2008 Study Update, Part 3

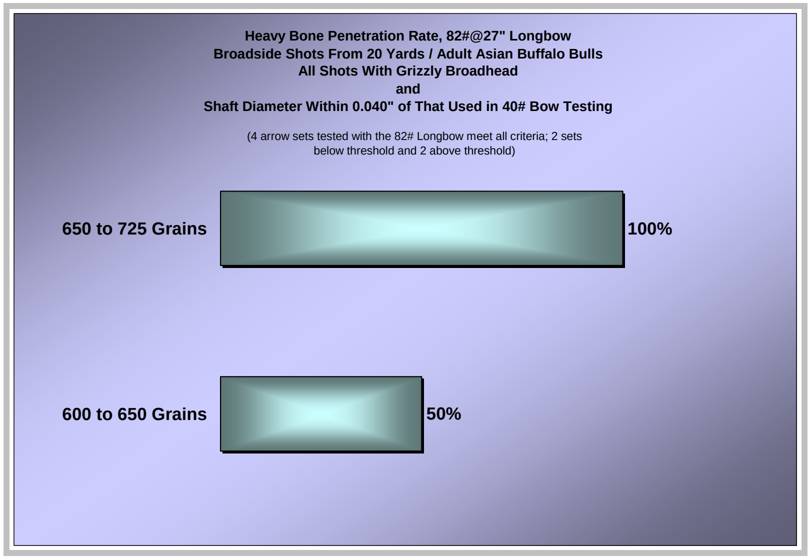
By
Dr. Ed Ashby

In Parts 1 and 2 we looked at the results of the 40# bow's Heavy Bone Threshold testing and compared those results to that shown by 'commonly used' arrows from the heavier draw-weight bows. In Part 3 we'll look at how the results correlate with other threshold testing and why FOC affects arrow penetration.

Arrow Force and the Heavy Bone Threshold

The arrow's impact force has shown only slight effect on the Heavy Bone Threshold.

Graph 10

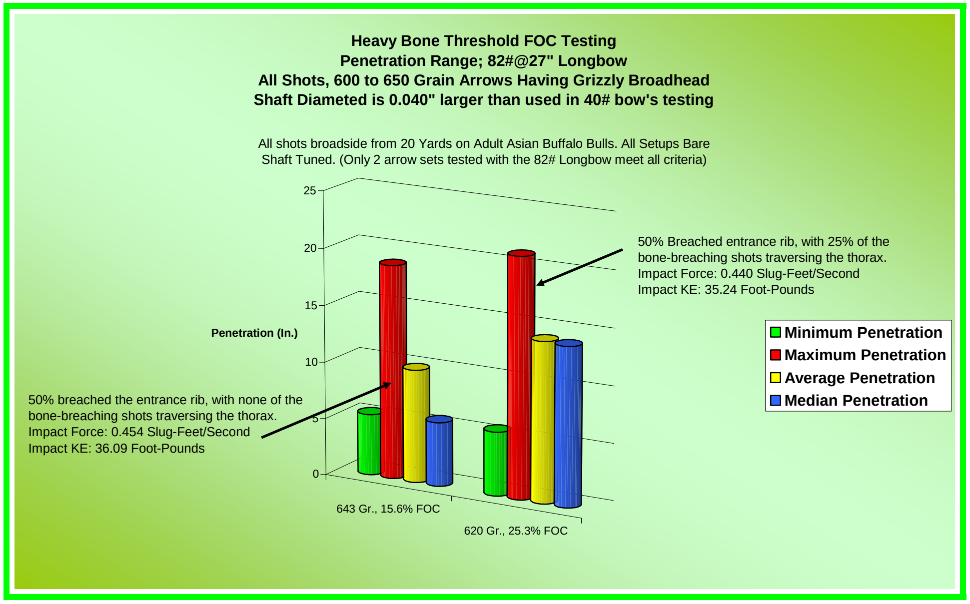


Graph 10 shows the heavy-bone penetration rates for all arrows from the 82# longbow that are: (1) within the same relative weight range as those tested from the 40# recurve; (2) have near-equal shaft diameter; (3) used the same broadhead (the 190 grain Grizzly); (4) retained structural integrity; (5) were fired from the same shooting distance and angle, and; (6) had thorax impact. Despite the substantial difference in bow-derived arrow force, the bone-breaching rates are identical to that shown for the 40# bow.

