PROJECTILE DAMAGE
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INTRODUCTION

There are several kinds of damage that a gun projectile or bomb or missile can suffer on impact with a target, with the type of and amount of damage being determined by the projectile size and type (based on the size of its internal cavity for explosives, if any, and the purpose of the projectile); thickness, hardness, strength, and toughness of the projectile nose and body materials; whether the projectuile has any nose coverings (Hood or AP Cap) that can provide some protection to the nose; the thickness and type of material struck; the striking velocity; and the obliquity angle (with right-angles or normal being zero degrees).

The thicker, stronger, and/or more rigid the target is, the more chance of damage occurring to the projectile. In some cases the damage gets progressively worse as the target gets more resistant. the striking velocity goes up, and/or the obliquity increases (though there may be a maximum obliquity beyond which the damage ceases to increase and, in some cases, may actually decrease at high obliquity angles). In other cases the damage may be rather minor up to some level of plate resistance, striking velocity, or obliquity and then suddenly change for the worse above a critical value for the given parameter.

The damage can be generally sorted out into the following categories. Note that more than one kind of damage may occur simultaneously, though some forms of damage are mutually exclusive, with the advent of one making the other impossible or of no consequence.

I. DEFORMATION. This is the compression, bending, or stretching of a projectile with soft, ductile, or malleable regions, or some portion of it, that makes the required energy to penetrate that target under those conditions more difficult, usually by making the required hole bigger and/or by absorbing internally some significant portion of the impact energy that otherwise would have gone to damaging the target. It ALWAYS makes penetration of the target more difficult, sometimes completely impossible. In many cases, though, the explosive filler and base fuze are not affected, unless the base is strongly distorted, crushing the fuze or loosening and/or knocking off the base plug holding the filler in the projectile, or the projectile body is so distorted that it pinches the filler and the filler is sensitive enough to ignite or even explode due to this. In more extreme cases, the projectile can be deformed enough so that pieces of it around the edges are torn off as it passes through the target, breaking the projectile up, but this is not due to brittle cracking and splitting as occurs in the next forms of damage.

II. SHATTER. This is the sudden breakup of the front end of a hardened, rigid projectile (at least the nose is hard) on impact with the target that causes extensive damage in the form of the nose breaking up into several pieces. In many cases, this results in the rest of the projectile also breaking into pieces due to extensive cracking in the projectile body just behind the nose and increased target resistance to the now-poorly-shaped and weakened remaining portion of the projectile, though this is not always true -- I define "nose-only shatter" as shatter where the initial shatter effect did not reach down into the portion of the projectile where the explosive cavity exists, though later damage due to the weakening of the projectile just mentioned may finish the breakage if there are any further resistant portions of the target impacted behind the portion that caused the initial shatter. Note an important condition here: The damage must occur PRIOR TO any significant penetration into the portion of the target causing the shatter, regardless of what is the cause or whether or not the shatter is complete of nose-only. Thus, the effects of this kind of damage will be applied to ALL further motion of the projectile from that instant on, including changing its penetration ability into the plate causing the damage to the maximum extent possible. Note also that at higher obliquities over 45 degrees, the damage will suppress ricochet (the projectile nose can no longer drag the rest of the projectile with it if the nose ricochets off of the plate) and this can actually make the projectile penetrate EASIER than if it had suffered no damage or some other kind of damage -- the projectile will be in fragments, of course, but it will have many pieces behind the target portion that caused the shatter where otherwise none would do so. This improvement is due to the suppression of ricochet just mentioned and/or to the fact that broken projectile pieces can fit through a smaller hole in the target than the original intact projectile could. There may be more than one possible cause of this kind of damage, but it is all "shatter" if it meets the above criteria.

III. OTHER BREAKAGE. While in some cases -- severe nose damage and, usually, complete projectile breakup -- this damage is superficially similar to shatter, it can occur to any and all parts of the projectile separately due to various causes and, unlike shatter, it occurs AFTER the projectile has finished a major portion of its penetration process through the part of the target causing the damage, so its effects are usually less pronounced. This damage may occur to the nose, like shatter, and/or to the middle and/or lower body as the projectile tries to force itself the rest of the way through the plate, especially at an oblique angle where there is a set of huge twisting forces on various portions of the projectile and the rotation of the projectile from its original direction of motion can cause the middle and lower body to slam up against the side of the forming hole like a baseball bat, what is termed "base slap", causing all sorts of damage, much of it severe, unless the projectile designers provided major design modifications to lessen or eliminate as much as possible these negative effects. There is a major difference in the damage-resistance of various projectile types, dates of manufacture, and the competence (understanding of the causes of the damage and how to go about minimizing it) and capabilities (metallurgical and manufacturing skill) of the companies that made the projectiles. Projectile designs varied considerably as to projectile damage-resistance due to the purpose for which the projectile was made (a light-case HE shell, for example, will not do well against even very moderate thicknesses of armor, but it was not designed to be able to, after all). This includes the internal details as to the shape of the internal cavity, if any; how the base fuze, if any, was designed and attached; how the base plug was shaped and how its threads were designed to hold it to the inside of the projectile lower body; the hardening and tempering processes used for the metal of the projectile body; and so forth. This can vary wildly from projectile to projectile, even though externally the given projectile may look exactly like another of that size and type. Note that the breakup of the shell due to premature explosion of the projectile's explosive filler, if any, due to the filler being crushed, due to its impact shock sensitivity, or due to the projectile's fuze being instantly set off by the impact while the projectile is still in the process of penetrating the plate causing the damage, can also be considered part of this criteria, as the results are similar or probably even more catastrophic to the projectile. However, these filler-related problems are somewhat separate design and manufacturing problems from the ability of the projectile body itself to punch through the armor plate with the lowest practical striking velocity under the most likely expected battle conditions.

This will be covered in more detail below.

DEFORMATION

Deformation is caused by the forces on the projectile exceeding the Yield Strength of the projectile so that it no longer is in its original shape (ignoring the loss of the windscreen or armor-piercing cap or other portion of the projectile that is expected by design to be lost during penetration, if any) when it ceases contact with the armor plate or, if stuck in the plate, ceases its motion relative to the plate. These are permanent changes, not mere temporary distortion of the projectile's shape that spring back to its original form after the impact is over (this can be considered part of the projectile's design criteria). But, here we assume that the Tensile and Shear Strengths are not exceeded and thus the projectile suffers little if any breakage (knocking off of parts of it, large or small) -- any pieces torn off the deformed projectile only affect its penetration through any later portions of the target after leaving the plate causing the deformation and tearing.

Deformation can COMPLETELY prevent penetration by an otherwise high-quality projectile. It is potentially the worst thing to happen to a projectile as to its penetration ability when it is severe, even worse than shatter. In most cases, there is no situation where deformation improves the penetration ability of the projectile compared to a rigid, intact projectile of the same initial shape and weight. (We are not talking about projectiles with sub-caliber, heavy-metal penetrators which, by design, have the outer casing deformed and torn off during the penetration process.)

During the impact, as mentioned above, as the forces are applied, any material will have some large or small amount of resilience where the deformation is temporary and the object snaps back to its original form when the forces are removed. This will obviously affect the ability of a projectile to pass through the target, but as this always occurs for any impact no matter the strength of the projectile and can be considered a built-in part of the "Projectile Quality Factor" (Qp) for adjusting the its baseline penetration ability comparted to the nearest-to-perfect projectile used as the standard against which all others are measured, I am not going to consider this as a separate problem.

Well-made, hard-nosed, thick-bodied armor-piercing (AP) projectiles are designed to deform as little as possible in their nose and upper body under the large forces applied during the attempted penetration of a target, most especially when the object is made of very strong materials like steel armors. The lower body and base of the projectile is of less consequence as it will only get in contact with the armor much later in the penetration process where any damage to it will have limited effect on reduction of penetration, though possibly much effect on the explosive or other damage-causing capability of the projectile after the impact. If, however, the projectile is made too rigid, then forces have a much higher chance of, even if just for a moment, exceeding the Yield Strength of the projectile material where the force is being applied-- the material has insufficient "give". In such hard, rigid materials, which all metal AP projectile designs incorporate, they will not only start to deform, but will almost instantly break apart when cracks form. It is thus very important to balance how rigid the projectile will be and how much temporary resilience-type deformation is allowed to minimize the size of the hole in the armor directly impeding the projectile's forward motion into the target, thus minimizing the amount of armor involved over the entire penetration process. Toughness (crack resistance) and hardness (strength) are both necessary for the best result possible against the expected targets of the given weapon.

I. **Compression**

Compression deformation (termed "upsetting" in metalwork) is the most obvious kind at near right-angles impact, whereby the projectile shortens as some portion of it flattens out and the maximum diameter of the projectile widens there. As mentioned, the later that this occurs, the less effect it has on penetration of the target. As with shatter, the effect begins at initial impact, delayed only by the speed of sound in the projectile bringing in portions more and more toward the base, so that deformation will occur later for those portions of the projectile closer to the base.

Upsetting deformation of the nose in those projectiles with too-soft noses, usually results in the nose and, possibly, upper body of the projectile shortening and widening so that it beings to look something like the Onion Domes in the Kremlin in Moscow, Russia. The tips of the bulges may remain pointed if the nose was able to dig deep enough into the target before the deformation set in, but in many cases the tip is flattened. In extreme cases of very soft projectiles, such as made of wrought iron, hitting thick hard armor plates, the projectile can "mushroom" with the upper end flattening out into a large disk and only the lower body and base remaining more-or-less in their original cylindrical shape. It is these more extreme cases where the deformed portion of the projectile may have pieces torn off of it as the projectile passes through or ricochets off of the target. Obviously, such effects will significantly reduce the ability of the projectile to penetrate that target unless the striking velocity is increased, though if the striking velocity has to be raised too much, the projectile may begin to suffer breakage first -- usually shatter -- so penetration might not be possible within the range of striking velocities possible.

