equivalent to that of another 20-ton vehicle slamming into a stationary FCS at over 72 kilometers per hour! Even if the armor was able to prevent penetration, the impact shock will certainly cause severe internal vehicle damage and will probably incapacitate the crew. This physical reality has led the Army to concede that it is highly unlikely a 20-ton vehicle will survive given a direct hit.[52] The impact shock that accompanies a direct hit by a long rod penetrator makes the armor's ability to contain the projectile within its own envelope nearly immaterial.

Kinetic Energy Example

Mass of the vehicle = 20 tons (or 88,000kg)

Velocity of the vehicle = 72km/hr (or 20.22 m/sec)

$$KE = \frac{1}{2}MV^2$$

$$KE = \frac{1}{2}88,000 \times (20.22^2)$$

$$KE = 18MJ$$

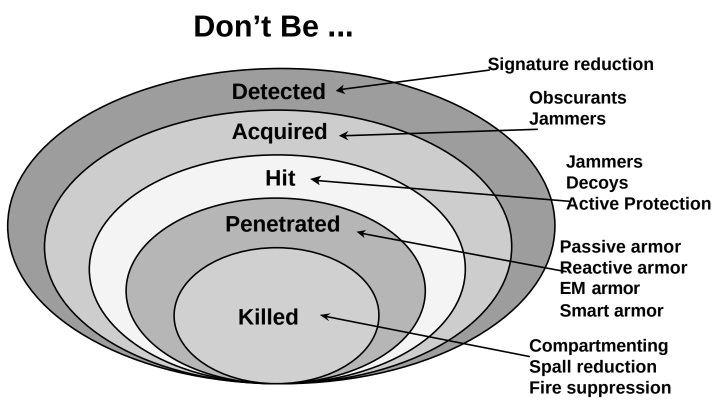
As menacing as the KE threat seems, the impact energy of shaped charge weapons is no less horrifying. As previously discussed, the detonation energy of a shaped charge is concentrated into a conical liner, producing a jet of intensely hot plasma. This jet is capable of producing penetration pressures ranging from 1-10 million kg/cm^2 or more – the equivalent of up to 10-million atmospheres. Small shaped charges, of the type found in hand held HEAT configurations are capable of penetrating 10-12 inches of rolled homogeneous armor (RHA), while a large shaped charge can penetrate 20 inches of armor.

The problem is intensified by the fact that optimal protection against one type of threat does not guarantee success against the other. KE and CE weapons have different characteristics that require different mechanisms to defeat. Consequently, FCS engineers must tackle what has long been a tacit reality within the Armor community…if you can be seen, you can be hit… and if you can be hit, you can be killed. This leads to an intuitive conclusion that survival on tomorrow's battlefield is perhaps more a function of hit avoidance than survival given a hit. The strategy, as depicted in Figure 9, is a global approach to survivability that will depend as much on not being detected, acquired, or hit as it does on preventing penetration and a kill given a hit.

Among the keys to avoiding detection is the concept of signature management – reducing the visual and acoustic evidence of the vehicle on the battlefield. Reducing the vehicle's size, camouflaging its silhouette, attenuating engine and drive train noise, and reducing exposure time have become compulsory design factors for future combat vehicles. Vehicle size is directly related to interior volume, much of which is dedicated to crew space, so one solution to making a smaller vehicle is to reduce the size of the crew. By installing an autoloader for example, we can eliminate one member of the crew and a corresponding amount of interior volume. Some have even suggested two-man crews where both members would share responsibilities for driving and manning the weapons system. This concept has been kicked around for a number of years but there are major issues that make it impractical. With only two crewmembers, 24-hour operations would make it very difficult to accommodate crew rest requirements. The assumption in this case is that each crewmember would be trained to accomplish all functions so one of them could rest while the other remains on watch. Unfortunately, that leaves only one crewmember awake, which, in itself would have psychological consequences in a combat environment, and furthermore, leaves no one on the ground to provide local security. The most likely solution would be to add yet another local security mission to an already over-tasked infantry unit.

Figure 9

Survivability Strategy



Source: Future Combat Vehicle – a multi-mission system of systems concept, Briefing by Dr. Richard McClelland to the ASB Plenary Session, 13 Apr 99

Conventional methods of camouflage, such as special paint schemes and adding foliage to the outside of the vehicle will no longer suffice given advanced acquisition devices like radar, thermal, and laser imaging. Borrowing from aircraft stealth technologies, it is possible to significantly reduce radar cross-section by using radar-absorbing materials and by designing the hull such that the external surfaces are flat, continuous, and angular. Likewise, rerouting exhaust emissions, installing protective materials to reduce the "solar loading" effect, and adapting the passive signature of the vehicle to the background can reduce the thermal signature.