To be considered is a difference in the size of the test animals. All testing with the 40# bow was on a young adult Asian buffalo bull, with an 'impact-zone' rib thickness ranging from 7.15mm (0.281") to 8.1mm (0.319"), depending on the specific location of the bone-thickness measurement. The shots shown for the 82# bow are on a mixture of adult bulls and trophy class bulls. There is an aggregate difference in average rib thickness between the young adult bull and the mature bulls of approximately 18%; or roughly 0.10". Those differences notwithstanding, the Heavy Bone Threshold's persistence is consistent with that shown in all prior testing.

There are only two below-threshold arrow sets for the 82# longbow that meets all comparison criteria stated above. Let's take a closer look at those 2 sets.

Graph 11



Heavy Bone Threshold FOC Testing
Penetration Range; 82#@27" Longbow
All Shots, 600 to 650 Grain Arrows Having Grizzly Broadhead
Shaft Diameted is 0.040" larger than used in 40# bow's testing

All shots broadside from 20 Yards on Adult Asian Buffalo Bulls. All Setups Bare Shaft Tuned. (Only 2 arrow sets tested with the 82# Longbow meet all criteria)

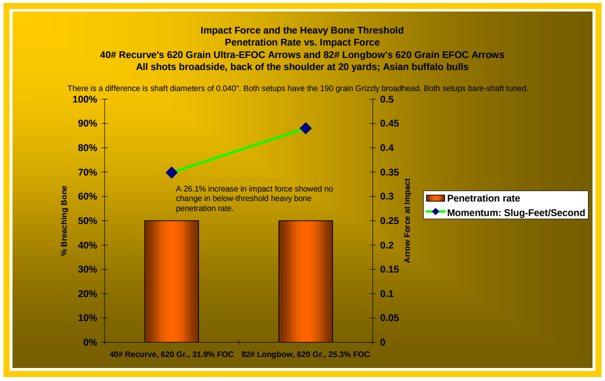
50% Breached entrance rib, with 25% of the bone-breaching shots traversing the thorax.
Impact Force: 0.440 Slug-Feet/Second
Impact KE: 35.24 Foot-Pounds

50% breached the entrance rib, with none of the bone-breaching shots traversing the thorax.
Impact Force: 0.454 Slug-Feet/Second
Impact KE: 36.09 Foot-Pounds

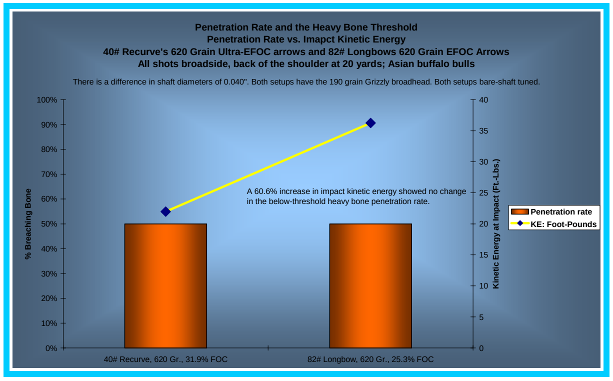
Other than a 0.040" difference in shaft diameter and a difference in shaft length these arrows have external dimensions identical to the below-threshold arrows tested from the 40# recurve. Despite their significantly higher impact force both below-threshold sets from the 82# longbow show the same heavy-bone penetration rate as those from the 40# recurve; 50%. The 82# bow's EFOC set, though of slightly lower mass than the High FOC set, shows the same penetration trend the 40# bow's Ultra-EFOC arrows showed over each of its companion test sets; a substantial increase in post-breaching penetration.

The 82# bow's two below-threshold arrow sets are a near-match in external dimensions to the two below-threshold arrow sets tested with the 40# recurve. Though impact force and impact energy differs greatly the bone-breaching rate for all four sets is identical.