Projectiles with large internal cavities for explosive fillers located in the lower and, if large enough, middle and upper body pf the projectile have the most of a problem here, even if the nose of the projectile is hardened and toughened properly, in that the squeezing of the thinner sides of this cavity between the inertia of the base and the sudden deceleration of the nose can cause them to bulge outward and possibly fold and break the projectile in half, on top of possibly setting off the filler and blowing the projectile to pieces. Even if the bulging is not enough to break the projectile immediately, it will require a larger hole to pass though the target region hit and if that region is heavy armor, this will not be easy, causing the projectile to jam in the hole, which raises the needed striking velocity to penetrate, or, even worse, the projectile may have the bulged region recompressed or sheared off by the armor, which will almost always cause the projectile to break apart there and, again, will likely cause the explosive filler to explode, so only the upper end of the projectile, usually in pieces, will get through the armor.

II. **Bending**

Bending deformation (termed "offsetting" in metalworking) is the twisting the original symmetrical projectile shape into a "C" or "J" shape somewhere along its length. In hard-nosed AP projectiles, this rarely occurs in the nose region, where brittle fracture and breakage are much more likely when the forces get too high to withstand, but it can occur to some extent in the upper, middle, and lower bodies and bases of many projectiles, even very strong designs, where toughness to prevent breakage is of more importance and there are more kinds of forces from several directions on the projectile than in the simple case of deceleration forces at low-obliquity directed along the projectile centerline.

Of course, bending can occur anywhere, even at right-angles impact, when the strength of the projectile is uneven and it "gives" under the loads on one side more than on the other, but the higher the angle of obliquity, the greater are the asymmetric forces from the side of the projectile with more area in contact with the target, so the more likely bending will be. Under conditions where penetration is possible within the striking velocity range we are discussing here (under 3500 ft/sec (1148.3 m/sec)), as the impact obliquity increases, the thickness of the target armor that can be penetrated decreases, slowly at up to 40 degrees or so, but more rapidly above that, since, at the higher obliquities, the ricocheting of the projectile by glancing off due to redirecting the projectile nose away from the plate rather than trying to slow all of it down to a stop becomes the major method of plate resistance. As such, as the obliquity angle gets to be at and above 60-65 degrees, the bending forces on the projectile begin to decrease again since the angle change needed to successfully deflect the projectile becomes rather small and the needed plate thickness thus also becomes rather small (thicker plates cannot be penetrated at such angles within the defined striking velocity range, so can be ignored here), so the forces that the plate needs to apply to keep the projectile out are not very great, decreasing any bending of the projectile by the plate at any time during the penetration process, successful or not.

Since bending deformation anywhere along the length of a projectile can inhibit penetration -- even the base jamming in the hole will stop the entire projectile which otherwise remained intact and rigidly straight -- this form of deformation has more negative effects than compression deformation when the projectile nose was adequately designed, which usually is enough to prevent compression deformation even if the lower body is excessively soft. For example, WWII British large-caliber naval capped AP projectiles had very soft lower bodies to minimize breakage due to base slap at oblique impact -- which worked rather well once perfected -- but very hard, rigid noses much like most other AP projectile designs then in use, and they penetrated moderately thick high-quality armor plates (up to the projectile's diameter in thickness) at moderate obliquity with no negative effects, but against very thick plates (greater in thickness than the projectile diameter), even at the same moderate obliquity, the projectile middle body bent into a crescent shape and, as a result, the projectile had virtually nil penetration ability against such plates at any but near-right-angles impact.

III. **Stretching ("Extrusion")**

This form of damage is the most unusual that I know of. In fact, I know of only one case of it in my extensive ballistic database. It is caused by a projectile punching a hole in an armor plate that was smaller than the projectile diameter, as is the usual case when striking face-hardened armor at low obliquity when a hard AP cap gouges a hole of its face diameter -- smaller than the projectile's total diameter -- at and above the Holing Ballistic Limit (HBL), and the projectile fails to be able to widen that hole to at least the projectile diameter when it tries to pass completely through that hole at and above the usual Naval Ballistic Limit (NBL, the complete penetration of the entire projectile, if intact, or at least 80% of its body weight, if broken up). Usually such a situation simply means that the projectile has hit below the somewhat higher NBL and the projectile rebounds or remains stuck in the plate, broken, somewhat deformed, or intact. It never, other than this one case, ever meant that the projectile even when hitting at ABOVE the NBL suffered such extensive damage and yet did not break apart.

In this case, this rather unusual plate's NBL was well above the typical plate NBL against that projectile under the impact conditions, indicating an exceptionally strong plate. It was even more unusual in that the projectiles involved were two variations of a late-WWII-model US 8" (203mm) hard-capped AP shell that was superior to all but a very few other US and most foreign AP projectiles that had NEVER previously suffered from such damage in any tests against any other plates ever made (and it was tested against several during and after WWII).

The details were as follows:

The plate was an experimental 184mm (7.25") Japanese face-hardened Vickers Hardened (VH, the non-cemented type used only on the YAMATO Class battleships, but never under 250mm (9.84") in those ships), this plate being manufactured during WWII to improve that kind of armor, which previously had not been required to be much better than the original British Vickers Company 1912 Krupp Cemented (KC)-type armor, called Vickers Cemented (VC) by the Japanese, that had been used in all prior Japanese heavy warships. The Japanese seem to have been given samples of new German Krupp Cemented New Type (KC n/A) armor, which was significantly superior to the usual VH plate, and desired to see if they could match it. This plate did indeed demonstrate that they had the capability to do just that and more! This plate had an unusual, for VH, hardness pattern of somewhat over 40% face, unlike the 35% face of regular VH, indicating that it was using a different hardening process than the regular VH armor, more like KC n/A did -- otherwise, the plate had exactly the same metallurgical alloy composition of the thicker VH plates and the same somewhat inferior toughness, compared to KC n/A, during tests as the old VC and new VH did.

Regular thick VH plate, under US Navy tests after WWII, showed that it was, as mentioned, a somewhat-improved version of the WWI-era Vickers Cemented (VC) armor that the Japanese had adopted from the British Vickers Company in 1912 when they had the IJN KONGO, their first large battle-cruiser, made there. These tests of the thick regular VH armor showed that it was somewhat inferior to US WWII Class "A" face-hardened armor, but no terribly so, being similar in grade to US WWI-era average Class "A" armor. Indeed, the regular VH showed itself to be the best non-cemented face-hardened armor -- this means that it had no thin super-hard "cemented" (case hardened) surface layer added as was used in almost all other 20th Century face-hardened naval armors -- ever used on warships (the US Bethlehem and Midvale Non-Cemented Class "A" armors used prior to WWI were of spotty quality and production was immediately ceased by both companies when they started to make the usual cemented KC armor type starting around 1910-12 and both of those US non-cemented types were definitely inferior to VH or any other WWII-era face-hardened plate).

This thin VH plate, on the other hand, was much better than regular VH; in fact, it was THE BEST FACE-HARDENED PLATE EVER TESTED BY THE US NAVY for any scaled-thickness type plate made by any country, US or foreign, hit by any scaled-size projectile, US or foreign.

What happened to the projectiles fired against it is what determined that plate's superiority. The plate was hit by two versions of a single form of new US Navy AP projectile, the 335-lb 8" (203mm) Mk 21 MOD 3 (early WWII through 1944) and MOD 5 (1944 and after). Both of these projectiles were essentially identical in all respects but one: The MOD 3 had an oval nose and a very thick, 17% of projectile weight, AP cap that was otherwise of standard type used by all other late-WWII US Navy AP shells, 555-580 Brinell Hardness Number (BHN) for most of its forward volume going down to about 225 BHN in a thick layer just above the projectile's nose under the cap (this non-uniform hardness contour was widely used by all hardened AP caps through the end of WWII under an incorrect idea that the AP cap somehow "cushions" the projectile nose when it impacts a face-hardened plate). The MOD 5 had the same projectile body as the MOD 3, but the AP cap, though shaped and weighing the same as the MOD 3 AP cap, was totally new. It was made of a special "triple-alloy" using molybdenum that was hardened to 650-680 BHN everywhere (except a very narrow region touching the edge of the lower nose that was kept soft enough -- about 225 BHN -- to crimp into the ring of shallow pits in the projectile nose, as used by all US Navy AP caps as a safety precaution on top of the usual solder holding the cap on). This new-concept AP cap was based on a new and correct theory of hardened "cap action" where the nose of the projectile was much better protected by the cap when the cap destroyed a deeper portion of the plate's hard face before the projectile nose reaches the face, and this super-hard cap, as hard as the hardest face-hardened plate surfaces used by anyone, could destroy that hard face all the way through to the soft. tough back layer before the cap was itself destroyed in the process -- caps are designed to be sacrificial projectile add-ons whose whole purpose is to destroy themselves to prevent the projectile nose from being heavily damaged, usually due to shatter, by a face-hardened plate, which improves penetration markedly compared to uncapped projectiles under the same impact conditions. (In effect, "the best defense is a good offense.") In tests with US WWII "Thick Chill" (55% face) Class "A" face-hardened armor, the MOD 5 performed significantly better than the MOD 3, being at least as good as the best large-caliber US Navy AP shells, such as the 14" Mk 16 MOD 8 and 16" Mk 8 MOD 6, which were superior to most other, foreign or previous US Navy, AP shells as to remaining intact during penetration and being nearly equal to the very best foreign AP shells under all other circumstances (the British and German WWII AP shells had harder caps -- though not nearly as hard or as thick as the late-WWII MOD 5 cap -- and this was the reason that they were slightly better than the other, standard-hardness versions of capped US AP shells at low obliquity).