In an effort to address the global issue, the ASB recommends that the FCS rely on a suite of survivability measures and that it be less dependent on traditional passive armor designs than current generation vehicles.[53] Table 2 includes a list of some of the survivability factors it recommended for further investigation and potential development.

Table 2

Survivability Approach for an Advanced Technology 20-Ton Vehicle Concept

Detection Avoidance

- **Reduce visual silhouette**
- **Emphasize signature management:**
  - **IR reduction - advanced materials and selective cooling**
  - **Radar reduction - vehicle shaping and materials**
  - **RF and EO emissions**

Hit Avoidance

- **Hard kill and soft kill mechanisms**
- **Requires integrated subsystems**
  - **Early warning sensors**
  - **Jammers, spoofers**
  - **Obscurants**
- **Active protection system (CE and KE)**

Penetration Avoidance

- **Innovative vehicle structures with advanced armors**
  - **Frontal arc - Large caliber KE debris**
  - **Frontal arc - Rapid fire medium cannon and dumb CE**
  - **Flank - Medium caliber and CE missiles**
  - **Top - Fallers, smart munitions**

Kill Avoidance

- **Consolidate and compartment crew and ammo**
- **Key subsystems:**
  - **Integral shielding/liners**
  - **Regenerative overpressure for crew compartment**
  - **NBC detection**

Source: FY 99 Army Science Board Briefing on the Final Report, Full Spectrum Protection for 2025-Era Ground Combat Vehicles, 17 August 1999

PASSIVE ARMOR

At the risk of oversimplification, providing protection against KE projectiles is a relatively simple matter. In order to defeat the penetrator, one or a combination of three things typically has to be accomplished:

- Slow the projectile
- Turn the projectile
- Break up the projectile

Slowing the projectile is usually accomplished by simply putting more armor in its path. This technique was the primary means of armored protection in early tanks but as penetrators became more effective, the amount of armor needed to stop them became thicker and heavier - to the point where vehicle mobility became a factor. Engineers later determined that they could significantly reduce a projectile's penetration capability by turning it from the horizontal shotline so that it hit the basal armor broadside instead of head on. One of the most common ways to turn the projectile involves placing a thin sheet of 'standoff' armor a few inches from the basal armor. As the round penetrates the standoff armor, it begins to turn and, by the time it hits the basal armor, it may be nearly perpendicular to its flight path. Certain materials possess inherent characteristics that cause the penetrator to turn within the armor after impact. In the case of aluminum for example, certain KE projectiles turn and run up the length of the armor plate vice penetrating its thickness after impact.

Most KE projectiles are quite brittle and that leads to another advantage of using standoff or spaced armor configurations. Using standoff armors composed of very hard materials, such as high-hard steel or ceramics often causes the projectile to shatter upon impact. Upon contact, the penetrator breaks up and the pieces separate as they fly across the distance between the standoff armor and the basal armor. One particularly effective technique is to use perforated or ‘holey’ armors as the standoff armor. The material is lighter than homogeneous armor and more effective in turning or breaking up the penetrator. Ceramic tiles also effectively shatter the penetrator but, because the tiles also shatter upon impact, do not offer good multi-hit capability.

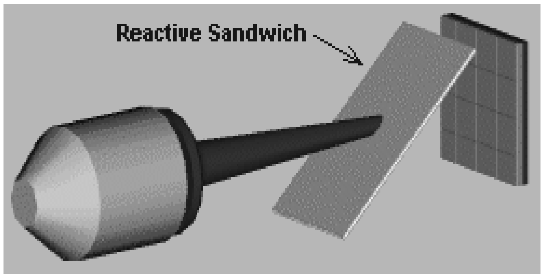
All armored vehicles derive a degree of protection from their own structural configuration, as even the lightest armored vehicles require considerable hull structure to accommodate the armament, power plant, suspension system, and crew. Light vehicle hulls are typically constructed of relatively thin (18-48mm) steel or aluminum, which protect the crew against small arms and some heavy machine guns (normally up to 50 caliber or 14.5mm heavy machine guns). Again, however, the challenge is to protect the crew against medium cannon and larger threats.