Graph 12



Graph 13

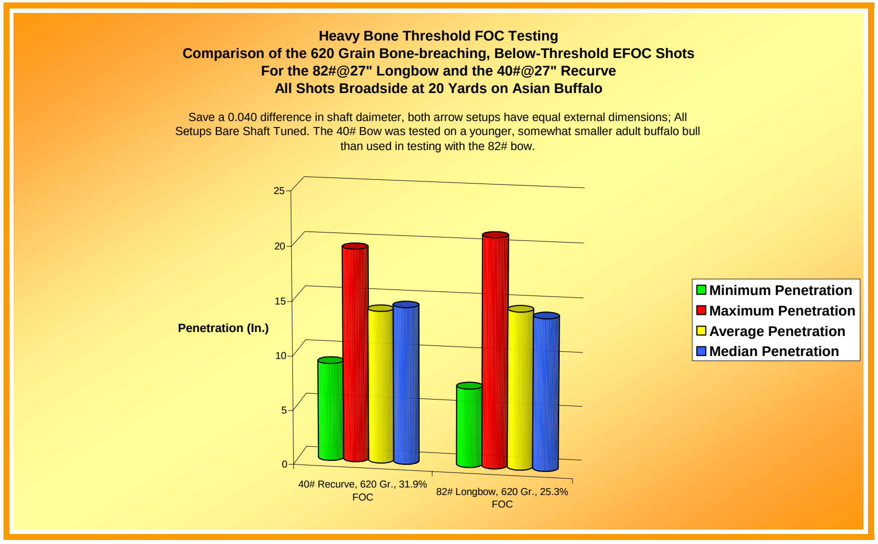


Graphs 12 and 13 shows a comparison of just the two below-threshold 620 grain arrow sets: one from the 40# recurve and the one from the 82# longbow. The columns show the bone-breaching rates, which is 50% in both instances. The diamond shaped line-markers in Graph 12 show the arrow's impact force (momentum). The line markers in Graph 13 show the difference in impact kinetic energy (KE).

Despite impacting with 26.1% more momentum and 60.5% greater kinetic energy the below-threshold arrows from the 82# longbow show no increase in the bone-breaching rate.

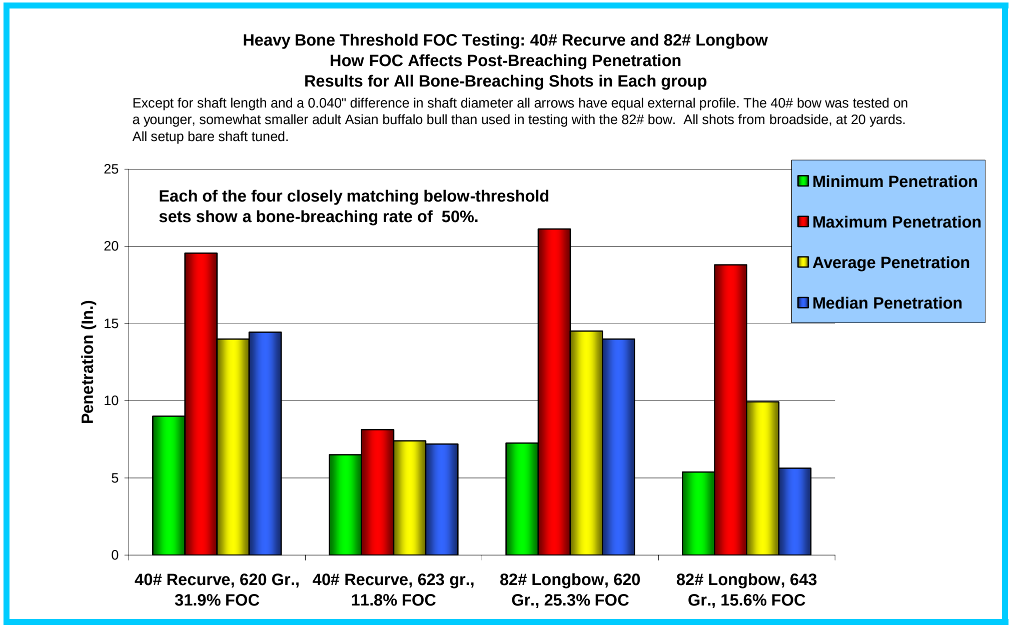
With arrows having a weight below-threshold even substantial increases in arrow force and energy show very little effect on the Heavy Bone Threshold.

Graph 14



Graph 14 shows a comparison of the outcome penetration *for the 50% of shots breaching the bone* for both 620 grain arrow sets; those from the 40# recurve and from the 82# longbow. Despite the enormous difference in impact force (26.1%) and impact energy (60.5%) the similarity of outcomes is striking.

Graph 15



Graph 15 shows penetration outcomes for all bone-breaching hits for the two below-threshold sets used with the 40# recurve (the 620 grain Ultra-EFOC arrows and 623 grain Normal FOC arrows) and the two comparable below-threshold sets from the 82# longbow (the 620 grain EFOC arrows and 643 grain High FOC arrows). Remember that the only difference in the external dimensions among all these arrows is shaft length and a 0.040" larger shaft-diameter for the two arrow sets from the heavier bow.