When tested with the 8" Mk 21 MOD 5 AP shell at 30 degrees obliquity angle (standard US Navy obliquity angle for armor testing in WWII), the plate was superior, as mentioned, to all previous plates so tested (it had a noticeably higher NBL velocity), but the AP projectile was able to penetrate just above the NBL totally intact, just as with any other plate type that it had been tested against. When tested by the MOD 3, however, the superiority was much greater (though here due to the projectile damage, not the intrinsic plate strength noted against the MOD 5) and the projectile that barely penetrated at just above the NBL (as determined by the a straddle of penetrating and non-penetrating hits) suffered the following very strange damage: The projectile was crushed inward radially and exited the plate back at well under the shell's original 8" diameter, lengthening in the process (hence the term "extruded" in the US Navy test report). The rigid upper end of the nose suffered some breakage, but the very tough centerline and lower body, designed to prevent breakage at highly oblique impact up to 40 degrees (well above any foreign test standard), held the shell together, otherwise, though ejecting the base plug in the process (these test shells all had an inert filler material replacing the explosive for the tests, as usual). This so surprised the US test conductors that they really could not figure out how that plate could possibly have done this due to the face being so strong that the projectile could not even widen it with a deep hole already made in it. Only with the MOD 5 cap, which destroyed the entire plate face all the way to the soft back layer over a wider area, could the projectile fit through the resultant full-diameter hole and remain undamaged. In fact, because of this result, the US test personnel had to admit in their report that they did not really understand how face-hardened armor works, since all of their prior ideas were shown to be false. What a result! The only good that came out of it was a major confirmation that their new AP caps were definitely superior to those used by anyone else (they were also used in the last versions, MODs 9 and 10, of the US Navy WWII 6" (152mm) Mk 35 AP shells, but never retrofitted to any battleship ammunition prior to all AP shells being rendered obsolete after WWII).

As an aside, this indicates that the Japanese metallurgists were second to none and could possibly have done the same to the thicker, production-grade VH armor, too, but were prevented from making such radical, and then-unproven, changes by circumstances in the 1930s and during WWII (lack of knowledge of how much better new foreign face-hardened armors had become). What the Japanese did to the US automobile and electronics industries after WWII shows that this talent was not an exception, but was the rule.

SHATTER

As mentioned, shatter is nose or, more usually, complete projectile breakup, spreading its pieces out from the original smaller impact point, prior to the plate suffering any significant damage due to the impact. At low obliquity it makes penetration of face-hardened armor, the first armor type designed specifically to make shatter occur, much more difficult -- actually, shatter effects are worse when it happens on impact with homogeneous, ductile armor, such as used on tanks, which is tougher and more difficult for a broken projectile to penetrate, but shatter requires a much higher striking velocity to cause it against such softer armor than against very-hard-surfaced, but also rather brittle, face-hardened armor. However, at higher obliquity angles, the breakup of the projectile means that the nose pieces bouncing off do not pull the rest of the projectile along with them, so the body can drill into the pit made by the nose and penetrate at a LOWER velocity than an intact shell could. While this happens with other forms of breakage, too, they occur later on in the penetration process and thus have much less effect to reduce the penetration at low obliquity or increase it at high obliquity. One thing about shatter is that it always includes the nose (though not necessarily the very tip of the nose, which is held together by being imbedded a short distance into the plate struck), which suffers some significant breakage, while other forms of breakage damaged (described below) can cause the lower body or base to break up without causing any damage whatsoever to the nose or upper body.

Shatter can have two major causes:

1) Impact shock when the nose tip is suddenly stopped by the plate and an intense, very narrow compression-wave spike is generated and moves backward from the nose tip at the extremely high speed of sound in the steel (about 16,000 ft/sec (5249 m/sec)) down the length of the projectile and inward in the plate, too, at a similar speed. This shockwave can move outward in a hemisphere in the plate until it hits something that interrupts its motion, resulting in a partially or, at the plate back surface, completely reflected shockwave coming back in the opposite direction. Partial reflections occur in laminated plates where there are sudden changes in the properties of the metal, sometime on purpose (Compound armor) and sometimes by mistake (too abrupt hardness steps in thick-faced face-hardened armor, or manufacturing hardness defects called "laminations" in all armors); these can be minimized by proper armor design. Complete reflections occur at the back surface of the armor plate (any small transmissions into the ship structure and air can be ignored as far as the penetration process cares), causing a large reflected shockwave that can add significant brittle-fracture-causing energy to the face from behind, while that face is still under major stress from the impacting projectile and, therefore, this "stab in the back" can definitely reduce the plate's ability to resist the projectile. In the projectile there is such a reflection point directly down the length of the projectile at the base of the nose in a chilled cast iron through-hardened nose where the hardness abruptly stops along a line at the nose base or, in more modern projectiles with much more gradual softening of the hard nose as one goes toward the base and thus no such hardness step if manufactured properly, at the tip of the filler cavity, which can take about as long or longer to reach in a long projectile as the reflection time in the plate. Thus, for our purposes, the shockwave in the projectile moving directly back from the nose toward the base can be ignored. However, SIDEWAYS in the projectile nose, there is no way for the shockwave to expand to any significant degree and it immediately reflects along the nose, this reflection moving from the tip toward the base of the nose where it meets the cylindrical projectile body, where it has its maximum possible strength, so that above the shatter velocity of the particular projectile/plate combination and impact obliquity, the reflected shockwave blows the sides of the nose outward like an over-inflated balloon -- as mentioned, sometimes the tip itself, which was imbedded in the plate a short distance, allowing the shockwave to exit it and go back into the plate, remains intact. Hence, the nose,

which is, after all, made of an iron-based metal similar to the armor it is hitting, will break up first when the shockwave goes above a certain energy content, depending on the striking velocity and rigidity of the surface of both the projectile's nose and the armor's face -- this is about 1000-1100 ft/sec (328.1-360.9 m/sec) as determined from British post-WWI tests of uncapped AP projectiles against thinner British Cemented Armor (CA) face-hardened plates (thin enough that they can be completely penetrated at such a low striking velocity by large-caliber AP shells) at right-angles, as an example of the maximum that even good AP shells can withstand against good face-hardened armor -- and the toughness of the projectile's hardened nose. In comparison, during early WWII, it was found that at right-angles, British high-quality uncapped 2-pounder (40mm) anti-tank gun's AP shot would shatter against half-caliber-thickness (20mm) medium-hardness homogeneous, ductile tank armor at about 2700 ft/sec (823 m/sec), plus or minus 100 ft/sec (30.5 m/sec), somewhat below the gun's muzzle velocity, showing that high-quality face-hardened armor, when it can be made in adequate thicknesses (these are always far above 20mm, though), is considerably superior in shattering ability, which is why it was used (note, however, when it does not shatter the projectile, face-hardened armor, being brittle, is usually inferior to homogeneous, ductile armor, most especially at high obliquity). I call this shockwave-induced shatter "Primary Shatter". It is the kind that occurs against both face-hardened and homogeneous, ductile armor, but only at highly-elevated striking velocities in the latter case, as the 2-pdr tests show.

2) If the projectile nose fails to destroy itself due to Primary Shatter, such as by using a soft AP cap to surround the nose and absorb the shockwave, destroying the cap but leaving the nose intact, it then will have the advantage against the older, more-brittle face-hardened armors and against any homogeneous, ductile armors, so it will not suffer breakup at all or at least until much later in the penetration, where its effects are muted. If, however, even when Primary Shatter fails due to a properly- functioning AP cap, the still-undamaged face-hardened plate is so tough that its face will not collapse in a brittle manner -- the plate face stays in one piece under the combined pressure from the projectile from the front and the reflecting shockwave from the back -- under the rapidly-rising nose-tip pressure of the no-longer-capped, but still intact nose of the AP shell, as more and more of the projectile body is "informed" of the impact by the shockwave moving from the nose down and throws its inertia into the penetration attempt, the result will crush the stopped nose tip literally "between a rock and a hard place". If the nose breaks apart first, before the plate face does, this will give the exact same results as Primary Shatter, though it occurs slightly later and takes longer to occur. I call this additional shatter-causing effect "Secondary Shatter". Note that this form of projectile nose damage rarely occurs against homogeneous, ductile steel armor other than with thin-nosed, light-cased, base-fuzed HE shells (US WWI railway-gun "Bombardment" projectiles, for example) or any brittle chilled cast iron projectiles, which can fail by either form of shatter. It also is very rare against face-hardened armor if a hardened AP cap is used, which gouges a deep hole in the plate face as it is destroyed and thus the plate virtually never can out-last the projectile nose when it comes to which one will break first. Secondary Shatter was the case when soft-capped shells, whose caps do not cause any significant damage to the plate (other than some surface flaking), hit improved, extra-high-toughness armor. These improved armors were most post-1930 face-hardened armors (other than VH) and in pre-WWI US Navy Midvale Non-Cemented Class "A" Armor and Austro-Hungarian Witkowitz KC armor. Later tests showed that US Navy soft-capped Midvale Unbreakable AP shells, which were immune to most WWI armors of any thickness at right-angles impact when first introduced around WWI, would shatter just like any other soft-capped shells against the new US Navy "Thick Chill" Class "A" armor introduced in the latter half of the 1930s and used through the end of WWII. Other tests showed that the Midvale Non-Cemented armor could only shatter the Midvale Unbreakable shells when the specific tempering process Midvale used for that armor was employed, while substituting the usual hardening and tempering processes

used by most other face-hardened armors in WWI caused the same Midvale plates, otherwise of identical thickness and steel quality, to fail dismally, just like the other WWI US Class "A" plates did against these projectiles. The later tougher shells and hardened AP caps that gouge deep pits into the face of face-hardened plates could counter the tougher armor, but not when using the older soft-capped shells, no matter how good they had been against the older, more brittle plate types.

Shatter at right-angles causes a face-hardened plate to act as if it were suddenly 20-40% thicker (depending on specific conditions) against a high-quality steel uncapped AP projectile, both as to holing and to complete penetration. As obliquity increases, the lack of the nose being able to control the motion of the projectile as it moves forward due to the projectile being in pieces (even if most of the lower body remains intact in "nose-only" shatter) makes the effects of increasing obliquity steadily go down until at about 55 degrees obliquity (if "pure" shatter with no other damage occurring too), for the average 30% thickness-increase-at-right-angles case, the shatter stops being a benefit (as to the plate resisting holing or complete penetration) and becomes a liability from that obliquity up. From that obliquity up, holing always follows the shatter curve, shifting from the higher-resistance intact projectile curve even if the projectile does not shatter, since the Universe always uses the lowest-energy path ("Law of Least Action") and the flatter shattered-projectile penetration velocity increase curve would allow less energy to penetrate, shattered or not. Note that this is not the case for any other kind of damage when a complete penetration occurs, so such non-shattered projectiles will continue to follow the no-shatter angling-multiplier curve with a higher velocity needed to penetrate. Thus, above the 55-odd-degrees value, the ability of an unshattered projectile to make a hole in the plate (HBL) will begin to rapidly diverge as an ever-increasing gap from the NBL. Other damage can adjust this, of course, so that the gap between the HBL and NBL may not be a simple predictable value under any case.