The armor community has made significant progress in materials research. Unfortunately, materiel solutions to contemporary challenges appear to have reached a technical limit – especially for light vehicle applications. The armor thickness required to withstand larger threats is just too heavy for practical application on the FCS. Alternative solutions include special armors that can be modularized and tuned to specific threats. Among the most hopeful candidates are reactive armors and active protection systems.

Reactive Armor

The terms reactive armor (RA) and explosive reactive armor (ERA) apply to energetic armors that respond violently to the impact of shaped charge warheads and, in some cases, KE penetrators. While most of the actual designs are classified, the basic concept consists of a sandwich of two metal plates with either an explosive or inert energetic materiel between them. The plates are mounted obliquely to the path of the shaped charge jet or penetrator in a manner such that, when attacked, the energetic materiel reacts causing the two plates to fly apart (Figure 10). Because the plates fly obliquely across the path of the jet, they continuously insert additional metal in front of the jet, forcing it to penetrate much more material than the nominal thickness of the plate. The transverse

Figure 10
Reactive Armor Technology



Source: Rank Enterprises, Inc., Website http:www.fortunecity.com/skyscraper/siliconex/575/body_reactive.html, accessed 25 Oct 99.

movement of the plates also disrupts the jet or breaks up the KE penetrator. These characteristics make ERA much more efficient than homogenous armor and allow much greater protection at a fraction of the weight.

ERA development dates back to the late 70s and early 80s and although originally a German invention,[54] the Israelis pioneered its applications with main battle tanks outfitted as early as 1982. By the mid-'80s the Soviet Army had equipped its T-64 and T-80 tanks with ERA tiles.[55] The U.S. Army also developed ERA suites for the M60 tank and Bradley Fighting Vehicle in the mid-'80s.

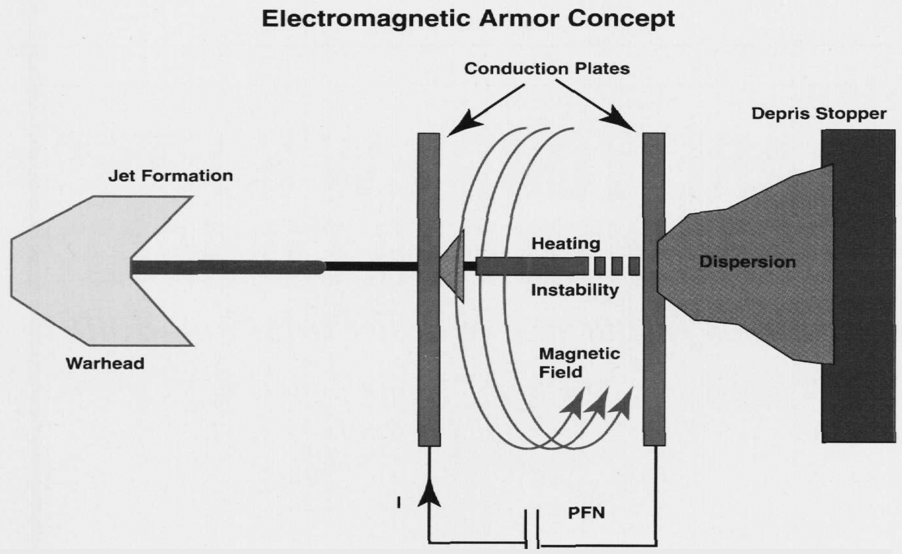
The original ERA designs were developed to counter shaped charge anti-tank weapons by using thin steel plates (2-3mm thick) in the reactive sandwiches. While efficient against CE weapons and some Soviet designs claiming armor protection three to four times as effective as RHA, these "light ERA" designs were not very effective against high-velocity KE projectiles. The plates would have to be considerably thicker to degrade the performance of these weapons – a fact that led to the Soviet development of "heavy ERA" in the early '80s. This design offered no improvement against shaped charge warheads but the Soviets claimed an overall mass effectiveness of 1.7 against APFSDS tanks rounds.[56]

Despite impressive mass efficiency, the application of reactive armor to lightly armored vehicles still presents unique challenges. Because of its tremendous velocity, the tip of the shaped charge jet typically penetrates both plates before they begin to move. For this reason, the vehicle hull must be thick enough to stop the tip before it enters the crew compartment. The basal armor must also be rigid enough to absorb the tremendous shock of impact of the rear plate as it slams into the vehicle hull upon detonation. ERA works quite well on main battle tanks because of the significant hull structure and thick basal armor, but the flying rear plate can cause significant damage to lightly armored vehicles. This problem will be difficult to eliminate but can be mitigated somewhat by segmenting the explosive in order to limit the amount of explosive material that detonates.

