1 Armor Technology

by Paul Lakowski

1.1 Basics

Modern AFVs. are rated in three important areas; firepower, armor and mobility. Mobility is often the most important capability viewed from an operational context but armor and fire power determine success and failure on the modern tactical battle field. **Historically the battle between projectile and plate has determined the out come of most tank battles.** It's probably true that fire power is the more important of the two, but often it's the level armor that becomes the 'rate determining step'.

In order to keep pace with gun penetration, designers were forced to focus more armor to the front at the expense of flank protection. To combat this, gun designers resorted to high tech ammunition, the and the battle went on. After WW-II, Soviets and Americans both experimented with ERA equipped tanks, while the Americans experimented with the silica ceramic armored *T-95*. These technologies offered potential but were too costly and the main solution adopted was to up the weight. The main battle tank went from 20—30 tons in WW-II to 35—48 tons in the fifties. **In other words, this year's heavy tank turned into next year's medium tank just by changing the name.**

In the 60 & 70s the dramatic rise in the potential of the ATGM forced another evolutionary step. The British resorted to the 'heavy tank' with 16 inches of armor called the Chieftain, while the French opted for a medium tank, and the Americans developed the M-60 which was a cross between the M-48 & M-103 designs. **The German solution was the Leopard 1, a 40 ton hybrid tank with the turret armored like a heavy tank while the hull was a medium tank – a smart solution**. The Soviets developed the T-64, their own version of the ***Leopard***. In some respects this was still the heavy tank of the 40s & 50s as the armor of the T-64 was on the same level of the Chieftains in most places but in other places it was medium tank armor. The Soviet armor solution was similar to the German solution, just arranged differently.

The 80s saw the introduction of western Chobham armor to counter ATGMs [**A**nti **T**ank **G**uided **M**issiles], while the Soviet solution was to add Explosive Reactive Armor („ERA") to the T-64—80 tanks, but the gun designers were able to keep pace. By the 90s even these armors were obsolete and required upgrading to compete against the latest warheads. The current solutions are dU [Depleted Uranium] armor for the M-1s and Challengers, "Wedge armor" for the Leopard 2A5, and K-5 for the Russians. **The one thing in common here is that the new heavy armor only covers about ½ the front profile.**

So the first solution in the ever increasing upward need for more armor is **to transfer armor mass to the most vulnerable sections of the tank at the expense of the less exposed vehicle areas**. In addition special materials have been relied on increasingly to help boost armor levels at some cost to the design.

1.2 Geometry

1.2.1 Slope and ricochet

The next factor in determining the effectiveness of a tank's armor is slope. **On the face of it, slope should not impact on armor design at all since the more you incline a plate to armor a volume or profile, the more material you need to cover that profile**. Where slope becomes a factor is in the effect it has on the attacking projectile. This means that whatever effects it has, it's tied to the projectile nose design as much as the armor slope.

Firstly, all projectiles will ricochet. The real question is at what angle and velocity do they ricochet. Ricochet occurs when a attacking projectile glances off the sloped armor of an AFV without digging in far enough to penetrate the plate. If it has no time to dig in before it ricochets, it can't penetrate even modest amounts of armor. A complex model has been developed to predict the angle at which a projectile is expected to ricochet, this is called the 'critical ricochet angle'.[1]

The longer the rod, the higher the ricochet angle and the faster the rod, the higher the critical ricochet angle. In addition, heavy metal rods of WHA or dU[2] ricochet at higher angles that steel. The critical ricochet angle is measured from the vertical plane [i.e. 90° is horizontal]. A rod of 10:1 L/d [**L**ength to rod **D**iameter ratio] @ 1.7km/s should ricochet at ~78° when made of steel, while its WHA /dU counterpart will ricochet @ 81°. Stretching the penetrator to 15:1 L/d increases the ricochet angle to 82—83°, and it's likely that 30:1 rods will ricochet at >84—85°. Tate's ricochet formula predicts a ±5° variation around these values, so 50% of the 10:1 steel rods should ricochet @ ~78°, while ricochet will occur as high as 83°and as low as 73°. The above cases apply to thin plate targets, but if the plate is over 4:1 T/d [plate **T**hickness / rod **d**iameter ratio] the ricochet angles should go down a few degrees.

Since the time it takes a projectile to 'turn' is around 40—60 micro seconds, and since the entire penetration event takes 300—400 microseconds [large warhead], even shaped charge warheads [**HEAT**] will ricochet when the right combination of striking velocity and angle are reached. **Modern HEAT rounds will ricochet as well, the only question is whether this is before or after jet penetration**. Modern shaped charges with standoff probes and base initiation will start the jet penetration process before the main round impacts the slope armor. Since this is a 400 micro second event [½ a millisecond], it is quite likely that the main body of the round will not even have reached the plate by then.

The second aspect of slope is the asymmetrical force acting on the penetrator. When a projectile strikes a sloped plate, the side of the penetrator closest to the plate will suffer more force, erosion, and damage than the opposing side. This puts an unbalanced force on the rod, turning it in towards the plate – and then into the opposite direction. The penetrator takes a longer overall route through the armor, resulting in less penetration of sloped armor.[3]

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[1] See: J. Phys. D. Appl. Phys. Vol 12-1979 pp. 1825—1829.
[2] Wolfram Heavy Alloy –Tungsten & depleted Uranium
[3] See: Rheinmetall Handbook on Weaponry [figure 1128] (1982)

1.2.2 Projectile shape

This asymmetrical force on the penetrator varies from projectile to projectile, but it is tied to the nose shape of the projectile. **Anderson Jr et al has shown that the effects of nose shape disappear after the projectile has penetrated to a depth of two projectile diameters.** Now since AP shot only reach two projectile diameters penetration, this nose effect is quite dramatic, but for 20:1 and 30:1 L/d long rod penetrators at higher velocity the effect is marginal at best. What it means is that by the time you stretch to these rod lengths, any effect of slope is only a few percent at best and by the time you reach shaped charge jet L/d ratios [100:1], the effect is no more than 1%.[4]

The change of effect from slope [45—60°]. All values are for a pointed rod and show how much the LOS is increased by the change in plate thickness and increasing rod length.[5]

T/L	AP	APDS	APFSDS		
L/d	**3:1**	**4.5:1**	**1st Gen.: 10:1**	**2nd: 20:1**	**3rd Gen.: 30:1**
thin	1.03	1.02	1.00	1.0	1.0
spaced	1.33	1.19	1.09	1.04	1.025
moderate	1.4	1.22	1.11	1.05	1.03
Semi Inf.	1.46	1.26	1.13	1.06	1.04

The effect of increasing the armor resistance by slope can also be achieved by curving the armor. The slope then is a combination of both the 'tangent' of the horizontal and the vertical planes. To determine the net 'compounded armor slope' the following formula is used.

$$\sqrt{\left(\left(\frac{1}{\cos(V^\circ)}\right)^2+\left(\frac{1}{\cos(H^\circ)}\right)^2\right)-1}$$

COS= Cosine
V°= Vertical angle
H °= Horizontal angle

With the increasing use of special armors their impact on sloped armor must also be assessed. When ceramics are struck the effect is to create a huge 'shatter zone' radiating outwards in an elliptical pattern that's larger than the same damage into a steel target. **When the ceramic plate is slanted, the effect is to dramatically reduce the efficiency of the sloped armor.** Tests on sloped ceramic steel targets struck by AP shot show the effective resistance is only 1.6 times the **L**ine **O**f **S**ight [LOS] thickness @ 60°. The same impact on a all steel target should result in the effective LOS increasing from 2.1 to 2.5.[6]
Test of APFSDS on slanted ceramic steel targets report no difference in the penetration compared to the LOS thickness, suggesting this problem doesn't apply to the all important APFSDS.[7]

1.2.3 T/d & Free Edge Effect

When determining the resistance of steel plate, several additional factors should be included. These are 'lateral confinement' and the 'T/d effect'. T/d

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[4] See: Int. J. Impact Engng. Vol. 22, pp. 189—192 (1999) plus Int. J. Impact Engng. Vol. 17, pp. 263—274 (1995).