Shatter, for a given set of plate/projectile conditions (fixed plate thickness and fixed obliquity angle), once it starts to occur at a given striking velocity will NEVER stop if the striking velocity is raised, no matter if the projectile penetrates the plate or not (making a hole does not help since the projectile nose has already broken apart BEFORE the hole was made). For many kinds of non-shatter breakage, increasing the striking velocity to allow holing or complete penetration or, if a complete penetration already has occurred, to shorten the time that the impact forces are impinging on the projectile, especially at oblique impact, can reduce or even eliminate the damage. This is a good way to sort out shatter from other nose damage if you can reduced the damage by using a markedly higher striking velocity -- if so, it is not shatter.

Shatter almost always occurs when chilled cast iron projectiles hit even thin steel plates. The only exception to this that I know of is very thin pre-WWI steel "protective" decks where soft AP caps were added to chilled cast iron explosive shells intended to be fired by Coast Defense weapons, at long range from high-angle guns or at shorter ranges from very-high-angle mortars through the first few years of the 20th Century (when improved steel shells became cheap enough, they very quickly replaced these older, weak-body iron shells). Such large guns/mortars were not employed in any warships back then (many ship guns could not be elevated to even 10 degrees back then; even at the end of WWI, most ships had at most a 20-degree maximum). The caps worked here like they did for steel projectiles against face-hardened armor, but over a somewhat wider angle of impact range (up to maybe 45 degrees) due to the impacted thin steel deck plates -- many of them not even armor- grade steel -- denting deeply and holding the cap on, which did not happen against rigid face-hardened armor.

"Nose-Only" shatter occurs when something protects the projectile nose to restrict the initial brittle fracture of the hard nose tip in area in such a way as to reduce the spreading rate of the fracture such that by the time the entire nose is destroyed, the plate face has itself cracked through and the force on the projectile nose drops drastically, allowing the softer, tougher projectile material behind the nose to remain more-or-less intact (unless damaged later by other forces as the projectile moves through the plate) so that the explosive filler and base fuze function properly. This form of shatter almost never occurs unless the projectile completely penetrates and thus reduces the time that the resistance forces on its broken nose are applied -- if no complete penetration occurs, projectiles that have nose-only shatter when they completely penetrate will have complete shatter if they do not under almost every set of impact conditions. The tougher WWII-era KC-type face-hardened armors (US "Thick Chill" Class "A" armor, German Krupp KC n/A (and variants), British post-1930 CA, etc.) -- plus the pre-WWI Austro-Hungarian Witkowitz KC armor and US Midvale Non-Cemented Class "A" armor -- virtually never allow nose-only shatter under any condition where shatter happens at all; they are so tough that the face NEVER is broken through fast enough to reduce the full effects of shatter on the projectile when it happens. With the more brittle, mostly older face-hardened armors (US CKC, German Krupp KC a/A (all types), etc.), with strong, tough projectiles, even the higher-quality SAP-type Common projectiles, a thin Hood (a few millimeters of soft mild steel sheathing the tapered nose area and holding the windscreen) can act like a soft AP cap on the tip of the projectile nose. However, since the Hood is so thin, it cannot absorb the shockwave energy over the larger area of the nose behind the tip, so that portion of the nose suffers some major cracking due to the Primary Shatter effect. BUT, the short delay due to the tip itself remaining intact and hammering into the face like a center-punch cracks the plate face much like no shatter had occurred at all, thus, by the time the nose of the shell shatters from the major cracking lower down on the nose surface, the face resistance has suddenly dropped and in some cases the shatter damage will stop then if the projectile can completely remove the plate material in front of it before those nose cracks apply too much pressure on the upper body and split it open, too. This was discovered when early-1930s US 8" (203mm) Special (Hooded) Common projectiles were used to test some clandestinely-obtained 125mm (4.92") late-1920s German Krupp KC n/A plates of the initial thinner type used in the turret faces of the "Pocket Battleships" (not the later, much improved and toughened form of KC n/A used in the SCHARNHORST and BISMARCK Classes of battleship in the mid-1930s and after). These 8" projectiles shattered as expected on this armor, which is why this kind of armor existed, after all, but, interestingly, those shells that hit at a high-enough velocity to completely penetrate even with shatter, suffered only nose-only shatter, unlike any previous, bare-nosed form of Common projectile, with or without a windscreen (in those earlier Common projectile designs with added windscreens to reduce drag and increase the maximum gun range, the windscreen attachment screw-on threads were cut directly into the projectile's lower nose, which was found to weaken the nose due to excessive cracking on impact with thicker armor plates, though admittedly the thickest armor that these projectiles were expected to penetrate undamaged was much less than a heavily-constructed AP projectile with a much smaller explosive charge, even without this problem -- the addition of the Hood solved this cracking problem, allowing the maximum penetration ability possible for a Common projectile to be restored even with a windscreen added). Later tests against US WWII-era Class "A" plates, of higher toughness, never allowed this with these uncapped projectiles, penetrating or not, Hooded or not.

To illustrate why shatter has such a negative effect on the penetration ability of a projectile, I have the following perfect example:

In 1918 the new British Navy hard-capped, delay-action-fuzed, insensitive-filler ("70/30 Shellite") 12" Mark 7A ("VIIA" in these old documents) APC ("AP, Capped" in British terminology) projectiles were developed after the relatively poor showing of the previous generation of British soft-capped APC shells at the 1916 Battle of Jutland -- the older shells made holes in the Krupp plates exactly as expected, but other than blowing chunks of armor and projectile upper-body pieces into the space behind the armor, very few shells completely penetrated the armor first, so major damage was limited to hits on confined spaces like turrets and such where such holes could knock the targets out even without the shell itself penetrating, particularly in that newly-designed delay-action base fuzes allowing deep penetration behind the armor could not be added to the older shells, as designed. All older British major-caliber APC shells of all sizes (12", 13.5", 14", and 15"), which had only been tested at right-angles impact, were replaced with these new "Greenboy" shells (painted bright green to ensure no confusion with the older shells still in the supply chain) and two British steel companies (Vickers and Cammel) were considering putting in bids to make their versions of these 12" shells, in addition to the two companies (Hadfield and the English Ordnance Company (E.O.C.)) already making them.

A comparative test was performed with shells of each of these four manufacturers (actual or proposed) -- one APC shell each for Vickers and Cammel, two for E.O.C., and three for Hadfield -- fired at an 8" "Cemented Armor" (CA) face-hardened plate at the new 20 degrees obliquity angle requirement at well above the intact-projectile complete penetration velocity, similar to the new regular APC projectile acceptance test for these new shells, to see how good they were in comparison. The results were rather wildly varied, to say the least, which must have disturbed the British Navy testers considerably (ideally, all should have acted identically, since that is what was desired, after all!). (NOTE: A Russian 1040-lb 12" "tough capped" (not hardened, but otherwise I am not sure of what this means) M1908 (I think) APC shell type was also tested and one penetrated completely undamaged, while the other broke up during penetration, both at about the same average striking energy as the British shells; thus, even before WWI, Russia had shells only equaled at the end of WWI by the British -- only the new US Navy "Midvale Unbreakable" or "Midvale 1916" type of AP shells were better at 20 degrees obliquity, with also 50% remaining intact at this angle, though here this was even against face-hardened "Class 'A'" armor thicker than the projectile's diameter.)

Half (4) of the British 12" shells remained "whole" (the explosive filler cavity -- these test shells were inert-filled -- was still uncracked and the base plug still sealed it tightly), though with small or major nose or base damage after punching completely through the plate. In fact, only one of the four shells had virtually no damage ("entire" in British terminology and "excellent" in US Navy terminology). This was acceptable performance, since a shell in this condition could continue on into the ship hull and do major damage deep inside with a reliable delay-action base fuze, as these shells were now equipped, going through thin internal plates ("protective" deck plating or "splinter" bulkhead plating) designed only to stop blast and fragments that got through the main armor -- thick deck armor against the danger of downward-falling "plunging fire" from long ranges had only begun to be a problem at this time, since previously the guns could not elevate very much due to the inability to aim at any target outside of point blank range, with the new central director fire control systems with long-base rangefinders only just beginning to be effective at significantly longer ranges, requiring major heavy warship redesigns.

Three of the shells "broke up" -- one was noted to be "broken up badly", indicating that it was reduced to small pieces (not a good sign!) -- but they all completely penetrated with all of the shell fragments behind the plate, as required. Since the acceptance testing allowed a retest, then if the second one stayed whole, this was allowed, though an indication that the manufacturer had better make some improvements or there were going to be some expensive failures in the future (manufactured projectile lots rejected).

Looking at photographs of four of the holes made in the plate by the above seven shells, they were only slightly oval, with smooth round edges, whether or not the projectile broke up, indicating that the shell damage occurred AFTER the hole had been made (or at least almost completely made). These holes were slightly larger than the 12" projectile diameter; for example, one typical hole was 12.5" x 12.3", with even the widest being only 15.1" x 11.95" (it was the shell that broke up "badly" in this last case, which is why it could fit through a slightly narrower hole).