ELECTROMAGNETIC ARMOR

Electromagnetic armor is a dream dating back to the 1970s. The concept involves mounting two electrically charged spaced plates above the vehicles basal armor (Figure 11). Upon penetration, the shaped charge jet creates an electrical short between the plates, producing an intense electrical discharge and resultant magnetic field around the jet. The magnetic field creates magnetohydrodynamic instabilities within the jet, thereby disrupting its penetrating capability.[57]

Figure 11



Reprinted from Herskovitz, "Don't Be Killed…Armored Vehicle Survival," ***Journal of Electronic Defense*****, (Oct 1999): 49-56.**

Electromagnetic armor of this type is being considered for use against APFSDS projectiles as well as shaped charge jets. As in the case of jets, passing a very large electrical charge through the body of the penetrator also causes fluctuating and distending instabilities that can lead to their disruption.[58]

A similar concept, called electrothermal armor, also employs two electrically charge plates, except that, instead of a sizable air gap between the plate, there is a relatively thin layer of active insulating material. When a jet or KE penetrator pierces the plates, a surge of electrical current causes the insulating layer to expand explosively, throwing the plates apart with effects similar to that of ERA.[59]

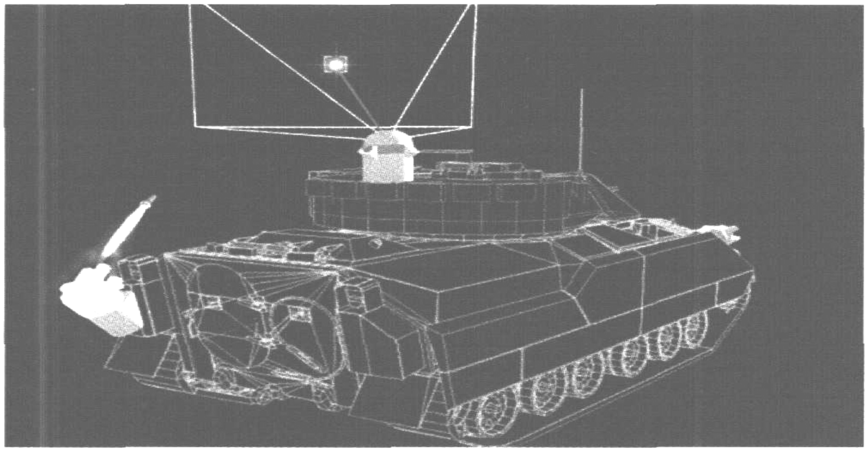
EM armor relies on capacitor banks to provide the necessary electrical energy, which, like EM guns, would be considerable. The energy required to launch plates against even contemporary KE projectiles would be on the order of 1MJ of KE per plate, requiring a 5MJ capacitor bank that would occupy $5m^3$ - roughly equal to one-third the internal volume of a modern tank. Even if considerable advances are made, EM armor is likely to be practical only as part of an all-electric vehicle, i.e., coupled with an electric gun and electric drive.[60]

Active Protection Systems

Under the Army's Full Spectrum Protection Program, ARL researchers are working on advanced protection systems and survivability concepts that may provide adequate protection to armored vehicles at a fraction of the weight of RHA. The intent of the program is to develop an Active Protection System, a leap-ahead survivability technology, to effectively defeat all known anti-armor threats, to include KE, CE, and high explosive anti-tank (HEAT) threats. The concept involves detection and tracking of an incoming threat and the deployment of a countermeasure to defeat it before it impacts the vehicle structure.[61]

While technically a leap-ahead technology, active protection systems (APS) have existed for quite some time. The first operational APS, named Drozd, was developed by the Soviet Union between 1972 and 1982 and was installed on T-55Ads in the early 1980s. The system was designed to provide protection against ATGMs and antitank grenades by employing primitive millimeter wave radar sensors to detect incoming rounds and then destroy the threat with fragmentation warheads. The system experienced a number of shortcomings but was reported to have been approximately 80-percent successful against RPGs in Afghanistan.[62] The French and the Israelis have also experimented with active protection systems with their Galix and LWS-2 systems respectively.[63]

Figure 12
Typical Active Protection System



The SLID — or Small, Low-cost Interceptor Device — consists of a maneuverable, hit-to-kill interceptor, high-speed launcher, passive threat-warning sensor and precision fire-control system. (Boeing Aerospace photo)

Reprinted from Herskovitz, "Don't Be Killed…Armored Vehicle Survivial," ***Journal of Electronic Defense,*** **(Oct 1999)**