[5] See Int. J. Impact Engng. Vol. 22, pp. 189—192 (1999), Int. J. Impact Engng. Vol. 17, pp. 263—274 (1995). Rheinmetall Handbook on Weaponry [figure 1128] (1982)

[6] See: Int. J. Impact Engng. Vol. 19, pp. 811—819 & Shock under Impact IV pp. 91—101.

[7] See: Int. J. Impact Engng. Vol. 23, pp. 771—782.

refers to the ratio of the thickness of the armored plate to that of the attacking projectile, while lateral confinement refers to the ratio of the diameter of the attacking projectile to the width of the armored plate. **Tests done on armor material will always yield different results if either the T/d or the lateral confinement ratios are too low**. For modern APFSDS & HEAT, the width of the plate must be more than 30 times the diameter of the attacking rod / jet for all results to be stable and transferable to another case for comparison. Along the main turret walls of a real tank target, this effect is marginal, but near the mantlet the effect reduces the armored resistance to 0.85—0.9. Further, test on ceramic steel targets show the effect is much more dramatic.

	Mantlet	1 o'clock	2 o'clock	**(** Front turret Hit location)
All Steel	**~0.88**	**~0.96**	**0.99**	(% reduction in resistance)
Ceramic/Steel	**~0.78**	**~0.85**	**~0.95**	(% reduction in resistance)

In all cases, the T/d must be 1.6 times the rod / jet expected penetration. When this is achieved, the target is said to be 'a confined semi infinite target'. **Confinement is important because as the shock wave of impact moves through a target plate it reflects from the 'free edge', crosses back over new waves emanating from the impact point, creating a 'weakened zone' through interference.** In the case of ceramics and composites, this area is much larger than steel and is visible in the form of ceramic tile shattering and composite 'delamination'.[8]

The T/d effect starts to diminish rapidly so that after 3:1 its not that much different than the semi infinite case [3—5% below]. This has its greatest impact on spaced armor. Against such plates the resistance of the plate is reduced to 95—60%.[9]
Lateral confinement has it's greatest impact in the turret armor on modern tanks. The gun embrasure area presents a 'free edge' which goes a long way to explaining why most tank turret armor thickens as you approach the mantlet area. In the past this effect was also responsible for reducing the strength and resistance of glacis plates around the hatch and MG-port areas.

1.3 Armor materials and composition

1.3.1 Steel

Any review of modern armor *materials* must start with steel. According to the [American Steel Manufacturers] ASM-96 guide there are literally hundreds of steels in use throughout the world, but only a few qualify as good armor material.

Firstly the type of steel must be relatively cheap as its still the most common material used in tank armor accounting for about ½ the weight. In order to survive the pressure and strain of impact, this steel must be both strong and ductile. A class of steels -that currently fit the bill- have been developed called '**h**igh **s**trength **l**ow **a**lloy steel' [HSLA], and the most common of these in research papers is 'Type 4340 steel'. This steel features low carbon [0.3—0.5%], with moderate manganese content [1—3%] and good ductility [on the order of 8—10%] and strength [~1.0—1.1 GPa – ultimate tensile strength]. The hardness range from ~250—300 **B**rinell **H**ardness **N**umber [BHN, a rating system for metal hardness] to BHN 350—390. **Other steels are available that are stronger like 'Maraging Steel' and harder like 'Tool Steel', but tests reveal these offer only 90% of the resistance of RHA.**

[8] See: Int. J. Impact Engng. Vol. 19, pp. 49—62.
[9] See Int. J. Impact Engng. Vol. 23, pp. 639—649.

Usually **R**olled **H**omogenous **A**rmor [RHA] appears in three forms; armored steel [**RHA**], **s**emi **h**ardened **s**teel [**SHS**] & **h**igh **h**ardness **s**teel [**HHS**]. Armored steel is about 270—300 BHN. It is most often found in thick armor and can appear as cast or rolled; all modern tanks feature rolled plate**. It appears that modern cast RHA offer's only ~90—92% of the resistance of rolled plate, while WW-II cast can offer anywhere from 90—50% resistance.** All Soviet tanks and British tanks feature cast turrets. While the British tanks and Yugoslav Versions of Russian tanks feature 270BHN cast armor, Russian sources speculate that their cast is high nickel and therefore harder. Thinner plates of RHA [several cm] can be machined still at 350—390 BHN offering 12—18% more resistance than RHA vs. **A**rmor **P**iercing **F**in **S**tabilized **D**iscarded **S**abot [**APFSDS**]. The M-1 is reported to feature **H**igh **Y**ield –120 plate that is about 350BHN plate. Semi hardened steel is usually 400—450 BHN and appears in moderate thickness of several cm and offers a Thickness Effectiveness [**TE**]of 1.2 to 1.25, that's 20—25% more resistance than RHA. All western Chobham armored tanks feature semi hardened steel as a part of their layered structure. This steel is harder to weld into the structure, which limits its use.

High hardness steel is about 500—600BHN and offers about 30—34 % more resistance than armored steel, but its costly [twice the price of RHA], difficult to weld, and can only be manufactured in thin rolled plates. Often this armor has to be bolted on to the main armor wall **The Leclerc tank and German Leopard 1A3 feature this armor layered with RHA and SHS, it's assumed Leopard 2s also featured triple hardness steel**. Layered steel with 250—430 and 515 BHN – as in the Leopard 1A3 – should offer an average hardness of 18% higher than RHA, but the exact layering should increase this by 25% to a TE of ~1.5 times the resistance of RHA for dual hardness and ~1.6 for triple hardness armor.

1.3.2 Light metals

1.3.2.1 Aluminum

The post WW-II period saw a number of special armors developed to enhance armor resistance to shaped charge warheads including, ERA, aluminum and ceramic armor to name a few, but all these were to expensive except for aluminum. At 1/3 the density of steel, Aluminum was an attractive alternative to steel especially in the construction of light AFVs. and support vehicles. Unfortunately along with the lighter construction comes a corresponding less resistance, AL5083 [M113; M2/3 and LTVP-7 AFVs] offers only 60% of the resistance of RHA [vs. API shot]. This type of aluminum is only 2.66 g/cm³ [compared to 7.83 g/cm³ for RHA], and resists corrosion well.

The main way in which armor is rated in relation to RHA is by thickness effectiveness [TE], as already noted Al-5xxx series aluminum offers a resistance of ~0.6 TE. This means that 100mm AL-5xxx will offer the equivalent to 60mm RHA [even though it's mass is only equivalent to ~30mm RHA]. The 5xxx series Aluminum has been supplemented by the AL 7xxx series, this aluminum [AMX-10, Scorpion /Scimitar AFVs. & Warrior ICV and BMP-3 ?] suffers from corrosion and stress cracks but offers better ballistic resistance.[10] Aluminum was experimented in the *MBT-80* design

[10] See: Int. Defence Review 4/91, pp. 349—352

and is included in the side hull skirting and rear armor of a number of tanks. The front armor of the Leopard 2 series may feature aluminum.