One E.O.C. shell, however, obviously suffered complete shatter (a VERY poor result!), only making a partial penetration (a hole with broken projectile pieces "front and back") at about the same velocity that the other shells were completely penetrating with negligible pieces in front, even that badly broken shell (I assume that the shattered shell could be considered badly broken too!). When applying my FACEHARD v8.0 program, I got the same partial shattered penetration, as opposed to complete shattered penetration, result if I increased the plate quality by only 1%, indicating that the plate was very slightly superior to the average of all plates that I used to set the quality of this kind of British CA in FACEHARD, which is completely expected (an average has plates both better and worse, by definition). The hole made, however, was quite different with shatter: 18.15" x 20.1" (I also assume that the hole was more irregular in shape, no longer a smooth oval, since that is what typical shatter holes look like). This gives a considerably greater weight of armor involved in trying to stop the projectile and drastically adds to the needed striking velocity -- FACEHARD for the more brittle average face-hardened plate type of that time period assumes that the plate against a shattered, but otherwise identical, projectile will now act like it was 30% thicker at right angles than it does against an entire/ excellent one, which is more like 27% thicker at 20 degrees (shatter suppresses ricochet so angling plates does less to increase resistance, especially at very high obliquity angles).

Note that the effective increase in plate thickness of 20-40%, depending on projectile and plate types, at right-angles used in FACEHARD for KC armors is less than the gain with homogeneous armors under similar impact conditions, which may be well over 50%. With hardened, high-strength-steel, flat-nosed cylinders tested at right-angles against high-quality high-tensile-strength steel plates of thicknesses up to 1.1 caliber, the projectile remained undamaged through 1-caliber plate complete penetrations, but when the 1.1-caliber plate was used, the projectiles shattered completely, making a deep, flat-bottomed, widened pits in the plate, but no holes. The striking velocity was then raised quite a bit and no noticeable change in the results occurred. Since below the shatter thickness the penetration versus striking velocity graph was quite smooth and nearly linear, one could extrapolate for a 1.1-caliber-and-up plate if no shatter had occurred and the increase in striking velocity attempted in later shots should have allowed a very thick plate to be penetrated without shatter, but here without success. A tough, ductile material, like high-quality homogeneous armor, resists a shattered projectile very much better than a brittle, hard material, like the face of a face-hardened plate. What the general rule is I do not know since the amount of velocity increase to allow penetration of that 1.1-caliber plate with shatter in that test series was never reached.

If shatter involves the explosive filler of the projectile, the crushing of the upper end of the cavity or the entire cavity as the shell flattens out on the plate face prior to penetration, if it occurs, will usually set off even the most insensitive filler types (US Army/Navy Explosive "D" until after WWII) in a low-order explosion that can range in power from merely shooting out flaming filler like a Roman Candle to a very powerful explosion, though a detonation as from a properly-functioning fuze and booster will be very rare. No internal target damage behind the plate due to this explosion and its incendiary effect will occur unless the projectile makes a hole in the plate through which the blast and flaming filler pieces can shoot into the target. If so, the toxic fumes of even such a flaming Roman Candle can cause the nearby spaces to be abandoned, so the results, while not as damaging as an intact projectile penetration, can still be effective in partially disabling the target hit. If a "low" explosive like black powder is involved, the breakup of the shell will be so fast that the relatively (compared to HE) slow-burning black powder will usually not be able to do much exploding at all before being spread apart, so much more flaming incendiary action will happen and very little explosive effect, with or without a hole in the plate.

A final point about shatter: Though not really applicable to Harvey or KC face-hardened armors against the usual naval anti-ship penetrating projectiles (AP and SAP), which shatter all uncapped shells except for sometimes the most minimal impact conditions -- such as the toughest shells hitting at near right angles against plates under half-caliber in thickness -- shatter occurs at a progressively lower velocity as the impact obliquity increases, so that at about 60 degrees and more, the shatter velocity against a given plate type and thickness will drop to around half of the velocity needed at right-angles (roughly). The purely compressive force of a shockwave/momentum increase moving inward into a shell from its tip along the projectile centerline at right-angles where the force is balanced in the sideways direction allows a stronger response from the shell to the impact -- even brittle cast iron can handle such forces, which is why it is still used in heavy supports where downward compressive forces are the only ones expected. As the angle of impact goes up, however, the forces on the impact side of the projectile increase both in magnitude and cross-wise direction, so that the metal in the projectile has more shearing (bending) stress put on the region touching the plate and around it, reducing the ability of the metal to resist being deformed and, in a hard, brittle material like the upper end of an AP shell, cracking. Once a crack "gets its foot in the door", the metal sides around that crack now are separated and less able to resist further cracking, leading to a catastrophic avalanche of expanding breakage until the shell hard nose region breaks completely apart, taking the rest of the shell with it in most cases (complete shatter). Shattered glass is a perfect example. This includes a "creeping shatter" that can happen to an automobile windshield that has a tiny crack put in it by a rock and, over an extended time, the cracks expand until they split the windshield in two. The point of the crack has a concentration effect that multiplies the forces there and can break even quite tough tempered glass, given time.

OTHER BREAKAGE

As noted in the discussion of shatter, above, the hole made in the plate is of a different shape and size in most cases when shatter occurs than if either no projectile damage occurs or other forms of projectile breakage occurs. Also, shatter always includes the projectile nose, where it starts, while other breakage can occur anywhere in a projectile, most especially under the bending forces of an oblique impact where some or even most of the force is at right-angles to the projectile centerline and/or direction of motion through the plate hit. Finally, there are only two forms of shatter, where the projectile's hardened nose is only involved, rather rare nose-only shatter, and complete shatter, where only the projectile lower body and base, if that, remain intact, but for other breakage the amount of damage may run from barely noticeable to complete breakup virtually indistinguishable from complete shatter. The effects on the projectile's explosive filler if the breakage includes the filler cavity will be identical to that of shatter, as mentioned above, though only the most extreme breakage will cause the more explosive results of complete shatter.

I. NOSE BREAKAGE

Breakage of the projectile nose is due to forces much like those that cause Secondary Shatter (see above), but being slower to build up to the breakage point and thus occurring while the shell is passing through the plate instead of prior to the shell moving into the plate, as with shatter. The shorter the time that these forces can act, the less damage that they can cause, so increasing the striking velocity above the NBL (but below the shatter velocity, though this velocity is usually always exceeded by an uncapped projectile fired at a face-hardened plate in a naval battle, so shatter would always occur instead in that case) can shorten this time and even result in the projectile no longer suffering any significant damage whatsoever. I call this higher velocity where a broken projectile with a compromised explosive filler or fuze no longer has this damage (though it may still have all other forms of damage) the "Effective Ballistic Limit" (EBL) and it is just my estimate from various test results when such might occur in the given situation -- shatter precludes this, and it may be above the gun's muzzle velocity even when bad non-shatter breakage occurs.

The best example of this is just inside the entrance of the US Naval Surface Warfare Center, Dahlgren Division, Dahlgren, Virginia, previously known as the US Naval Proving Ground (NPG) from 1917 through the end of WWII:

Figure 1 - USS Alabama (BB-60) Armor Test Plate. Photograph courtesy of NSWC, Dahlgren.

There a huge 19"(482.6mm)-thick Class "B" (homogeneous, ductile) turret port (face) plate used as the Plate Acceptance Test plate for a lot of plates for the USS ALABAMA (BB-60) turret armor on a concrete slab to the left and just inside of the entrance. It has two huge holes in it from 1500 lb (680.4 kg) US Navy Crucible Steel hard-capped 14" (355.6mm) Mark 16 MOD 8 AP shells, the standard shell used in most such heavy plate testing at NPG during most of WWII (and one of the best naval AP shells ever made by anyone).

The hole on the left is empty with the 14" shell that made it originally standing next to the plate on its left (it is now gone, while an older, fired and similarly undamaged, 2110-lb 16" Mk 3 AP shell is now on the right side). It hit at above the NBL and passed through with some Remaining Velocity. Other than the loss of its AP cap and windscreen and the deep slanted grooves in its copper driving band, the 14" penetrating projectile was entirely undamaged, barely scratched from punching through that huge plate at a 30-degree angle (from right-angles), the WWII US Navy standard plate test angle.

On the other hand, the right-side hole made under identical impact conditions, except for a lower striking velocity just below the NBL, has the projectile imbedded in the plate with only its lower one-third or so still inside the plate and the upper end of the projectile, again minus its AP cap and windscreen, projecting out the plate back at a small angle. The bottom of the projectile is a couple of inches (~5cm) inside the hole from the front surface. The projectile is *wrecked* (that is the only word for it). The hard, blunt, oval nose has some chunks missing and large cracks radiate into the body of the shell. The ductile and very tough, middle and lower body of the shell is split lengthwise nearly in two with the opposite sides offset sideways slightly. The base plug is gone, having been spit out like a seed in a lemon wedge squeezed over a glass of ice tea as the lower body was crushed and split apart; it is missing from the display, possibly broken into pieces. This projectile would not have exploded, with its filler, possibly burning due to being pinched as the body split, following the base plug out of the projectile bottom. Note: There is a very good chance that the turret would have been knocked out by this hit anyway, since much of the armor displaced would have been punched out the back by the very blunt nose and flown backward into the turret at a high speed (and there was a LOT of armor displaced in such a large plate!). At best, after some time replacing dead crew and fixing things, at most two of the three guns would have been all that could be brought back on line, well after the battle was over. The hit, while not a devastating as a complete penetration by an intact shell, would have been good enough to knock out that turret during the current battle and, possibly, depending on what was broken inside the turret, until repaired at a shore facility.

This huge difference in the damage suffered by the two shells is completely the result of *the difference in the time* that the forces set up by the extremely thick armor (not even a face-hardened plate, note!) had to work on the projectile -- only a short time for the left projectile and essentially an infinite time (until the projectile stopped moving completely) for the right-side impact. As you can see, the time difference in how long the forces will act on the shell can cause all sorts of major effects to happen on the projectile suffering them for the longer time, with the shorter time possibly preventing, as here, any effects at all. This makes analyzing damage rather difficult, especially with homogeneous armor, as with this test, where the results can gradually increase or decrease with the striking velocity rather than the more "all-or-nothing" effects of the hard face of a face-hardened plate, which is simpler to calculate.

Now back to the main discussion.