Active protection systems are essentially defensive systems designed to intercept, destroy, or confuse attacking enemy munitions. The objective is to defeat the anti-armor threats within the hemisphere surrounding the vehicle by utilizing two technologies: sensor/information and counter-munitions technologies.[64] The operational concept of active protection systems involves accurate detection and tracking of the incoming threat followed by the timely deployment of highly accurate countermeasures to defeat it. This requires an integrated team of advanced sensors, information processors, armor, and weapons technologies on the vehicle.[65]

Conventional wisdom for some time has been that active protection against KE penetrators falls in the "too hard to do" category. Because the penetrators are moving so fast, the acquisition, detection, intercept, and destruction must occur within extremely minute timeframes. Then again, the Army Science Board is optimistic and believes that a practical system could be demonstrated within the next few years. The Board bases its optimism on two beliefs: 1) that sensor requirements to detect and timelines to intercept are reasonable given projected technological advances in the industry, and 2) it believes explosive perturbation of the long rod's trajectory can cause it to miss the intended target. The ASB concluded that APS could provide excellent protection against KE penetrators except within certain ranges. For KE penetrators, that would be on the order of 500 meters and for hand held heat it may be as little as a few tens of meters.[66]

One of the most critical components of an APS is its counter-munitions system that must kill, deflect or disrupt tank rounds, missiles and artillery fire. Warheads, armor plates, and other devices launched from the vehicle platform are being developed as potential APS counter-munitions.

Optimism notwithstanding, the application of APS to light-skinned vehicles involves significant technical challenges. Successful development of an APS to defeat relatively slow-moving ATGMs and single KE threats pose challenges of their own but defeating multiple bursts from medium cannons will be extremely difficult. Similarly, the system must be sophisticated enough to discriminate against small arms fire and artillery fragments. Like the KE penetrators, these threats must be acquired at further distances, tracked at higher data rates, intercepted closer to the vehicle, and ultimately absorbed by robust structural armor.[67]

MOBILITY

One of the most contentious issues regarding the design of the FCS is likely to be the argument as to whether the primary platform should be tracked or wheeled. The dispute is nearly as old as combat vehicles themselves, with the Army having studied the issue for over thirty years. Among the many tradeoffs to be considered are the vehicle's mission, terrain profile and vehicle characteristics.

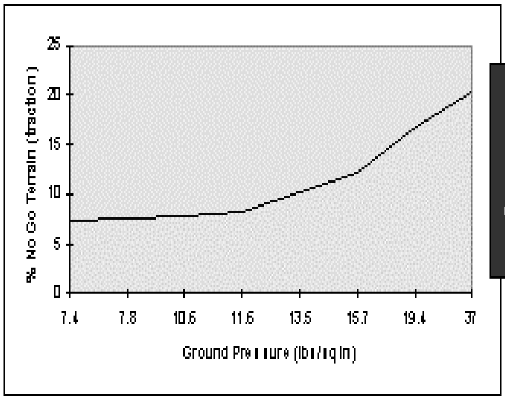
Tankers and mechanized infantrymen venerate tracked systems for their ability to negotiate virtually any terrain and they consider the move to wheeled vehicles a threat to their communities and, even worse, a potentially fatal blunder. Some have even accused the Army of stacking the deck in favor of wheeled technology. United Defense Corporation was especially vocal in its objection during recent "shoot-offs" for the Medium Weight Brigade vehicle competition, as it has a vested interest in tracked technology and entered a tracked vehicle in the competition.[68] Others go so far as to suspect GEN Shinseki's own personal goal is an all-wheeled force, despite his assertions that those decisions belong in the procurement and science and technology communities.

The debate is without doubt an emotional one, but rational decisions are the outcome of widespread understanding of the advantages and disadvantages of each system and the unique capabilities they contribute. Emotions aside, the Army should not lose sight of the fact that the issue is one of capability – getting the most for the dollars and technology available. For the sake of the individual soldier and unit, the Army must not misplace the notion that the fundamental issue is mobility. Mobility is *the* essential enabler of maneuver and freedom of maneuver is victory's cornerstone - be it in the desert or on the rolling plains of Western Europe.