1.3.2.2 Titanium

An interesting alternative to Aluminum is Titanium, which has a density of only 4.5 g/cm³ and offers resistance of 80-90% of RHA [APFSDS]. However, Titanium is many times the price of aluminum which itself is twice as expensive as RHA. Titanium is known to be used in select items of the M-1's armor to reduce weight and maybe used in the modern version of BDD armor in Russian tanks.[11]

1.3.3 Honeycomb structure & Fuel Cells.

Tests on thick honeycomb aluminum structures sandwiched between thin aluminum plates reportedly offered ~ 70% of the resistance of RHA, when the same resistance of solid Aluminum should be 47% of RHA; that's 1.5 times better. Apparently this kind of construction is quite cheap compared to modern layered armors and is already in wide spread use in industry…always an important consideration.

The fuel cells mounted around the driver of the M-1 tank are reported to feature honeycomb structure to increase resistance in the front hull.[12]
In addition, Diesel fuel has been shown to be a reasonable armor and by integrating it into the armor, it opens doors to increased protection. **To model fuel cells when estimating armor values, a value between water and Methanol was used**, Methanol has a TE of 0.63 against shaped charges. Water cells offer a TE resistance of 0.15 vs. APFSDS. While a target of 600mm of water offers the same resistance to shaped charges as 300mm Aluminum (which is equivalent to 150mm RHA) suggesting a TE value of 0.15 KE and 0.45 HEAT.[13]

1.3.4 Composites

Many lightweight materials have also been tested like Fiberglas in an effort to replace part of the dependence on heavy steel in AFV design. Usually these composites involve fiber material that is suspended in a medium for reinforcement and stiffening. The mediums can be Epoxy, Thermoplastics, Vinylester, Polyester or some Phenolic type material. These also boost the density of the material and allow it to change from 'cloth or fabric' to 'panels'.[14]
Steltexolite is a example of a lightweight Russian Fiberglas that uses glass cloth. It's known to be used extensively in Russian tank armor. **Steltexolites material compares well with aluminum' in terms of resistance vs. KE projectiles and is slightly better vs. shaped charges, this despite the fact that it is just 2/3 the density of aluminum**.[15]

1.3.4.1 Spall Liners

Kevlar is a common composite material used in the west as „spall liners" in tanks like the British Chieftain, but is also used as backing material for ceramics in armor like the M-1 Abrams. Kevlar offer less resistance to AP shot

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[11] See: Int. J. Impact Engng. Vol. 20, pp. 121—129
[12] See: Int. J. Impact Engng Vol. 19 pp. 361—379.
[13] See: Int. J. Impact Engng. Vol. 23, pp. 585—595
[14] See M. Szymczak in: DREV paper Sept'95.
[15] See Int. J. Impact Engng. Vol. 17; pp. 751—762

compared to Fiberglas but comparable figures for APFSDS and HEAT. Not as good as Steltexolites but lighter at just ¾ of the density, it's a good solution as a spall liner. **The effect of spall is like a 'small grenade' going off inside the AFV, with the addition of spall liners this is reduced to a 'shot gun blast'** [50% reduction in particles and blast cone]. Newer materials like 'Spectra Shield' and 'Dyneema' achieve the same effect but at 2/3 the weight of Kevlar. Dyneema is of note as being the liner in German AFVs, and has comparable resistance to Fiberglas at 1/3 the density.[16]

1.3.4.2 Ceramics

By far the most common 'special armor' studied to increase AFV protection are ceramics. It's assumed to be the main component in Chobham armor. Ceramics are light but very hard materials, over 4 times as hard as the hardest steel at only half the weight. **This combination of light weight and high hardness offers resistance to KE warheads comparable to RHA and, more importantly, resistance to shaped charge warheads up to twice the amount RHA offers**. While this makes them good armor material, there are several drawbacks to the use of ceramics in tank design. Firstly ceramics lack mechanical strength and can't be used as support structures. Furthermore, to be most effective they must be encased in metal, therefore diluting some of the weight and performance benefit. While the most basic ceramic, Alumina [AL_2O_3] is about as expensive as Aluminum or hard steel [twice the price of RHA], the really mass efficient ceramics can be up to 10 times the cost of Alumina.

Ceramics have additional performance problems: They shatter on impact because the mechanical strength can't survive the shock waves bouncing off the free tile edges. In tests, the resistance of a shattered steel-ceramic target ranges from 95% vs. AP shots to 80% vs. APFSDS. In addition, test on AP impacts of sloped ceramic-steel targets show that resistance is less than the LOS value, when the slanted resistance of RHA is more. **In tests against APFSDS against slanted ceramics [SiC, AIN, AD-96, B_4C & TiB_2] offered about the same resistance as the LOS suggests.** Here are the results of a battery of normal impact tests from the Journals.

Resistance relative to RHA Vs. APFSDS

Ratio of thickness of ceramic to steel in target	1:3	2:2	3:1
Resistance of Pyrex /Steel	**0.58**	**0.87**	**0.8**
Resistance of Pyrex /Tungsten	**1.06**	**1.12**	**1.16**
Resistance of Pyrex /Aluminum	**0.46**	**0.6**	**0.78**
Resistance of fuzed Quartz/SHS	**0.62**	**0.58**	**0.5**
Resistance of AD-85/RHA @ 1.7k/ms	**0.96**	**0.99**	**0.89**
Resistance of AD-96/RHA @ 1.7 k/ms	**0.96?**	**0.98**	**0.93**
Resistance of AD-97/SHS @ 1.7k/ms	**1.2**	**1.07**	**1.05**
Resistance of AD-97/SHS @ 1.3 k/ms	**1.3**	**1.18**	**0.98**
Resistance of AD-97/RHA @ 1.5 k/ms	**1.0**	**1.03**	**0.96**
Resistance of AD-99/RHA @ 1.7k/ms	**1.04**	**1.08**	**?**
Resistance of AD-99/SHS @ 1.7k/ms	**1.08**	**1.15?**	**?**
Resistance of UO_2-87/RHA @ 1.5 k/ms	**1.04**	**1.6**	**2.0 (est.)**
Resistance of UO_2-100/RHA @ 1.5 k/ms	**1.22**	**1.8**	**2.34 (est.)**
Resistance of AIN /RHA @ 1.8k/ms	**0.96**	**1.06**	**0.97**
Resistance of SiC /RHA @ 1.7k/ms	**0.96**	**1.02**	**1.02**
Resistance of B4C/RHA @ 1.7 k/ms	**0.93?**	**0.91**	**0.87**

Shaped Charge resistance @ standoff			
Resistance of Glass[fuzed Quartz]			
Vs. HEAT @ 2:1 standoff	1.1	1.23	1.27
Vs. HEAT @ 6:1 standoff	1.4	1.77	1.88
Resistance of 92% Alumina [AD-92]			

[16] See: M. Szymczak in: DREV paper, Sept'95

Vs. HEAT @ 2:1 standoff	1.26	1.38	1.44
Vs. HEAT @ 6:1 standoff	1.32	1.79	1.65
Same target with………			
plus rubber target @ 6:1 standoff	1.3	1.8	1.62
plus airgap target @ 6:1 standoff	1.22	1.65	1.72
Resistance of AD-97			
Tungsten liner @ 2:1 standoff	1.05	1.1	1.05

dU or Tungsten lined shaped charges seem to offer almost the same penetration into ceramic steel targets as all steel targets, suggesting they are unaffected by that special armor.