All four arrow sets show a 50% bone-breaching rate. It would be hard to get a clearer, more harmonious picture of both how consistent and persistent the Heavy Bone Threshold is, regardless of impact force, and the degree to which arrow FOC affects the "likely outcome" post-breaching penetration; as shown by the difference(s) in average and median values between the EFOC/Ultra-EFOC arrows and their respective matching Normal/High FOC comparison group.

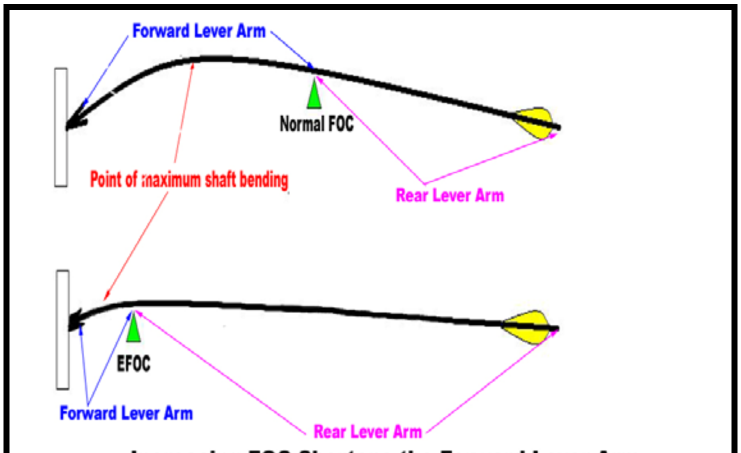
All testing indicates that the degree of arrow FOC has no effect on the Heavy Bone threshold but does have a very beneficial effect on the arrow's penetration-potential once the bone is breached.

Why Does Higher FOC Increase Penetration?

The simplest answer is that higher FOC arrows encounter lower resistance. The reduced resistance results from less shaft-flex on impact. Shaft-flex during penetration increases shaft-drag, and shaft-drag is a *major* resistance factor influencing tissue penetration. Increased shaft drag is so significant that having a shaft diameter a mere 5% larger than your broadhead's ferrule-diameter can rob your arrow of 40% of its penetration potential (See 2004 Update, Part 2). Simply altering the profile of shafts having the same maximum diameter can make as much as a 15% difference in penetration (See *Arrow Lethality*, Part 2, The Natal Study and 2004 Study Update, Part 2).

How does higher FOC reduce shaft-flex during penetration? Shaft flex is related to location of the *center of pressure* relative to the arrow’s center of mass. The center of pressure is that exact point where the maximum 'bending force' is exerted upon a projectile during its flight. Penetrating tissue(s) is simply flying through a very dense medium.

Higher FOC means the arrow has a shorter *forward* lever arm; that portion of the arrow in front of the center of mass. The shorter the forward lever arm, the stiffer that shaft section is and the less it flexes when any given level of resistance is applied at the arrow’s tip.



Increasing FOC Shortens the Forward Lever Arm, Reducing Shaft Flex on Impact

At least two characteristics of EFOC greatly reduce the amount of shaft flex on impact. These are:

(1) Less of the arrow's mass is behind the *center of pressure* (that point where the greatest bending force is exerted on the shaft). This reduces the force with which the arrow’s rear 'pushes' on the shaft as 'resistance' is applied at the shaft's front. To see this characteristic clearly, take a full length slender shaft and securely glue a brick to one end with a big glob of something like JB Weld. Now place the other end of the shaft (the one without the brick) on the floor. Unless you keep the shaft absolutely perpendicular to the floor the shaft flexes.

Next, bump the shaft up and down on the floor. Even when held perpendicular to the floor the shaft flexes at impact. The collision forces are *required* to go somewhere. The resultant force-vectors between floor-impact (the 'resistance force') and the 'push' exerted by whatever mass (weight) is at the shaft's rear must either split the shaft, compress the shaft linearly or be redirected, causing shaft-flex. Shafts don't show much linear compression. On forceful frontal impacts they will crack, split or break before compressing any significant amount.

Now reverse the shaft, placing the brick on the floor. The shaft-flex is minimal. Bump it up and down as forcefully as you like. Shaft-flex is scarcely visible, regardless of how hard the impact. This is a drastic example of one effect high FOC has on shaft-flex during direct impact, and clearly demonstrates the principle involved as the rearward weight of the shaft is reduced.