> **Mobility, as defined by the 1988 Mobility Analysis for the TRADOC Wheeled Versus Track Study, is the ability to move freely and rapidly over the terrain of interest to accomplish combat objectives. It is a measure of a system's freedom of movement and average speed or travel time over a given piece of terrain.[69]**

The two key contributing factors to mobility are a vehicle's weight and footprint (the area of the track or wheel that touches the ground). Together they establish the ground pressure that the vehicle imparts on the soil. The ground pressure coupled with the soil strength establishes a parameter called the Vehicle Cone Index (VCI), which is the primary discriminator of platform mobility. The higher the VCI, the less mobile a vehicle becomes. Figure 13 explains that as ground pressure increases so does the percentage of No-Go terrain due to traction loss. As a general rule of thumb, a lower VCI equates to better soft-soil mobility as well as performance on slopes, in sandy terrain, over obstacles/gap crossings, and when overriding vegetation. Tracks contact the ground over a larger surface area than do wheels, so in terms of mobility, tracked vehicles typically offer a better solution for platforms that are required to negotiate difficult terrain.

Figure 13
Ground Pressure vs. No-Go Terrain



Generally as Vehicle Ground Pressure Increases, Cross Country Trafficability Decreases

Reprinted from Hornback, "The Wheel Versus Track Dilemma," *Armor Magazine*, (Mar-Apr 1998).

Wheels on the other hand, are able to attain higher road speeds than tracks, a characteristic that offers a decided advantage where unrestricted mobility is not an issue or where units can use roads as the primary means of conveyance.

In terms of survivability, tracked vehicles offer other, less intuitive advantages. Apart from their ability to withstand small arms attacks, tracks contribute to survivability through intrinsic design characteristics that permit a lower silhouette and as a result, higher survivability. Most tracked vehicles utilize torsion bar systems that suspend the vehicle and dampen shock by means of steel torsion bars. One end of the torsion bar is rigidly mounted into the hull and a road wheel arm is attached to the other end. The wheel itself is mounted onto the road wheel arm and when it hits a bump, the road wheel arm rises, imparting torque onto the torsion bar. Since steel is naturally resilient, the torsion bar tends to return to its original position when twisted. The system is very effective and, since it fits under the vehicle floorboards, requires little hull space.

Wheeled vehicles, on the other hand, require multiple transfer cases and drive shafts in order to provide power to each individual wheel. According to one Army study, suspension components for wheeled platforms require up to six times more volume than tracked vehicle components.[70] This means engineers must make tradeoffs between vehicle height and available crew space. There are essentially two options - allow the drive train components to consume some of the crew and storage space or raise the crew compartment above the suspension system. Since internal volume is critical, the latter is the more commonly used option and it results in the relatively tall silhouette common to wheeled armored vehicles. The downside is that the additional vehicle height makes the vehicle more vulnerable since it can be more easily acquired and engaged. The larger size also tends to make the vehicle heavier, which also degrades mobility and deployability.

The inherent weaknesses of suspension system components and tires also make wheeled platforms more vulnerable to small arms fire and fragmentation from grenades, mines, and artillery fire. Run-flat tires allow continued operation at limited speed and distances but they must be repaired as soon as conditions permit. This results in a logistics disadvantage in that more downtime is likely to occur and more repair parts required.

Tracked vehicles have another mobility advantage in that they have a neutral or pivot steer capability that allows the vehicle to turn 180 degrees or more within its own length. This capability offers distinct advantages on narrow roads and during Military Operations in Urban Terrain (MOUT).

On the plus side, wheeled vehicles offer other advantages. They create less noise signature than tracked systems, primarily due to less vibration and metal-to-metal contact. Improvements in tracked technology such as Roller Chain Band Track and decoupled running gear have also reduced noise signatures but they remain noisier than wheeled systems.[71] Wheeled vehicles are also offer human factors advantages over tracked vehicles in that the reduced noise and vibration results in less fatigue for the crew. Finally, wheels offer another advantage that supports the Army's goal of reducing the size of the logistical footprint. By comparison, wheels consume as little as half as much fuel as tracks[72] and so; it directly targets the Army's largest logistics burden.

RECOMMENDATIONS

Without access to classified, close-hold, or proprietary information, it is difficult to predict the potential of some of the technologies discussed in this paper. That said, some of them appear tailor-made for a 20-ton vehicle and others promise "leap-ahead" capabilities that warrant further investment and exploration.

In the area of lethality, the Army should consider investing additional research and development dollars to missile-in-a-box, electrothermal chemical, and the electromagnetic gun, in that order. The missile-in-a-box is a relatively mature technology that contributes to both lethality and survivability. The combination of a lethal warhead with inherently high stowed-kill, engagement range, and accuracy makes this system worth serious consideration. In spite of the theoretical potential of the ECT and EM guns, formidable technological hurdles make full-scale application to the FCS by 2012 doubtful. These challenges notwithstanding, ETC and EM offer potential for true "leap-ahead" capabilities that should be considered for preplanned improvements to be developed now and integrated at a later date.