Unless otherwise stated, Alumina is assumed to be the 'ceramic' in modern tank armor. SiC [Silicone Carbide] is part of the M-8 AGS & and the Yugoslav M84 tank, while TiB_2 [Titanium Diboride] was experimented on a Bradley development vehicle. PYREX is a glasslike ceramic material that disintegrates on impact acting like a granular material and is a good model for T-72A 'Sandbar'. The T-64 is know to feature Kvarts, which is a Fused Quartz like material. Black ceramic is reported to be in the T-64B and possibly other Russian tanks; this could be Alumina, since it appears black when containing rare earth elements. Resent research questions the accuracy of these estimates because of scaling effect, but the actual difference may only be ~1—3%.[17]

1.3.5 SPACED ARMOR

One of the first methods to enhance the armor of tanks was the spaced plate arrangement. It was discovered the combination of air gap and plate detonated shaped charges before impact on the main armor. Where the air gap was large enough, the standoff of the shaped charge helped to defeat the warhead. This is because shaped charges have an optimum detonation range. **If the standoff distance is too little or too much, this reduces the jet efficiency.** All modern tanks have spaced armor somewhere over the design, like the rear hull and turret or the skirts over the side hull.

In addition, the spaced plates themselves also help to defeat the shaped charge by erosion. **Test on thin spaced plate's show that the collapse of the plate flows into the path of the jet, leading to a large disrupted zone**. Since the jet has little strength, it too is disrupted and the plate will offer a resistance 2—3 times the LOS thickness.

If the spaced plate arrangement is layered, the disrupted zone and shaped charge loss of penetration is larger. **A steel–aluminum–steel arrangement offers a resistance 7 times the LOS thickness of the plates.** The 'Wedge armor' added to the Leopard 2A5 seems to be of this construction with several plates of steel, probably of different hardness [triple hardness steel?][18]
Sufficiently large enough spaced plates can also offer increase resistance to kinetic energy attack [APFSDS], increasing plate resistance ~10% as well as 10% for slanted impact.[19]

If the layer includes an elastic material the plates will bulge at considerable speed [200—500 m./s], increasing the effectiveness of the plate in much the same way ERA works (see below). **These kind of arrangements could offer**

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[17] See: Int. J. Impact Engng., Vol. 18, pp. 1—22
[18] See: Int. J. Engng. Sci. Vol. 20, pp. 947—961
[19] See: Int. J. Impact Engng. Vol. 5, pp. 323—331

~10 times the LOS thickness against shaped charges. The Israeli EKKA armor added to M113 and AAVP–7 are examples of this armor.[20]

1.3.6 Explosive Reactive Armors

Due to the impact the T/d effect has on thin spaced plates, they never offer as much protection as the thickness suggests; usually it's only 60—70% of the thickness. In an effort to improve the effectiveness of these spaced plates, it was found that when in motion they offered proportionally more resistance, thereby offsetting the T/d impact. Tests on this type of armor reveal that the 'yaw' picked up by the penetrating rod / jet is magnified to such an extent as to reduce penetration by as much as half. **These test also reveal considerable variation in the results, this is also evident in spaced plate arrangements and usually results is ± 30% range between the minimum, average and maximum penetration**.[21]

ERA generally works in the following way: A flat layer of explosive is sandwiched between two steel plates, mounted some distance from the main armor wall. When this array is struck by a sufficiently large enough force [HEAT jet or KE penetrator], the explosive is detonated and the 'Flyer plates' are driven apart. **If this impact occurs at angle, the expanding movement of the plates will cut across the path of the jet or rod, thereby eroding it.** When the rod interacts with the flyer plate, it will suffer enhanced erosion and magnify its yaw resulting in 10—20% loss of penetration per plate. However it must be noted that since this is tied to the 't/d effect', any change in the rod or plate thickness will effect the resistance the array can offer.

The effect on HEAT jets is similar to rod shaped projectiles, but since the jet is already weak the disruption can be massive. In addition, tests on 'asymmetrical sandwiches' show that even at normal impact the HEAT jet is seriously disrupt. Thin plates offered 7—10 times the resistance at normal impact.[22]

1.3.6.1 Kontakt-*1* ERA

Late model Soviet tanks mounted 1st Gen Kontakt armor . These 5 x 8 inch blocks work as follows, inside the box, two plates lined with explosives underneath, stacked one on top of the other, are explode outward in the same direction. **Test show that outward propelled plates offer more resistance than inward propelled plates [2 times compared to 1.7 for the retreating plates vs. APFSDS].[23]** Kontakt is thought to be 10 times as effective as RHA plates vs. shaped charges, but the ERA coverage over the front & side of Soviet tanks is reported to be only 60%, while the glacis is about 80%.

1.3.6.2 Kontakt-*5* ERA

The patent for K-5 shows ERA is a box with K-1 type plates inside. **The outer 25mm plates hardly move at all and are fixed in place but there are 2—5 inner plates [similar to K-1] with no more than 2 layers 'active' and the others inert.** It might be that, since the 'active' layers are in segments themselves, they are intended to detonate separately -move the plates -like a 'bulging plate'- and be able to 'do it again' when the next projectile hits the

[20] See: Int. J. Impact Engng. Vol. 21, pp. 294—305
[21] See: Int. J. Impact Engng., Vol. 14, pp. 373—383
[22] Int. J. Impact Engng. Vol. 23, pp. 795—802
[23] „Principle Battle Tank" pp. 59, Arsenal books & Kontakt 5 Patent

next ‘segment’, in other words: It might be reusable! Since only a maximum of 2 of the 4-7 plates are ‘flyer plates’, the variation should be only about ±10% [instead of ±30% in K-1] .[24]

1.3.6.3 Non Explosive Reactive Armor NERA

A variation of this theme is Soviet ‘BDD’ or ‘Brow armor’. This is a thick armor added to the front turret and glacis of older tanks. The bulk of the thickness is rubber with a few thin [5mm] mild steel plates mounted freely. **When this is struck, the kinetic energy of the rod or jet is re-transmitted through the rubber to the mild steel plates, which bulge in the same manner described above.** The T-55 BDD glacis thickness is 150mm with 30mm RHA casing and alternating layers with 4 x 5mm mild steel sandwiched in between 100mm rubber. The effectiveness should be 3[RHA] + {2 x 0.8{mild steel] } + 10 x 0.1 [rubber] divided by 15; that’s a theoretical TE [Thickness effectiveness] of 0.37. But the actual TE of BDD is 0.44, or a 17% increase in effectiveness. **Steve Zaloga indicates the T-72B turret has NERA type armor, utilizing Aluminum instead of mild steel.** The insert should have a TE of 0.41 KE and 0.34 HEAT. similar to the figures for the BDD on the T-55/62. T-90 turret has an improved NERA type armor as well.

1.3.7 LAYERING

Test of AP shots on various aluminum–steel combinations has revealed that if the less dense layer is on top, the array offers **as much as 15%** more resistance than the other way around. Tests on APFSDS seem to show this same effect. **Test on ceramic with backing plates show resistance** changes with the backing material**. The Ceramic/Aluminum**, **offering much less resistance than the same Ceramic mounted on RHA**. **In addition, the same ceramic mounted on tungsten plate offers more resistance still.** In the case of aluminum, this is less dense than the ceramic and thus it fits into the above model. The case of the Tungsten backing is of note due to the possibility that this might be a key to dU armor effectiveness.