Nose damage happens by compression from forces down the projectile centerline or bending forces from the side that is touching the plate on an oblique impact. For strong hardened and tempered noses of steel projectiles, compression breakage damage to the nose is minimal, but for the original chilled cast iron AP projectiles -- originally developed by The British firm of Palliser and the German firm of Grüson (the latter also made immensely strong dome-shaped turrets for land forts with this material) -- used widely in the US Civil War, the hard nose was formed by pouring the projectile into a mold with the cylindrical projectile body surrounded by a regular sand mold allowing slow cooling to standard grey cast iron, but the entire tapering oval or ogival nose was in a mold formed by thick wrought iron, which had a much higher melting point, with water cooling behind it at times. The nose thus cooled extremely rapidly to white cast iron, which was very hard, but also very brittle (regular grey cast iron is brittle too, but it can survive even moderately hard handling when used in, for example, home frying pans, which would not be possible for pure white cast iron not supported by a thick layer of grey cast iron to soak up impact forces). The joint of the two molds was a sharp line at right-angles to the projectile centerline just below the beginning of nose taper. This technique is termed "Through Hardening". The reason that this nose worked was that it was only used against the very soft wrought iron armor of the time and that when you cut one of the noses in half lengthwise and etched it, you saw many narrow radiating lines of crystals from the center of the lower nose to the surface of the nose, all of identical properties from the center to the surface, so that the grain looked like a very narrow-fibered fan, which was quite strong against compression forces at right-angles to the nose surface. At low obliquity, the impact would severely compress the nose, making it stronger and less brittle, until it had passed entirely through the plate, at which point the nose would decompress and usually break to pieces (the lower body almost always broke up during the penetration, but in most cases it was only there to provide weight and inertia to force the nose through the plate). Only if thin wrought iron armor was hit at very close to right-angles would a black powder filler, as sometimes was used, remain in one piece and explode behind the armor, with the usual result being a broken shell behind the plate with flaming fragments of black powder and a rather weak explosion, if a hole was made entirely through the plate hit. Many Civil War AP projectiles were solid shot for this reason, so maximize mass and minimize weakness until the penetration was done. For this reason the German Navy refused to put any explosive filler in their AP projectiles ("Panzer-granaten" or "Pzgr.") until 1902 when they introduced block TNT fillers, changing the projectile designation to APHE projectiles ("Panzer-spreng-granaten" or "Psgr.") -- with an AP cap this added the term "with AP cap" ("mit Kappe" or "m.K.").

With face-hardened armor, other forms of nose damage can occur, such as "chewing" where the outer surface of the hard nose is ground off against the hard plate face, resulting in an irregular blunted nose and many small pieces on the ground surrounding the hole.

All of these forms of nose damage, unlike shatter, decrease as the projectile hits the plate at a higher and higher velocity over the NBL and the time spent touching the plate decreases. They can raise both the HBL and the NBL somewhat since this damage occurs most strongly when the projectile is hitting the plate at just below the HBL and only begins to fall off after the NBL is exceeded, sometimes abruptly, as the 19" plate example above shows. Such damage that is greater at below the NBL than just above it distorts determining the Plate Quality Factor since it becomes difficult to figure out how much plate resistance is due to the plate itself and how much is due to the weakness of the projectile. When this happens, more test results using different projectiles are needed to work out an average, with shells that have previously been given a reliable Projectile Quality Factor against other plates being the best for this analysis.

Oblique impact causes more nose breakage than compression forces at near-right-angles impacts. The sideways forces on the nose try to fold it away from the plate, rotating along a fulcrum on the lower portion of the far side of the nose, which can cause cracking much like breaking a wood plank on one's knee. The nose failures from these causes usually result in the nose upper portion shearing off either at right- angles to the centerline or along a slant plane, frequently at 45 degrees, taking anything from just the tip to the entire nose with it. As with compression damage, how much this affects the HBL and NBL depends on when it occurs as the projectile is digging into the plate. As with compression damage, the higher above the NBL you get, the less likely and/or less widespread that this damage will occur, again due to the reduction in the time that the forces impinge on the nose.

II. BASE BREAKAGE

Base breakage can be caused by higher-up projectile damage moving downward, as with complete shatter starting in the nose. The 19" plate case above has base damage mostly due to the splitting of the middle body in two lengthwise down to the bottom of the projectile and the two halves moving apart and sideways like scissor blades, allowing the base plug to be ejected and the base deformed, not due to independent damage at the base itself.

Base breakage that is independent of any damage to the rest of the shell is almost always caused by the projectile changing its direction of motion due to the sideways forces of an oblique impact, pivoting the shell on its nose so that the lower body and base swings sideways and hits the plate like the moving end of a baseball bat, base slap as previously mentioned. This requires major design changes to a projectile to minimize. Such changes are: A deeper length of threaded area of the base plug to the lower side of the explosive cavity (making the inside face of the base plug cup- or funnel-shaped); use of thicker, deeper, less-pointed threads holding the base plug; moving the threaded area high up inside the cavity and an air gap between the base plug lower sides and the inside of the very bottom portion of the cavity opposite the deep groove in the outside of the projectile cut to hold the driving band, which will weaken the projectile base there; making the lower body relatively soft and tough to allow some deformation without cracking; and so forth. If the shell is bouncing off, this base slap impact is on the same side as the side that first hit the plate, but if it happens during a holing or complete penetration, then the rotation is the opposite way and the lower body and base hits the far side of the hole in the same powerful manner, pivoting on the nose. These impacts, especially when the deflection is great (approaching 30 degrees or more), can flatten the side that hits the armor and even split it apart, as with the 19" plate case. This can also eject the base plug as the base plug is compressed and then rebounds with the threads no longer in their matching groves and/or it can crush the base fuze as the base plug is damaged, usually causing the fuze to be non-functional so any explosion and fire is due to the filler being crushed, not by fuze action.

The brittle bases of, for example, chilled cast iron projectiles at even right angles can break when the impact shockwave from the nose reflects from the base, though this will usually only be of any significance against thicker plates of wrought iron armor, especially at oblique impact, where the projectile does not completely shatter on the plate face, such as, as mentioned above, hits against thinner wrought iron armor or, with an AP cap at zero through moderate obliquity, very thin steel decks. If the brittle chilled cast iron projectile meets with any serious resistance that causes a major deceleration as it moves through the plate, the projectile will usually suffer breakage in the nose or middle body, with the base being broken up from cracks radiating from there, not from damage starting in the base itself. Any significant change in the chilled cast iron projectile's direction of motion at it penetrates will cause such brittle shells to break up due to base slap, which is why only very thin steel plates could be penetrated at low-to-moderate obliquity, where the impact velocity was always going to be well above that needed to penetrate such plating if the shell remained intact, even when an AP cap was used exactly like those used on major all-steel AP shells against thick face-hardened armor during the same time period.

Therefore, other than with very brittle chilled cast iron projectiles, most base-only damage to AP shells is due to base slap and inadequate attention to minimizing the high sideways forces involved or when the impact is against a plate the seriously exceeds the strength of even the best designs -- such as the above 19" plate against the US 14" shell that did not penetrate, though even here the base damage and ejection of the base plug was partially due to the cracking open of the cavity higher up in the shell body allowing the two sides to move somewhat, dislodging many of the threads holding the base plug.

III. MIDDLE BODY BREAKAGE

Breakage that starts in the projectile middle body instead of the nose or base, has several major causes:

(1) Middle-body slap, higher up than base slap, that happens when the rotation is faster compared to the remaining forward speed of the projectile so that the plate impact -- on the face when ricocheting or against the far hole side near the face when penetrating or sometimes on both -- is higher up the projectile so that the base is still projecting out of the face by some distance. The former, face surface slap would be when the projectile has dug into a thick homogeneous, ductile (deck or turret roof, usually) plate for some distance but the bent-upward armor spur forming over the nose tip (this cannot happen with a face-hardened plate) has not yet gotten thick enough to counter the ricochet forces, so the middle body slams onto the dented, gouged face that the nose had already ploughed through, but the projectile is long enough to have its base overhang this sloped gouged area with no support, not touching the flat face below the end of the gouge. The latter hole-side slap occurs as the projectile is punching through the plate and rotating in the opposite direction. Either case causes a major stress on the impact side of the shell, especially at the corner where the overhanging base tries to keep rotating and the middle body is suddenly stopped by the plate, bending the shell and cracking it at this corner like breaking a piece of wood over one's knee. Since the pivot point is closer to the corner, the rotation forces are less when the shell side is stopped than a true base slap at the other end of the entire projectile, but the inertia of the overhanging base can concentrate the force at the corner where the plate contact ends and make things worse. As with base breakage, it is critical that the hardness and toughness of the steel body be balanced to minimize the chance of cracking, but also prevent excessive bending, since a bent shell will not fit through the hole that the nose is making and the region at and below the bend will thus undergo major increases in stress that a projectile body weakened by base slap damage may not be able to resist, tearing the projectile apart. Shaping the internal explosive cavity to gradually narrow it, thickening the shell body at the sides, as one moves toward the nose can

increase the strength of the shell middle body against both nose damage and middle-body slap. Chilled cast iron projectiles cannot take either kind of slap, limiting them to low obliquity against plates of any substantial thickness or up to moderate obliquity against very thin plates hit at well above the NBL -- only the latter case can allow an intact penetration of such shells against any steel armor and only here when they have an AP cap. As might be guessed, the maximum amount of damage from this cause is around 45 degrees, where at and somewhat above the NBL the projectile is violently rotated to near right-angles to the plate back when it exits, breaking even high-quality projectiles that usually remained intact at obliquities under 40 degrees or over 50 degrees -- US Army 0.30-caliber machinegun M2 high-hardness bullet central AP cores, for example, where a friend of mine with such bullets, fired several of them both point- and base-first into annealed 4140-steel plates of half-to-full-core-diameter in thickness and they almost always broke up at this 40-60-degree obliquity range, though usually remaining intact outside it if a complete penetration occurred.