(2) Extreme and Ultra-Extreme FOC arrows concentrate arrow mass far forward. The *forward* lever arm is short. During impact the center of pressure (that point where the greatest bending force is exerted on the shaft) is also far forward. This is important on all impacts, and becomes increasingly important when impact is at angles other than perpendicular.

To understand how this short forward lever arm affects shaft-flex think of the distance from arrow tip to the center of mass as being a short section of shaft; the shorter the section, the stiffer the shaft. The stiffer it is, the less it flexes.

To observe this effect let's use a large raw potato and our same full length slender shaft, but without the brick attached. Hold the shaft by its very back end. Without supporting the shaft in any other manner, try to push it through the potato. Note both the degree of shaft bending and the amount of force you must to apply to push the shaft into the potato.

What happened as you pushed every more forcefully forward on the slender shaft's rear? Shaft flex increased and it became more and more difficult to push the shaft through the potato. In this example, because you are applying force with your hand to the shaft's rear, your hand is acting as the center of inertial mass; the epicenter of the arrow's 'forward push'. Because the epicenter of the shaft's forward push is at the shaft's very rear the forward lever arm is very long - the full length of the shaft - and the center of pressure - that 'maximum bending force' - is near the midpoint of the shaft's full length.

Now hold the shaft at a point close to the potato; just 4 or 5 inches away. Again push the shaft through the potato. What happens this time? It is now much easier to push the shaft into the potato. That's because your hand (which, once again represents the center of inertial mass; the epicenter of the arrow's forward push) is creating a shorter forward lever arm, reducing the distance between the center of pressure (which is now located about midway between the potato and your hand's position on the shaft) and the resistance force (the potato). Again note the degree of shaft flex and the force you must to apply to push the shaft into the potato.

In each of the above examples your hand is representative of the center of mass. It also represents the point of greatest impulsion; that point where the maximum amount of 'forward push' is centered. On impact the point of greatest impulsion for an EFOC arrow is very close to the arrow's front end, and the penetration effect is the same as when you had your hand very near the shaft's tip. Because that front section of the shaft; the 'forward lever arm'; is very short and stiff the shaft flexes less on impact. That means less of the arrow's force is required to penetrate the tissues, and less shaft flex at impact also means less shaft vibration (oscillation) during penetration. Less of your arrow's force is used up needlessly in flexing the shaft *and* the reduced shaft vibration lowers resistance as the shaft passes through the tissues. Both factors conserve arrow force, providing more 'useful' arrow-force that can be applied to arrow penetration.

As arrow FOC increases the arrow's center of gravity moves forward and the forward lever arm becomes progressively shorter. The shorter this forward lever arm becomes the stiffer the arrow's forward section becomes, and the less shaft flex there is on impact.

Shortening the forward lever arm has other advantages too; it means the *rear lever arm* becomes longer. A longer rear lever arm means your fletching will need less surface area to exert the same amount of stabilizing pressure upon the arrow's rear. When all else is equal this means faster arrow recovery from paradox. That, in turn, means the arrow is 'flying straight' in a shorter time, closer to its departure from the bow. Fast paradox recovery not only conserves arrow force, on close-range shots it means the shaft is oscillating less at the time of impact, and this means more penetration.

The affect of increased shaft oscillation on arrow penetration is easy to see. Using an arrow set having Normal FOC, shoot a few arrows into your broadhead target at very close range, say 1 yard, and compare the penetration to that shown when the same arrows are shot into the target at a somewhat longer range; 12 to 15 yards. Despite having less impact force and energy the arrows fired from the greater distance show greater penetration. The penetration loss at the close range results from the 'wasted' arrow force caused by the greater amount of arrow oscillation. In this case the major arrow flexion is a result of the arrow not having fully recovered from paradox - which is why the demonstration is best conducted with Normal FOC arrows; they recover from paradox more slowly. The principle is the same for all arrows and all shaft flexion.

Regardless of the origin of arrow flex, the more an arrow flexes during impact and penetration the less it will penetrate.

How Arrow Efficiency Compounds the Penetration Gain

Arrow penetration depends on the impulse of force, which is the arrow force (momentum) used multiplied by the time the force acts. Not all of your arrow's force is used productively. The 'productive force' is that portion which produces 'useful work': tissue penetration. Increasing arrow efficiency means using more of the arrow's total force 'productively'.

Increasing arrow efficiency also increases the 'time of action'; how long the 'useful force' can act before it's all used up. The increased penetration gain you get from improving your arrow's efficiency won't be the sum of the 'wasted force' you save and the increased 'work time' that saved force allows your arrow to perform; it will be their mathematical product. Force Used X Time of Action = Impulse Force.