Tungsten offers a TE of 1.44 compared to RHA. But when the ceramic was mounted on Tungsten, the resistance of the ceramic increased by 33% over the resistance offered by the Tungsten plate. Looking at it numerically the 1 part ceramic + 2 parts RHA offered 88% of RHA, making the ceramic only 0.75. The 1 part Ceramic +1 part Tungsten target was 1.16 times RHA. But it should have offered 97% resistance making the combination 11% better. **This implies that the backing material increases the resistance of all the components of the array**.[25]

Another way to increase the effectiveness of the ceramic /steel target is to confine [encase] the ceramic in steel. Tests of APFSDS impact have shown that a mild steel cover plate will increase the overall resistance by 12%, while SHS cover plate increases the resistance by 25%. If the backing material is SHS instead of RHA the resistance of the target as a whole goes up again. A ¼ ceramic ¾ SHS target offered 20% more resistance than SHS, [The SHS was BHN 440 and to adjustment to RHA means a further 25% increase], or 1.5 times. When the numerical value should have been 1.1, the increase is 36%. In the case ¼ SHS + ¾ Alumina target, the value should be 1.05, but the real value is 1.31 or a 25% increase. **These changes apply to the whole**

[24] See: Zaloga, Steven: „Artillery & Design Practices 1945—present“, pp. 122, 124/125, 147, 436

[25] See: Int. J. Impact Engng. Vol. 23, pp. 771—782

armor arrangement. It's likely that the secret to the generations of dU armor may be in the impact of high density and high hardness backing materials.[26]

1.4 *Notes & Sources*

The accuracy of estimates is of course always going to be in question, because we don't know the exact composition, thickness and effectiveness of every tank armor [debates still rage today as to the true protection of WW-II tanks]. Generally, the older the tank the more accurate the estimate. Tanks from the 70s or older should be with a few percent of the estimated value, while tanks produced in the 90s may be as much as ± 10% of the estimated value. In assessing 'Free edge effect' a 'typical threat round' had to be selected to determine distance. For all the tanks, 2nd Gen. APFSDS was used with a expected diameter of 25—30mm; it appears HEAT is unaffected by Free edge effect. All effective measure of armors used the Thickness Effectiveness (TE). This is the effective resistance the armor offers relative to RHA Rc-27 plate [usually Type 4340 steel].

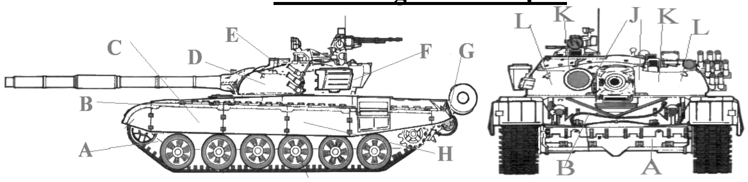
All measurements are taken from scale drawings in 'Abrams' [Hunnicutt] & „Soviet/Russian Armor and Artillery Design Practices: 1945 to Present." [Zaloga], and various Osprey booklets on each tank. The exception are the glacis armor thickness and composition and layout of front turret of the T-80A &T-72 & T72A, which were obtained from numerous discussions on the „Tankers Net" with Sebastian Balos; Vasiliy Fofanov & Col. Mourakhovsky.

The performance of materials are derived from numerous papers from the Int. J. Impact Engng.; Int. J. Solids & Structures ; Int. J. Mech. Sci. ; Journal of Applied Physics; J. of Battlefield Technology and The Int. Symp. on Ballistics. Other information is obtained from JANES ARMOR & ARTILLERY 1995/95; Rheinmetall Handbook on Weaponry[1982]; THE TANK, Christopher Chant; the „Principle Battle Tank"[Russian]; the Patent for Kontakt-5 armor [in Russian, *translated by* Vasiliy Fofanov] and articles in International Defence Review by R.M. Ogorkiewiczs and others.

[26] See: Int. J. Impact Engng. Vol. 17, pp. 409—418 & Int. J. Impact Engng. Vol. 19, pp. 703—713 (1997)

1.5 Estimates of various tanks' armor strength

Armor diagram Example



A = Lower hull	**G = Rear Hull**
B = Glacis	**H = side hull**
C = Front 1/3 side hull	**J =Mantlet**
D = Front side turret Side Turret	**K = Weakened Zone**
E = Upper front turret	**L = Front turret corners**
F =Rear Turret	**M = Side Turret**

1.5.1 General armor description: T-72A & T-80B

Turret front features 280mm cast and a 130mm insert from for a total of 430mm near the gun to 540mm LOS thickness at the turret corners. While the T-80B maximum armor level of the is reported to be 500mm KE armor and the front turret thickness is about 440mm with an 130mm insert for a LOS thickness of 530mm in the „weakened zone" and the corners. If the armor arrangement is similar to the T-64, that's…
STEF [TE of 0.41 KE and 0.7 HEAT] plus 'Corundum', which is likely a upgraded AD-90% [TE 0.9 KE and 1.5 HEAT]. The T-72A glacis is 215mm thick with 60mm RHA plus 105mm Steltexolite and 50mm RHA. The T-80B glacis is 205mm thick with 4 plates three steel of varying hardness and one layer Steltexolite [STEF ?], but it's reported the T-80B got an additional 30mm plate added to the glacis in 1984.

1.5.1.1 T-72A detailed armor estimate

A = 190mm KE & HEAT	G = 60mm KE & 300–400mm HEAT
B = 400mm KE & 480mm HEAT	H = 70–120mm KE & ~210–260mm HEAT
C = 70–120mm KE & ~210–260mm HEAT	J =270mm KE & 470mm HEAT
D = 180mm KE & 240mm HEAT	K = 270mm KE & 450mm HEAT
E = 280–290mm KE & 360–370mm HEAT	L = 390mm KE & 570mm HEAT
F = 80–90mm KE & 130–210mm HEAT	M = 160mm KE & 200mm HEAT

1.5.1.2 T-80B detailed armor estimate

A = 230mm KE & 380mm HEAT	G = 60mm KE & 300–400mm HEAT
B = 480mm KE & 540mm HEAT	H = 70–120mm KE & ~210–260mm HEAT
C = 70–120mm KE & 210–260mm HEAT	J =470mm KE & 540mm HEAT
D = 410mm KE & 510mm HEAT	K = 370mm KE & 500mm HEAT
E = 290–320mm KE & 340–370mm HEAT.	L = 420mm KE & 500mm HEAT
F =110–140mm KE & 180–270mm HEAT	M = 260mm KE & 340mm HEAT

1.5.1.3 T-80BV with K-1 detailed armor estimate

A = 230mm KE & 380mm HEAT	G = 60mm KE & 300–400mm HEAT
B = 500–540mm KE & 670–910mm HEAT	H = 70–120mm KE & ~210–260mm HEAT
C = 90–120mm KE & 300–410mm HEAT	J =490–530mm KE & 660–900mm HEAT
D = 410mm KE & 510mm HEAT	K = 390–430mm KE & 620–860mm HEAT
E = 350–390mm KE & 580–850mm HEAT	L = 440–480mm KE & 620–860mm HEAT
F =110–140mm KE & 180–270mm HEAT	M = 260mm KE & 340mm HEAT

1.5.2 General armor description: T-72B /BV/S

Steve Zalogas reports the turret has 435mm thick 'T-55 type BDD type insert', plus 380mm cast armor utilizing Aluminum instead of mild steel/ rubber combination. The stated resistance of the turret is 530mm KE armor and

520mm HEAT protection. The insert adds 180mm KE and 150mm HEAT armor, for a TE of 0.41 KE and 0.34 HEAT, similar to the T-55/62 BDD figures. The glacis is thought to be 30mm SHS plus 60mm RHA and 105mm Steltexolite and 50mm RHA. The BV and S models have K-1 ERA.