(2) Another problem with chilled cast iron is that the projectiles were "through hardened", which meant that the nose was hardened to a single high hardness (as high as white cast iron allowed, that is), but the hard material suddenly stopped along a line at or slightly below the forward bourrelet at right-angles to the centerline, with regular, much weaker, but still very brittle grey cast iron from there to the bottom of the shell. When the shell punched through a moderately-to-very-thick wrought-iron plate at low obliquity, the nose could remain intact at least until most of the nose passed out the far side, but the initial impact compression shock would run through the white cast iron nose into the grey cast iron body, where the mechanical properties of the iron were somewhat different. Much of the shockwave would pass through this sharp boundary, removing it as a source of damage to the hard nose, but some would reflect, as is normal with shockwaves moving from one medium to another. This reflection, if strong enough, would cause the stepped boundary to crack and the nose and body separate into two pieces, and as the penetration continued, this cracking would rapidly spread through the projectile body and cause the middle body to break up, taking the base with it as the cracks raced backward from the nose/body joint. Such cracking will also occur whenever there is such a sudden change in a property, such as hardness in any medium, including steel. German AP ammunition, even the best that they made during WWII, had a sheath-hardened nose (hardened like a coconut, getting softer near the middle of the lower nose until it reached the same hardness as the lower body just above the forward bourrelet at the centerline), but this outer high hardness at the projectile surface suddenly stopped, dropping in a single step from the highest level, the nose tip and outer surface, to the lowest level, the middle and lower body. As such, US post-WWII testing at 30 degrees against roughly caliber-thickness face-hardened armor, the same as was used for US AP shell testing, showed that these projectiles had a distinct probability of breaking up during complete penetration at and just above the NBL, requiring a somewhat higher velocity to penetrate intact, with cracking starting at that nose/body surface point. The German penetration curves in the 1940 German Navy's document G.Kdos. 100 (Secret Command Document #100) show the same thing, using two curves in each face-hardened armor penetration curve set, the lower one for estimated broken complete penetrations and a higher one for intact complete penetrations, with the gap getting bigger as obliquity increased. US WWII AP shells also had a sheath hardness pattern, but the hardness on the surface and just inside dropped much more slowly as one tested it down the projectile side, only reaching the internal lower body level about halfway down the shell to the base and thus preventing the sharp surface hardness step that the German shells had problems with.

(3) What I call "upset body failure" at low obliquity of projectiles with very large explosive cavities but heavy, AP-shell-like noses, including some with AP caps (British WWI-era Common, Pointed, Capped (CPC) projectiles, for example). If the projectile hits at a velocity where the penetration rate is

slow enough that the compression of the middle body by the inertia of the base and the slowing of the nose exceeds the Yield Strength of the thin steel casing making up the middle of this shell, then this causes the thin-walled, light-cased middle body to compress (upset) and bulge outward and, in the worst case, then fold up like an accordion pleat, crushing the filler, usually with low-order explosive results, and forcing the shell hole to be wider to allow the middle and lower boy of the shell though (assuming that it has not yet blown up). By this time, the heavy AP-shell-type nose of the shell, if hitting above the NBL, has already punched through the plate. This middle-body bulging and collapse requires a higher striking velocity to speed up the penetration so that this does not occur (at least to the point of the folding setting in) before the shell upper body makes it through the hole and the plate resistance drops precipitously (the hole is now opened up about as much as it needs to allow the entire shell through and any further enlarging is due to the rotation of the shell as it moves forward at an oblique impact -- though such a thin-walled shell cannot take much of such rotation without major base or middle-body slap damage). Thus, the HBL is increased somewhat and NBL is increased even more for such a shell suffering from this effect and against all but thin plates (up to one-third caliber in the case of CPC, for example); the shell will break up during penetration of such thick plates in any event, but after the penetration is almost complete at the NBL and above.

(4) Deflagration (rapid burning of the filler like a Roman Candle that will cause enough gas pressure inside the shell to split open the projectile body or, at least, blow off the base plug, releasing flaming filler material and toxic fumes around the projectile) or an explosion of the filler during the penetration process due to excessive sensitivity to impact shock (usually a near-maximum-power explosion similar to that with a properly-working base fuze) or from deformation and cracking of the body around the filler of the projectile that pinches, scrapes, and squeezes a sensitive filler enough to set it off (this explosion is usually only a low-order explosion of an HE filler, though black powder fillers, that are low-order explosives to begin with, may be set off much as with a properly-functioning base fuze). The deformation-caused effects are much like a brittle chilled cast iron projectile filled with black powder struck the plate and the powder was set off, though HE fillers tend to release a lot of toxic gases when they burn; much more so than black powder does. The damage to the projectile middle and lower body is increased by low-order effects, usually to the point of leaving only the thick nose and base plug of the AP or SAP projectile intact.

There are three major exceptions to the explosion being a low-order one when set off by the impact:

(a) The powerful (10% greater than TNT) explosive trinitrophenol (A.K.A. Picric Acid, British Lyddite, French Mélinite, Japanese Shimose) would detonate high-order due to impact shock on impact 90% of the time with any face-hardened plate under all impact conditions or even when hitting a homogeneous, ductile armor plate of half-caliber or more in thickness at right angles. Base slap during oblique impact of homogeneous, ductile armor (not face-hardened armor) might require a somewhat thicker homogeneous plate to set off Picric Acid when hitting this relatively soft armor at a higher obliquity where the deceleration is over a longer time. The effect of this sensitivity was identical to the effect of using its original non-delay base fuze (0.003 second delay due to inertia). No amount of cushioning could make this explosive remain inert against thick armor when trying to use a delay-action base fuze, as the Japanese found when they tried again and again until 1930 with their modified British-designed post-WWI APC projectiles (originally called "Mark 6" or, later, Type 88 (for the year 1928)).

(b) At this point the Japanese gave up and in 1931 they introduced trinitroanisol (TNA, which they called "Type 91 Explosive" after the Japanese year that it was introduced (1931)) as their new HE filler for both new nose-fuzed Type 0 HE shells and their new super-long-delay, delay-action-base-fuzed Type 91 APC shells. This explosive, about a powerful as Shimose and previously only used rarely by Japan and Germany for torpedoes and mines, was barely able to remain inert when penetrating thick armor in the Type 91 shells when encased in a thick plaster, wood, and aluminum case that filled from 33% to 40% of its volume (depending on the shell size) at the front and sides of the shell's internal explosive cavity, making the total amount of explosive much like the smaller amounts used in WWII by the US Navy AP and Common shells (where penetration came first and explosive power was secondary, since the US Navy AP and base-fuzed Common shell designers reasoned that failure to penetrate the armor made the shell hit almost useless). Since the large cushions in the cavity did not strengthen the shell from impact damage, this Japanese AP/APC shell design seems rather odd. I am not sure why the Japanese did not go to a much less sensitive explosive, as all other nations did just before, during, or just after WWI -- US Explosive "D", British Shellite (Lyddite with a 30% by weight mixture of the low-power, insensitive explosive dinitrophenol as a desensitizer) or, for smaller shells, TNT with beeswax, French M.F.D. (a Shellite-type filler, but with 20% by weight of a different weak explosive call DNN to desensitize the Mélinite), and German multiple pre-cast blocks of TNT with thick linings of felt and paper around each block and a large wood cushion in the tip of the cavity. It seems that the Japanese Navy had a cultural thing about high-power explosives after the success of Shimose AP and HE shells against the Russians in 1904/05 and were ordered by somebody at the top of the Navy to retain Shimose until it became completely clear that it could not be used with delay-action-fuzed AP/APC shells hitting thick armor, at which point they then were ordered to use the next most powerful explosive that could barely be kept inert, which was TNA even if it meant giving up a very large part of the filler to do so (this is crazy from a technical standpoint, of course). While this explosive was able to penetrate thick armor nose-first, battle results showed that when the shell suffered powerful base slap against face-hardened armor when ricocheting, it would detonate fully high order just like Shimose as the shell lower side slammed into the plate and deformed, since the much thinner inner cavity plaster cushion along the sides of the cavity was not thick enough to prevent this.

(c) Up through the end of WWI, British battle-cruisers and battleships had CPC, as mentioned above, for use against smaller and more-thinly-protected armored cruisers, reserving APC for use against other large heavily-armored warships (mostly assumed to be Germany, though until just before WWI, France was also a potential threat). CPC was filled with 10% by weight of compressed black powder and thus was a rather long projectile with most of its length behind a thick AP-projectile-type nose with a soft AP cap being rather thin-walled, to keep its total weight the same as the much-more-heavily-constructed and shorter APC shells -- at that time the new ballistic computers for aiming the guns could only compute one trajectory (had only one set of gears and other internal devices), so the CPC shell was designed to give roughly the same trajectory as an APC shell at some fixed medium range, while at other ranges CPC fall-of-shot would be more and more in error, but the guns at that time mainly used the spotters with their telescopes to see where the shells actually hit and to tell the computer operators to adjust their aim-point, so after the first few salvoes, the calculators were firing at offset aim-points anyway, not where the range-finders were aiming (unless they lost the target or were told to switch targets), so the range-finders were only being used, anyway, at the start of an action to get somewhere near the target, never in the middle of the action, so using APC or CPC did not matter.

Black powder, when set off by its base fuze after penetrating a thin cruiser-thickness plate at low obliquity where the shell could stay intact, would take a rather long time to build up pressure in the shell to blow it open, so that CPC shells would have usually a 0.025-0.075-second delay, even with a non-delay base fuze similar to that used with the APC shells, before the shell exploded, going very deep into the target ship's hull before causing its major damage. Also, the explosion was rather of low power, throwing relatively few and rather large chunks of projectile body at a rather low velocity from the sides, with the thick, AP-like nose remaining in one piece, so that the shell acted much like a shotgun inside the target, with a cone of heavy fragments surrounding the heavy projectile nose, which remained intact against such thin armor, plus a large amount of flaming black powder in the region of the target where the shell initially exploded, having a large incendiary effect there.