When arrow penetration is anything less than a complete pass-through the force used to penetrate as far as it did will equal the arrow's total force; which was entirely used up during whatever time period it took the arrow to come to a complete stop. Part of the 'total force' was used productively, to propel the arrow farther through the tissues, and part was 'wasted'; i.e. not applied to penetration. Anything you do to increase the efficiency of your arrow increases the productive "work" your arrow can do with whatever force it has which, in turn, increases the time of action; with each *multiplying* the other's affect.

Here's an example that may make it easier to understand exactly how increasing arrow efficiency affects penetration. For simplicity, it takes the liberty of simplifying the force involved into pure component parts.

Let's suppose your arrow has an overall efficiency is 50%, meaning 50% of the arrow's total force at impact is applied to the 'useful work' of penetrating tissues and 50% is lost to non-productive resistance factors, such as friction, sound of impact and vibration. Let's also assume your arrow carries a total momentum of 0.5 Slug-Feet at impact. The available 'useful momentum' your arrow carries is: 0.5 Slug-Feet X 50% = 0.25 Slug-Feet. Your arrow's other 0.25 Slug-Feet represents 'wasted momentum' … wasted arrow force.

Now, without changing either arrow weight or arrow velocity let's change the design of your arrow to conserve 10% of the 'wasted momentum'; force previously lost to non-productive resistance. This might be by something as simple as using a broadhead with a higher mechanical advantage, or something with an effect as complex as altering the arrow's FOC.

This change in arrow design saves you 0.025 Slug-Feet (which is 10% of the 0.25 Slug-Feet that was previously 'wasted'). The total 'useful momentum' is now 0.275 Slug-Feet (that's the sum of the 0.25 Slug-Feet of 'useful momentum' you started with plus the 0.025 Slug-Feet of previously 'wasted momentum' you've 'saved'). This means overall arrow efficiency is now 55% (0.5 Slug-Feet X 55% = 0.275 Slug-Feet). Overall arrow efficiency has increased by 5%, but 'useful momentum' has increased by 10% (from by 0.250 Slug-Feet to 0.275 Slug-Feet).

Next, for each arrow let's assume a hit against an infinitely thick target that exerts a penetration *resistance rate* of 0.50 Slug-Feet/Second. Because our target is 'infinitely thick' our arrow cannot 'pass through'; it will expend its total force in the target. That total force will be expended during whatever time it takes the arrow to come to a stop.

Our 50% efficient arrow has a 'useful momentum' of 0.25 Slug-Feet/Second with which to overcome a uniformly applied resistance force of 0.50 Slug-Feet/Second. All of the arrow's force will be expended in the target, therefore the total force used will equal the rate of resistance multiplied by the time the arrow was able to apply its force on the target. In formula form we have: Total Force Used = Resistance Rate X Time of Action.

This formula can also be stated as: Time of Action equals Total Force Used divided by Resistance Rate. Applying this last formula, our 50% efficient arrow will use up all of its available 0.25 Slug-Feet in 0.5 second (0.25 Slug-Feet divided by 0.50 Slug-Feet/Second). As far as penetration is concerned the impulse of 'useful force' for the 50% efficient arrow will be: 0.25 Slug-Feet/Second X 0.5 Second = 0.125 Slug-Feet.

Our more efficient arrow (55%) has an available 'useful momentum' of 0.275 Slug-Feet/Second. Against that same uniform resistance rate of 0.50 Slug-Feet/Second it can act for 0.55 seconds before all its available force is expended (0.275 Slug-Feet divided by 0.50 Slug-Feet/Second). What does your arrow do during this extra 0.05 second? It continues to penetrate. Its impulse of 'useful force' will be: 0.275 Slug-Feet/Second X 0.55 Second = 0.15125 Slug-Feet.

What does all this mean? By increasing arrow efficiency a mere 5% you've conserved 10% of your arrow's 'wasted force' but, far more importantly, you've increased the effective, penetration-producing impulse of 'useful force' by a whopping 21%!

A small percentage increase in arrow efficiency yields a far greater percentage gain in penetration.

So far this year's updates have only looked at Ultra-EFOC arrows having a mass-weight below the Heavy Bone Threshold. The bone-breaching Ultra-EFOC arrows have shown post-breaching penetration that exceeds that of heavier and more forceful arrows having lesser amounts of FOC. What outcomes would an above-threshold Ultra-EFOC arrow show? In the next Update we'll look at the performance of just such an arrow.