1.5.2.1 T-72B detailed armor estimate

A = 210mm KE & HEAT	G = 60mm KE & 300–400mm HEAT
B = 500mm KE & 580mm HEAT	H = 70–120mm KE & ~210–260mm HEAT
C = 70–120mm KE & 210–260mm HEAT	J = 470mm KE & 540mm HEAT
D = 410mm KE & 510mm HEAT	K = 500mm KE & 520mm HEAT
E = 280–290mm KE & 370–410mm HEAT	L = 470mm KE & 490mm HEAT
F =110–140mm KE & 180–270mm HEAT	M = 260mm KE & 340mm HEAT

1.5.2.2 T-72BV & S with K-1 detailed armor estimate

A = 210mm KE & HEAT	G = 60mm KE & 300–400mm HEAT
B = 520–560mm KE & 670–910mm HEAT	H = 70–120mm KE &~ 210–260mm HEAT
C = 90–120mm KE & 300–410mm HEAT	J =480–500mm KE & 600–700mm HEAT
D = 460mm KE & 560–760mm HEAT	K = 510–530mm KE & 580–720mm HEAT
E = 350–390mm KE & 580–850mm HEAT.	L = 490–530mm KE & 620–880mm HEAT
F =110–140mm KE & 180–270mm HEAT	M = 260mm KE & 340mm HEAT

1.5.3 General armor description: T-72B with Kontakt-5

Steve Zalogas reports the turret has ‘improved’ 435mm ‘T-72B BDD type insert’ plus 380mm cast armor, maybe Titanium bulging plates. In Checheny the T-72 B with out Kontakt couldn’t resist Konkurs ATGM but the T-90 without Kontatk did [Konkurs has a ~600mm penetration]. This means the T-72B must be much less than 600mm protection while the T-90 must be much more. The K-5 glacis effectiveness should be 7.1-7.5 cm ÷ 0.38 = **190—200mm** KE armor The T-72BM turret is flat at the front and sloped like the T-90 turret so the K-5 benefit here should be **~170—200mm**, but the flat front should add just **170—180mm** KE protection. The Glacis armor should be the same thickness as T-72 B however one RHA plate may be replaced by SHS plate.

1.5.3.1 T-72B with Kontakt-5 detailed armor estimate

A = 240mm KE & 380mm HEAT	G = 60mm KE & 300–400mm HEAT
B =670–710mm KE & 990–1070mm HEAT	H = 70–120mm KE &~ 210 – 260mm HEAT
C = 90–140mm KE & 510 – 560mm HEAT	J =560–580mm KE & 940–1060mm HEAT
D = 420–640mm KE & 680–850mm HEAT	K = 700–740mm KE & 1040–1120mm HEAT
E = 350–390mm KE & 560–940mm HEAT	L = 650–710mm KE & 1000–1100mm HEAT
F =110–140mm KE & 180–270mm HEAT	M = 280mm KE & 340mm HEAT

K-5 coverage seems to be about 60%, the T-90 without K-5 looks a lot like the T-72BVwith K-1

1.5.4 General armor description: T-80U

The maximum front turret armor is reported to be 815mm thick and the insert similar to the T-90 with ~380mm thickness suggested, while the thickness may reach ~920mm in the „weakened zone“.. The mass increase is 8% but the thickness goes from 530—815mm thus the density goes from ~5.3 g/cm³ down to ~3.76 g/cm³. If the insert thickness resembles T-90, its density can’t be much more than ~2 g/cm³. Assuming Corundum reinforced with 5 parts STEF, this should fit and offer a TE of ~ 0.71 KE & 0.9 HEAT. The glacis may be reinforced by substituting one of the RHA plates for SHS, boosting the resistance by 30—40mm

1.5.4.1 T-80U

A = 210mm KE & HEAT	B = 520mm KE & 570mm HEAT

C = 70–120mm KE & 210 – 260mm HEAT
D = 400mm KE & 510mm HEAT
E = 280–290mm KE & 370–410mm HEAT
F =110–140mm KE & 180–270mm HEAT
G = 60mm KE & 300–400mm HEAT
H = 70–120mm KE &~ 210 – 260mm HEAT
J =470mm KE & 730mm HEAT
K = 490mm KE & 520mm HEAT
L = 480mm KE & 640mm HEAT
M = 260mm KE & 340mm HEAT

1.5.4.2 T–80UM–1 with K–5

A = 240mm KE & 380mm HEAT
B =680–720mm KE & 960–1040mm HEAT
C = 90–140mm KE & 510 – 560mm HEAT
D = 420–640mm KE & 680–850mm HEAT
E = 350–390mm KE & 560–940mm HEAT
F =110–140mm KE & 180–270mm HEAT
G = 60mm KE & 300–400mm HEAT
H = 70–120mm KE &~ 210 – 260mm HEAT
J =560–580mm KE & 940–1060mm HEAT
K = 640–660mm KE & 1080–1120mm HEAT
L = 660–680mm KE & 1100–1140mm HEAT
M = 280mm KE & 340mm HEAT

K-5 coverage seems to be about 60%, the T-80 without K-5 looks a lot like the T-72BVwith K-1

1.5.5 General armor description: T-84

The T-84 uses the same hull as the T-80U, but features a new welded turret. The maximum armor thickness of this turret is probably similar to the T-80U front turret armor, which is reported to be 815mm thick and the insert is probably similar to the T-90 with ~380mm LOS insert thickness suggested. The turret is welded and probably similar to the T-80UM with an insert of TE 0.71 & 0.9. Based on the assumption of welded RHA plates, we get 380mm [1.0 **TE**] + 435mm insert [x 0.71 **Te**] ÷ 815mm = **0.85 KE & 0.95 HEAT**. The angles on the T-84 seems close to the T-80 and therefore the 'T-80UM' K-5 numbers apply.

1.5.5.1 T-84 detailed armor estimation

A = 240mm KE & 380mm HEAT
B =680–720mm KE & 960–1040mm HEAT
C = 90–140mm KE & 510 – 560mm HEAT
D = 420mm KE & 680mm HEAT
E = 500–670mm KE & 740–1160mm HEAT
F =110–130mm KE & 270–350mm HEAT
G = 60mm KE & 300–400mm HEAT
H = 70–120mm KE &~ 210 – 260mm HEAT
J =620–640mm KE & 940–1060mm HEAT
K = 740–760mm KE & 1080–1120mm HEAT
L = 720–740mm KE & 1040–1080mm HEAT
M = 280mm KE & 340mm HEAT

1.5.6 T-95/Black Eagle speculation.

The glacis looked sharper than the T-80/90. If the thickness and layout is like T-90, then the armor should be 235mm @ 70° with 4 plates, three steel of varying hardness and one layer Steltexolite [STEF]. **680mm KE & 710mm HEAT.** With K-5 that should be **830—880mm KE & 1110—1210mm HEAT.**. Just a 10% increase in the turret weight combined with nearly 100% coverage of K-5 type ERA the front turret armor might reach **~580—630mm KE and 760—810mm** *with K-5;* and **800—900mm** HEAT **& 1200—1400mm** with K-5 type ERA.