APC, on the other hand, with its 3.3% or so of very powerful Lyddite HE detonating (supersonic burning rate) explosive, was reduced to many small, high-speed sideways-thrown fragments forming a heavy-damage-causing ring of blast and fragments at roughly right-angles to the shell's nose, with only the base plug and the upper part of the thick nose still being in a larger chunks and only the few large nose pieces still doing any damage in the forward direction, but the nose fragments' rather light weight compared to the usually intact solid nose of a CPC shell allowed the internal layered light armor to stop most of these APC nose pieces, too. Thus, CPC caused deep damage with high incendiary effect due to burning black powder being thrown around, while APC, which at that time had no delay-action fuze, would completely destroy the space just behind the armor plate just penetrated, but do rather little damage deep into the ship hull if hitting the thick waterline belt armor. This APC filler and fuze combination was good enough for hits on turrets and other such confined spaces, but against the layered internal light armor ("protective/splinter" bulkheads and decks) used in the large ship hulls, the deep damage it could cause was quite limited or negligible (at the Battle Of Jutland, several German AP shells that penetrated the hulls of British warships and exploded in the side coal bunkers caused so little damage that a number of them were not even known to have happened until after the battle).

After the battle, some major investigations were undertaken to find out why some less-than-desired results seemed to be due to problems with British AP shells, in addition to why some British battle-cruisers had blown up during the fight (a different investigation). It was found that the testing specs for the APC shells had not been updated from the old cannon balls against wooden ships concept still in use when the first British ironclad HMS WARRIOR was commissioned in 1859, where hull hits with solid shot were supposed to punch holes to create leaks, with minimal internal damage-causing ability expected against the thick wood hull supports in such heavy "ships of the line". Nobody had told the projectile designers and manufacturers that the object of the later shells with powerful HE fillers was major INTERNAL enemy target damage WELL BEHIND the hull armor, so they were still designing and testing their APC shells for major waterline ARMOR PLATE solid-shot-like damage, with the shell's detonation in many cases happening while the shell was still going through the thick belt plate, making a bigger hole (as specified), but doing little to the ship's hull equipment behind coal bunkers and protective plating layers.. This rather shocked the British Admiralty's group of civilian investigators. It lead to a complete redesign and re-specification of both APC and CPC projectiles in the middle of WWI (which was a quite expensive thing to do, in both time and money, especially in the middle of a war). A stronger projectile capable of penetrating face-hardened armor reliably intact at 20 degrees obliquity, the use of a hardened AP cap to ensure this would happen by preventing shatter (soft caps tended to get unreliable at 15 degrees obliquity, from US Navy tests), the introduction of an insensitive Shellite filler that could remain inert through even thick armor if the shell was intact, and a delay-action fuze to allow penetration of about one-third to one-half of the hull width before exploding the shell to cause maximum damage effects. A complete overhaul of all of their APC ammunition, stating that their existing supply was not to be used except for a set of specified circumstances, with CPC being substituted instead in a number of cases. It is rather important that weapon acceptance specifications be reviewed regularly to make sure that they are still valid concerning the current threats they are to be used against.

To see what CPC could do to heavily-armored targets, which resulted in this shell being specified instead of APC under several battle conditions, even though this shell was never designed for those situations, being intended for use against armored cruisers only, the post-Jutland investigators had a number of CPC shells fired along with APC shells at battleship hull plate targets to compare results, using regular black-powder-filled Service CPC shells in full-up tests to see how much damage they could make against real heavy battleship hull belt plating, by hitting thick face-hardened hull belt armor at right angles and hitting at a high enough velocity to punch through. It was expected that they would badly break up during penetration of the very thick face-hardened plates but the flaming black powder and the largely-intact heavy single nose piece would hopefully cause some acceptable damage, as was known from the thin-plate tests where the deep penetration ability of these shells was quite effective, but here the impact shock would set off the black powder immediately, just as it did the Lyddite HE in the APC shells. The test personnel expected a narrow shotgun-like blast of flaming black powder and armor and shell fragments jetting out of the hole as the now-broken-up CPC projectile's intact nose moved away from the plate back, much like they found the APC did, though the latter did not produce very much flame and the majority of its pieces thrown into the ship when the shell exploded in the plate were very tiny and could not go very far through even rather light spaced steel plating, as was known previously. The results were somewhat different and unexpected.

The black powder in the CPC shells was indeed set off by the impact against the thick armor as the shell passed through the plate, exploding in most cases while the shell upper body was imbedded inside the armor, but this explosion occurred much sooner than had been the expected result if the shell went off like it did with the fuze after penetrating thin plates *and it did not act like regular black powder at all*. Instead of the rather weak, slowly-increasing, low-order explosion with large, slow-moving side-body pieces forming that shot-gun cone of fragments out the hole in the plate back (compared to the tiny-sized, very-high-speed ring of fragments and very powerful localized blast that resulted from a 3.3% Lyddite detonation), the 10% black powder filler acted almost exactly like Lyddite APC filler did, blowing up so violently inside the thick battleship belt test plates that several of these plates actually broke in two, which was even a better result than the current APC did with their old cannon-ball spec!

Here is my theory: This extremely superior performance of the black powder here compared to its usual effects seems to have been caused by the sudden deceleration of the soft-capped CPC shells against the hard, rigid face of the face-hardened armor used in such thick plates in British (and all foreign) battleship waterline side hulls -- the projectile could not move forward at all until the plate's face layer was completely cracked apart and punched out, which causes a significant time interval during the penetration process where major projectile nose and upper body deceleration is occurring, but as yet there is no significant plate damage and no forward motion of the projectile nose (this is the cause of both types of shatter). The soft AP cap did virtually nothing to the plate and removed the initial intense shockwave energy from the projectile nose by destroying itself, so the now-bare-nosed shell was just waiting for the plate face (or the nose, if the plate was hit at under the HBL) to fail, with the pressure on the nose tip rapidly ramping up due to the increase in inertia from the rest of the projectile "piling on". When the plate face finally caved in and allowed further projectile forward motion, enough time had passed for the internal black powder filler to compress itself forward and the remaining velocity of the projectile had dropped considerably as its kinetic energy was absorbed by the plate to break it.

Lyddite and all other HE explosives were physically thick, solid masses of a single chemical (though later some were mixtures of two such solid materials -- either two HE types, one powerful and one much weaker but very insensitive, or one powerful HE type and a desensitizer like beeswax or oil -- to reduce the impact shock sensitivity when using the now-standard delay-action fuzes). As such, they had few internal air spaces and only could be compressed by a rather small amount like thick clay. Black powder, on the other hand, is made up of three totally separate materials, charcoal, sulfur, and potassium nitrate (saltpeter), the first two fuel and the last one the source of the oxygen and nitrogen used to burn the other two and create the explosion. They are ground up separately into very fine powders, then they are thoroughly mixed in specific proportions, and then this mixture is (very carefully!) ground up again and the final powder mixture compressed into various forms for explosive fillers and, in the mid-19th Century and before, gunpowder cannon propellant, though nitrocellulose-based "smokeless" powders completely replaced gunpowder during the latter half of the 19th Century and thereafter. The much more powerful detonating HE fillers also replaced most black powder fillers in gun projectiles by WWI, with only a few, CPC being the main one, still using it as a filler by WWI. Black powder, because of its composition, is made up of many tiny separate grains of the three components that are irregular in shape and that have rather a lot of empty space in-between the grains, since trying to compress all of the air out would cause the mixture to explode by friction. This is why it burns so slowly compared to HE fillers under most conditions, with usually no ability to detonate, as they can (which is why it is a mere "low order" explosive compared the HE fillers, which are "high-order" explosives, in modern terminology).

In this case, though, when the CPC shell was punching through a thick face-hardened plate and its nose had just made it through, the violent deceleration had cut the shell's velocity roughly in half or by even more within just a few inches of forward travel and squeezed the black powder filler suddenly and violently due to inertia into the front end of the cavity, probably reducing its volume to only about half of its usual volume when filling the entire cavity prior to the impact. As expected, such friction and pressure set off the black powder instantly, but in this case it happened *virtually everywhere in the powder's entire volume at the same time*, not radiating rather slowly (sub-sonically, hence no detonation) from a single spot as with a normal fuze-initiated explosion. This made the powder have much of the effect of a full HE detonation, though at only one-third the power for a given weight of explosive as, say, Lyddite. But, countering that, there was three times the weight of black powder in the CPC shell as there was Lyddite in an APC shell, so the total energy available was the same. Since the heavy nose and the armor plate locked the blast in from the front and sides and the heavy base plug and the inertia of the black powder itself still moving forward capped the explosion at the rear, the "pseudo-detonation" of the CPC's black powder had all the confined power of an APC shell filled with Lyddite, plus a much larger weight of explosive material (three times) being turned into super-hot gas, so the huge pressure in that enclosed volume was rather greater and more long-lasting than a very-fast-and-powerful, but very-short-lived, Lyddite detonation would give, hence the better breakage ability against the brittle and already cracked face-hardened plate's face layer and the resultant splitting of the plates in two. The CPC projectile also was broken up into smaller pieces, including the heavy nose, though not quite as pulverized as Lyddite accomplished with an APC shell. This is a perfect example of a completely unexpected result that, however, makes total sense once it occurs and can be analyzed -- an "emergent phenomenon" result.

Due to these unexpected, but favorable, results with CPC, whenever it was thought that old Lyddite-filled APC and black-powder-filled CPC both would give similar results against a ship's hull (rather a lot of the time it was determined), CPC was to be used instead, as it seemed to give better armor-plate-breaking results. Against such things as turrets and other confined spaces, both would give similar results when they penetrated, virtually total destruction, so APC was superior, preserving the CPC shells for use when desired. As it was not possible in most cases to aim at a particular spot on an enemy ship, types of targets and various range intervals and Target Angles (US Navy terminology for the relative course of the target compared to your line-of-fire, with 90 degrees being a broadside-on target) were used to specify what shells, old APC or CPC, to fire at that target. When the new improved, hard-capped, delay-action-fuzed, 2.5% Shellite-filled "Greenboy" APC shells became available in 1918, the old APC shells were removed from Service and CPC went back to its previous job against cruisers, remaining in Service in some British warships during the 1920s before finally being relegated to shore bombardment only through the end of WWII.

CONCLUSION

The black powder's unexpected results shows that no matter what you might think, the Universe has its own plans, so you should NEVER say, "Why bother to test something?" You may be quite surprised by the actual results!

THE END