As mentioned earlier, making a 20-ton vehicle survivable by today's standards will be extremely difficult. By comparison to the M1 tank, the Army will probably have to accept significant degradation in survivability given a hit and will have to employ additional measures to ensure acceptable protection levels for its combat troops. Again, I recommend an incremental approach by incorporating the most technologically mature concepts at the outset and integrating newer technologies later on.

First and perhaps most importantly, engineers should focus on minimizing the size of the vehicle silhouette. Here, the most promising concept appears to involve limiting the size of the crew to three (no fewer) in order to reduce interior volume. Furthermore, the crew should be moved as low and as far to the rear of the vehicle as possible - perhaps by employing a front engine design like the Israeli Merkava.

Providing protection against long rod penetrators and large shaped charge warheads will be difficult with such a light hull. At a minimum, the hull should offer protection against heavy machine guns and artillery fragments. Beyond that, the Army should continue development of modular armor systems such as ERA that can be installed or removed depending on levels of protection required. Another advantage of modular systems is that they can be independently and continuously developed and then integrated at a later date.

The Army should certainly pursue the development of active protection systems. Like the ASB, I believe there is reason for optimism with this system but only given ample resources over time. Despite concerns over timelines to intercept and sensor requirements, the concept has already been proven on foreign combat systems. Moreover, "don't be hit" appears to be the most reliable defense against the highly lethal threats of the future.

The tracked versus wheeled issue fuels interesting academic debate but the Army must put mission first. The FCS is a combat system that must be able to negotiate all types of terrain, not just improved roads. Multiple studies conducted over decades have conclusively demonstrated that tracked vehicles offer markedly superior mobility on most terrain, lower silhouettes, and greater reliability than their wheeled counterparts. While wheeled vehicles can rightly claim higher speeds, lower noise, and less fuel consumption, none of these advantages has as direct an impact on mission accomplishment as the advantages offered by tracked systems. The Army should increase investment in advanced tracked systems to include lighter materials and noise attenuation.

I would also offer two notes of caution as the Army proceeds with this program. First, the Army envisions a combat system that will serve a number of diverse roles and must therefore guard against the propensity for mistaken public perception regarding the system's capabilities. That is, the Army must clearly articulate what it expects the system to be and furthermore, what it is not to be. Failure to clearly identify performance requirements and survivability expectations could severely jeopardize public support and the ultimate success of the project. A good example is the 1980s case where the Bradley Fighting Vehicle System endured severe scrutiny because the public thought it was a tank. The critics were surprised that, with its one and a half inch aluminum hull, it could not survive direct hits from enemy tanks and hand-held high-explosive antitank weapons. Those weapons represented design overmatch for the Bradley and the Army clearly did not expect the system to survive against them. Unfortunately, with the help of some ill-informed critics, the public assumed that any vehicle in the company of tanks on the battlefield should be designed to withstand tank main gun assaults. Public and congressional disparagements threatened the program and, were it not for the Gulf War, it may have faced even closer inquiry and program risk. As it was however, the Bradley performed precisely as designed and delivered a brilliant performance in the Gulf War.

Secondly, the Army should be careful when describing the product of the Army Transformation as lighter. On the contrary, as the initiative develops the Army will probably become heavier in the aggregate, at least in the interim. Of the 10 active divisions, six are heavy armored divisions and four are light infantry divisions. In relative comparison, the light divisions seem to be struggling to maintain relevance in today's busy Army. GEN Shinseki even admitted that our light forces lack staying power, lethality, and tactical mobility once inserted,[73] and with a mission profile that has increased by 300 percent since 1989[74], the Army is simply too busy to allow 40 percent of its 10 active divisions to sit on the sidelines. Consequently, the Army's plan for the Interim Force (between now and when the FCS is expected to be fielded in 2012) will actually result in heavier light forces. The first units are already being equipped with the necessary vehicles and equipment to enable sustained operations against a lethal and determined enemy. As a result, the Army in the aggregate will be heavier, not lighter. In order to avert future criticism, the Army should be plainspoken about that fact now.

Conclusion

The Future Combat System program clearly represents the most revolutionary enterprise the Army has undertaken in decades, perhaps centuries. Not since the horse, the stirrup, or the tank itself has any program had the potential for such widespread consequence. It may be that the initiative is not widely understood, but it is surprising that it has not generated even more controversy.