1.5.6.1 T-95 detailed armor speculation

A = 360mm KE & 480mm HEAT
B = 830-880mm KE & 1110-1210mm HEAT
C = 90-140mm KE & 510 – 560mm HEAT
D = 420-640mm KE & 680-850mm HEAT
E = 350-390mm KE & 560-940mm HEAT
F =110-140mm KE & 180-270mm HEAT
G = 60mm KE & 300-400mm HEAT
H = 90-120mm KE &~ 210 – 260mm HEAT
J = 700-740mm KE & 1060-1200mm HEAT
K = 790-810mm KE & 1300-1400mm HEAT
L = 760-780mm KE & 1200-1280mm HEAT
M = 280mm KE & 340mm HEAT

K-5 coverage seems to be nearly 100%. Note these estimates assume quantitative not qualitative increases, the figures should be higher.

1.5.7 General armor description: Challenger-1

This tank was designed with cast turret plus Chobham armor and hard steel outer cover plates. The front turret thickness of the Challenger seems to range from 920mm along side the gun, narrowing to 880mm and ~800mm at the turret corner. Assuming the same volume as the Chieftain, then the weight increase to Challenger suggests a 13% armor increase overall [should be 54/92; 48/88 & 44/80] suggesting an average density of 4.3-4.6 g/cm³. This sounds like 1.5 part steel, 2 part Alumina [97%?] and 2 part GRP[average 4.4g/cm³], similar to an armor tested in a RARDE paper[27]. That's 0.82 KE and 1.22 HEAT. A 1991 IDR article reports the Challengers armor was ~1000mm HEAT and a 1985 engineering estimate put the front turret @ > 620mm KE armor.[28]

1.5.7.1 Challenger-1 detailed armor estimation

A*** = 520mm KE & 710mm HEAT	G = 100mm KE & 500mm HEAT
B = 550mm KE & 800mm HEAT	H = 80mm KE &~ 470–490mm HEAT
C = 80mm KE & 470 – 490mm HEAT	J = 590mm KE & 1120mm HEAT
D = 550mm KE & 830–1070mm HEAT	K = 610mm KE & 1070mm HEAT
E = N/A	L = 620mm KE & 970mm HEAT
F =150mm KE & 500mm HEAT	M = 220mm KE & 330–380mm HEAT

***Lower Hull Mk 1/3 version =520mm KE & 800-1000mm HEAT
***Side Hull Mk 1/3 version ~ 130mm KE & 820-840 mm HEAT

1.5.8 General armor description: Challenger-2

The front turret thickness of the Challenger-2 seems 870mm along side the gun, narrowing to ~740mm at the turret corner. Since the Challenger 1 & 2 have the same weight there's no change in the armor mass all round, except for the „Dorchester" armor. Its been reported 'Dorchester' is 'dU nuggets' probably suspended in a elastic medium, and 12 inches of this armor stopped the M-829. The new mass figures should be ~5.6g/cm³. If we transfer mass from rear turret to front turret, that's 5.25 g/cm³, and since the Challenger 2 turret has a smaller surface area than Challenger 1 [by about 1.06 times], the density goes up to 5.6g/cm³. If we assume 1 part steel, 1.5 parts UO² 'dU ceramic' [11g/cm³] and 2.5 parts Kevlar [1.44 g/cm³]/5, that's 5.59 g/cm³, close enough!. Based on UO² that's a TE of 1.17 KE & 1.96 HEAT. Finally 'Dorchester' elastic effect should be similar to the advantage NERA offers, so the TE value should be 1.17 x 1.17= 1.36 KE.

1.5.8.1 Challenger-2 detailed armor estimation

A = 590mm KE & 860mm HEAT	G = 100mm KE & 500mm HEAT
B = 660mm KE & 1000mm HEAT	H = 100mm KE &~ 470-490mm HEAT
C = 100mm KE & 470 - 490mm HEAT	J = 920mm KE & 1700mm HEAT
D = 550mm KE & 830-1070mm HEAT	K = 950mm KE & 1600mm HEAT
E = N/A	L = 960mm KE & 1450mm HEAT
F =140mm KE & 500mm HEAT	M = 340mm KE & 520mm HEAT

1.5.9 General armor description: M-1A1

Weight went up 4 tons over the old M-1 and the front turret was redesigned, increasing the armor thickness to 700—860mm thickness. That's a 11% mass increase, the HY-120 plate thickness remained the same at 101mm back plate and 62mm cover plate, just the cavity increased leading to an increase in filler density ~2.25 g/cm³. A change to AD-92 and 2 parts rubber should fit the density [2.22g/cm³]. The new TE values should be = 0.61 KE and 1.07 HEAT

[27] See: Int. J. Impact Engng 1995 Vol. 17, pp. 263—274
[28] See: Int. Defence Review 4/91, pp. 349—352

x 1.08 [backing] = 0.66KE & 1.15 HEAT. The variation in the glacis armor is the rating with the fuel cell full & empty. **From a ± 30° angle the turret armor is 390—400mm KE & 720—880. The maximum published values for ± 30° are 400mm KE & 800mm HEAT, so the estimates are close**

1.5.9.1 M-1A1 detailed armor estimation

A = 430–470mm KE & 570–790mm HEAT	G = 100mm KE & 500mm HEAT
B = 350–490mm KE & 510–800mm HEAT	H = 90mm KE & 680mm HEAT
C = 160mm KE & 900mm HEAT	J = 440mm KE & 990mm HEAT
D = 240mm KE & 440mm HEAT	K = 450mm KE & 920mm HEAT
E = N/A	L = 440mm KE & 800mm HEAT
F = 90mm KE & 410mm HEAT	M = 240mm KE & 440mm HEAT

1.5.10 General armor description: M-1A1(HA)

The weight went up 6 tones over the M-1A1, representing a 20% armor mass increase while the thickness stayed at 700—860mm. The big boost came from ~ 4 inches of dU armor added to the front turret. If we assume the 4 inches of dU/steel replaces the 4 inch back plate, then the weight works out. Tests on changing the backing material show the resistance goes up 1.38 times for the whole structure and if it's ½ steel and ½ dU, the multiple should be x 1.19. If we further assume the armor is AD-92 + 2 x Kevlar that should be 0.77 x 1.08 [Hard Backing] = 0.84 x 1.19 [dU multiple] = 1.0 KE. The values for HEAT armor should be 1.54 HEAT. **The turret armor value for ±30° is 590—610 mm KE and 960—1180 mm HEAT, when the published value is 600mm KE.**

1.5.10.1 M-1A1(HA) detailed armor estimation

A = 580–630mm KE & 800–900mm HEAT	G = 100mm KE & 500mm HEAT
B = 560–590mm KE & 510–800mm HEAT	H = 90mm KE & 680mm HEAT
C = 160mm KE & 900mm HEAT	J = 670mm KE & 1320mm HEAT
D = 300mm KE & 480mm HEAT	K = 680mm KE & 1230mm HEAT
E = N/A	L = 660mm KE & 1080mm HEAT
F = 90mm KE & 410mm HEAT	M = 300mm KE & 480mm HEAT

1.5.11 General armor description: M-1A1HC/M-1A2

The weight and the front armor thickness remained the same, however 2nd Generation dU armor is included. If the dU/steel backing plate includes hard steel backing, the overall Ceramic-Steel resistance should lead to a increase in the backing plate to 55% the base values, which in turn has probably been upgraded to AD-95 + 2 x Kevlar plus 4 inches dU /SHS . This equals 0.85 x 1.55, for a TE of 1.32 KE. & 1.88 HEAT. **The ± 30° turret armor case is 790—800 KE and 1180—1450 HEAT, when the published maximum values is 800 mm vs. KE.**

1.5.11.1 M-1A1HC/M-1A2 detailed armor estimation

A = 590-650mm KE & 800-970mm HEAT	G = 100mm KE & 500mm HEAT
B = 560-590mm KE & 800-1050mm HEAT	H = 90mm KE & 680mm HEAT
C = 160mm KE & 900mm HEAT	J = 880mm KE & 1620mm HEAT
D = 300mm KE & 480mm HEAT	K = 900mm KE & 1500mm HEAT
E = N/A	L = 880mm KE & 1310mm HEAT
F = 90mm KE & 410mm HEAT	M = 300mm KE & 480mm HEAT

1.5.12 General armor description: M-1A2 /SEP

The weight and the front armor thickness remained the same, however density increase is achieved by substituting Titanium for some structures and armor in the rest of the tank. In addition 3rd generation dU armor is included. With dU/SHS backing plate the target resistance is up 55%, and adding a thin

Graphite confining layer acts like a seal and increases the confining effect on the armor over 5%. The M-1A2 is rumored to have ‘Dorchester armor’. If we assume this is the case and work in the weight saving from Titanium, then an insert density of 2.3g/cm might be possible leading to a 1x UO^2 100 / 6x rubber = 2.3 g/cm^3. This would also be BDD type NERA arrangement, leading to the third generation dU armor. The TE values should be 0.47 x 49 + 29 x 1.63[dU/Back + Graphite] x 1.17[BDD] ÷70 = **1.41 KE & 1.97 HEAT**

1.5.12.1 M-1A2/SEP detailed armor estimation

A = 590–650mm KE & 800–970mm HEAT
B = 560–590mm KE & 800–1050mm HEAT
C = 160mm KE & 900mm HEAT
D = 350mm KE & 540mm HEAT
E = N/A
F = 90mm KE & 410mm HEAT
G = 100mm KE & 500mm HEAT
H = 90mm KE & 680mm HEAT
J = 950mm KE & 1620mm HEAT
K = 960mm KE & 1510mm HEAT
L = 940mm KE & 1320mm HEAT
M = 350mm KE & 540mm HEAT

1.5.13 General armor description: Leopard 2A1—A3

The turret thickness ranges from 1000mm near the corners and 1300mm in the middle 700mm along the mantlet, composed of a 50mm cover plate + 600mm cavity + ? thickness back plate [300—700mm?]. The conversion from Leopard 1A3 turret to Leopard 2 turret yields 270=>630mm armor mass change, suggesting the solid thickness is not all steel. R.M. Ogorkiewicz reported a German armor in the mid 70s as SHS + Aluminum + Ceramic. See If we assume 2/3 aluminum + SHS + AD-85 + Rubber we get a insert density of 2.4 g/cm^3 when the mass suggests a 2.35 g/cm^3, close enough. The hull is reported to be spaced armor construction. Going from Leopard 1 to Leopard 2 resulted in a hull armor mass increase of 50%, leading to a hull armor mass of only ~210mm RHA.. The Leopard 1A3 featured 250—430 & 515 BHN plates welded together to form triple hardness steel. The turret armor should be SHS [TE x 1.2] + 0.41/0.61 Al-7xxx 0.82/1.4 (TE AD-85) + 0.1/0.34 (TE of rubber) ÷5, which equals a TE of 0.59 vs. KE and roughly 0.83 vs. HEAT.

1.5.13.1 Leopard 2A1—A3 detailed armor estimation

A = 350mm KE & 520mm HEAT
B = 350mm KE & 520mm HEAT
C =90–100mm KE & 500mm HEAT
D = 210mm KE & 290mm HEAT
E = N/A
F = 70–90mm KE & 400mm HEAT
G = 70mm KE & 400mm HEAT
H = 60–70mm KE & 370mm HEAT
J = 590mm KE & 810mm HEAT
K = 670mm KE & 1080mm HEAT*
L = 570mm KE & 830mm HEAT
M = 210mm KE & 290mm HEAT
*) gun sight area is 610mm KE. & 890mm HEAT

1.5.14 General armor description: Leopard 2A4

The Leo 2A4 features second generation Chobham armor, while the weight & turret thickness look the same as previous versions. If we assume 2nd generation composite – AD-92/5 – and keep the weight and rubber the same, this should be sufficient. Redoing the above calculations that's 1.2 [SHS] + 0.41/0.61 [TE Al-7xxx] + 0.95/2.0 [AD-92] + 0.2/0.4 [Dyneema]÷4. This equals a TE of 0.69 KE and 1.05 HEAT. In addition, the hull may have composite armor instead of spaced.

1.5.14.1 Leopard 2A4 detailed armor estimation

A = 600mm KE & 710mm HEAT
B = 600mm KE & 710mm HEAT
C =130mm KE & 670mm HEAT
D = 270mm KE & 420mm HEAT
E = N/A
F = 70–90mm KE & 400mm HEAT
G = 70mm KE & 400mm HEAT
H = 60–70mm KE & 370mm HEAT
J = 590mm KE & 810mm HEAT
K = 760mm KE & 1370mm HEAT*
L = 650mm KE & 1050mm HEAT
M = 210mm KE & 290mm HEAT

*) gun sight area is 710mm KE. & 950mm HEAT

1.5.15 General armor description: Leopard 2A5

The 'Wedge Armor' is reportedly ~32mm thick steel plates @ ~70° compounded angle, that's about 90mm LOS value. If it's a series of hard steel plates in a spaced plate configuration, it's 'Triple Hardness Steel'. This should offer 1.6[THS]x 1.3[yaw effect] x 90mm or ~190mm KE armor. The 'free edge effect' will modify this by 0.95; and the 'T/d' by 0.88 to ~160—180mm KE. The HEAT values are 90mm x 1.3 x 3 plus 4—8cd standoff = ~500 mm HEAT. The tank uses 3rd Generation Chobham armor which is at least AD-99 and Aramid 'Dyneema'. This makes the values 1.2 [SHS] + 0.45/0.7 [TE Al-2xxx] + 1.05/2.6 [AD-99] + 0.2 /4 ÷4. Which equals a TE of 0.72 KE & 1.22 HEAT. The interior turret and front hull is reinforced with a Dyneema liner, adding another 20mm KE and 40mm HEAT.

1.5.15.1 Leopard 2A5 detailed armor estimation

A = 620mm KE & 750mm HEAT
B = 620mm KE & 750mm HEAT
C =190mm KE & 670mm HEAT
D = 370mm KE & 660mm HEAT
E = N/A
F = 70–90mm KE & 400mm HEAT
G = 70mm KE & 400mm HEAT
H = 170mm KE & 520mm HEAT
J = 920mm KE & 2000mm HEAT
K = 970mm KE & 2000mm HEAT*
L = 860mm KE & 1720mm HEAT
M = 290mm KE & 460mm HEAT

*) gun sight area is 900–920mm KE. & 1380mm HEAT