As any good salesman will tell you, if he wants to sell a product, he absolutely must overstate its capabilities and understate the limitations and costs. If he doesn't, it simply won't sell. This is not to suggest the Army should discontinue the program, but many experts doubt whether industry will be able to produce the desired capabilities within preferred timelines. Given the high technological risk associated with these technologies, the Army risks jeopardizing recognized dominance in pursuit of greater strategic mobility. By making a decision on any one of these technologies too soon, the Army clearly risks rushing to failure.

Again, the issue underscores the importance of managing the technological uncertainties. Many of the technologies discussed offer real potential for leap ahead capabilities but may not be mature enough by 2003 to justify a selection decision. That said, it would be a shame for some of these technologies to be shelved because of marginal differences in exhibited capability in three years. This dilemma could be solved with an acquisition process that fosters technological maturation through selective investment in some of the most promising candidates. Those chosen could then be brought to the prototype phase for parallel testing. This strategy is likely to be more expensive and may delay production and fielding, but it will greatly reduce the risk of premature obsolescence. The advantages appear to far outweigh the costs. With no peer competitor for our legacy systems in sight, the issue is not one of parity on the battlefield, at least not for the foreseeable future. Similarly, current investment in the Medium Weight Brigade concept is a prudent and timely measure that will soon provide a capability to rapidly deploy forces that are much more relevant in terms of lethality and sustainability. With those two arguments satisfied, the new acquisition framework is much more likely to deliver leap-ahead capability when truly required. With adequate time, competition is arguably the most reliable catalyst for delivering maximum capability at minimum cost.

Meanwhile and although not included in this paper, the Army should aggressively pursue improvements to strategic mobility by investing in improved airlift and/or sealift. Doing so will increase capability in either case, whether for contemporary forces or the Objective Force. No doubt, the deployment, operational, and logistical support costs of today's Army are high. But to those who argue that we should reduce those costs I would respond by suggesting that war perhaps ought to be expensive. The intuitive extension of "war on the cheap" is a government more apt to engage in the process. With less at stake, these "dime store wars" it seems, will only come more frequently. The intent of course is not to argue deliberate cost growth but human nature often tends to the path of least resistance, so let's not make the path to conflict too easy.

Whatever shape it takes, the FCS must provide America's combat soldiers with the most lethal and survivable system possible for obtainable dollars. As the 1980s Bradley controversy demonstrated, the American public is not likely to support a system that places the safety or the lives of our troops at risk. The Abrams and the Bradley are proven winners and our troops had faith in those systems even before they rode them into battle. The FCS must engender the same sort of confidence among our troops because if it can't, the Army should leave well enough alone and stay with the proven winners.

It is indeed a tough problem and Deputy Defense Secretary John Hamre summed it up quite well when he recently acknowledged that the Army Transformation is a controversial plan but Army leaders "deserve credit for tackling a problem that many said was too big."[75] Similarly, Dr. Andrews said that the Army is literally battling for its soul.[76] With these kinds of risks and so much at stake, the Army had better get it right.

ABBREVIATIONS AND ACRONYMS

AGS – Armored Gun System
APFSDS – Armor piercing, fin-stabilized, discarding SABOT
APS – Active protection system
ASB – Army Science Board
ATGM – Anti-tank guided missile
AUSA – Association of the United States Army
BFVS – Bradley Fighting Vehicle System
CE – Chemical energy
DARPA – Defense Advanced Research Projects Agency
DERA – British Defence Evaluation and Research Agency
DPG – Defense Planning Guidance
EM – Electromagnetic
ERA – Explosive reactive armor
ET - Electrothermal
ETC – Electrothermal chemical
FCS – Future Combat System
HEAT – High explosive anti-tank
IR - Infrared
kA - Kiloamps
KE –Kinetic energy
LAV – Light Armored Vehicle
M1 – the Army's Abrams main battle tank
M2 – the Army's Bradley infantry fighting vehicle
MJ - Megajoules
MNS – Missions Needs Statement
MOUT – Military Operations in Urban Terrain
MWB – Medium weight brigade
NBC – Nuclear, biological, chemical
OPTEMPO – Operational tempo
OVE – Organic Vehicle Equipment
RA – Reactive armor
RF – Radio frequency
RHA – Rolled homogeneous armor
RPG – Rocket propelled grenade
PSO – Peace support operations

TRADOC – The Army Training and Doctrine Command

VCI – Vehicle Cone Index

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