A critical look at Luis Alvarez's jet effect explanation for the head movement of John Kennedy when he was assassinated on November 22, 1963

By Tony Szamboti, mechanical engineer April 17, 2012

In his article published in the September 1976 issue of the American Journal of Physics, Dr. Luis Alvarez claimed that he was pushed by a graduate student of his (Paul Hoch) to develop his explanation for what he calls "the odd behavior" of President John F. Kennedy's head (as seen in the Zapruder film) when he was assassinated in Dallas, Texas on November 22, 1963. The full article, which also covers his analysis for determining the number and timing of the shots, an explanation for the deceleration of the limousine, and the speed of Abraham Zapruder's camera, can be found at any large public library by asking for the September 1976 issue of the American Journal of Physics. For the convenience of the reader the part of the article, where Dr. Alvarez espouses his theory and shows his calculations, for what he calls a jet effect, is provided below. My critique afterward is of his jet effect explanation for the rearward head snap and follows the portion of his article shown.

> *Dr. Luis Alvarez's attempted jet effect explanation for John Kennedy's left and rearward head movement being possible when allegedly shot from the right rear*
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> Paul Hoch often pressed me for an explanation of the odd behavior of the President's head, and although I hadn't observed it myself, I usually suggested that the head had probably been held erect by muscles controlled by the brain, and that when the controls were suddenly damaged, the head fell back. I was finally convinced that this explanation was incorrect after Paul Hoch handed me a copy of Thompson's book as I was leaving Berkeley for the February 1969 meeting of the American Physical Society in St. Louis. On the plane I had time to study the book carefully. It is beautifully printed, with excellent photographs and carefully prepared graphs. When I studied the graph showing the changing position of the President's head relative to the moving car's coordinate system, I was finally convinced that the assassination buffs were right; there had to be a real explanation of the fact that the President's head did not fall back, but was driven back by some real force.
>
> And the answer turned out to be simpler than I had expected. I solved the problem (to my own satisfaction, and in a one-dimensional fashion) on the back of an envelope, as I sat in solitary splendor in the beautiful suite that the St. Louis hotel management supplied me in my capacity as president of the APS.
>
> I concluded that the retrograde motion of the President's head, in response to the rifle bullet shot, is consistent with the law of conservation of momentum, if one pays attention to the conservation of energy as well, and includes the momentum of all the material in the problem. The simplest way to see where I differ from most of the critics is to note that they treat the problem as though it involved only two interacting masses: the bullet and the head. My analysis involves three interacting masses, the bullet, the jet of brain matter observable in frame 313, and the remaining part of the

head. It will turn out that the jet can carry forward more momentum than was brought in by the bullet, and the head recoils backward, as a rocket recoils when its jet fuel is ejected. (Col. William H. Hanson came to the same conclusion, independently.)

If a block of wood is suspended by strings from the ceiling, it is called a ballistic pendulum, and physicists or gunsmiths can calculate the velocity of a bullet shot into it to be

$$v_B = v_W M_W / M_B, \qquad (1)$$

where v_W is the velocity of the wooden block after it stops the bullet, M_W and M_B are the masses of the wooden block and bullet. Equation *(1)* follows directly from the law of conservation of momentum:

$$v_B M_B = v_W M_W. \qquad (2)$$

In using a ballistic pendulum, we normally forget that the collision of the bullet and wooden block is very inelastic. Of the incoming kinetic energy of the bullet, only a small fraction appears as kinetic energy of the moving wooden block; the remaining fraction *(1 – f)* goes into heating the wood. If $M_B << M_W$,

$$KE_W = f(KE_B),$$

$$M_W v_W^2/2 = f \times M_B v_B^2/2. \qquad (3)$$

From *(3)* and *(2)*

$$f = M_B/M_W \qquad (4)$$

For the case of a 10-g bullet, and a block weighing 10 kg, it can be seen that 99.9% of the incoming kinetic energy goes into heating the block, and only 0.1% appears as mechanical energy. Ballistic pendulums are designed so that they contain the inelastically dissipated energy. Unfortunately, the human head is not able to contain the major fraction of the energy carried in by the bullet. This tragic aspect of the assassination is clearly visible in frame 313 of the Zapruder film, and is discussed in detail in the reports of the autopsy surgeons.

The mechanism of the retrograde recoil turns out to be rather simple, if one remembers that 99.9% of the incoming energy must be accounted for. The momentum associated with a given amount of kinetic energy varies as the square root of the mass of the object carrying that kinetic energy:

$$p = (2MK)^{1/2} \qquad (5)$$

where p is the momentum, and K is the kinetic energy of the object with a mass M.

Figure 4 shows what happened when my friends and I fired bullets at melons that had been wrapped with Scotch glass filament tape, to mock up the tensile strength of the cranium. Under the influence of the bullet, some of the material making up the melon breaks through the reinforcement, and carries momentum in the forward direction. (Frame 313 of the Zapruder film shows this same phenomenon.) As we shall now see, the momentum carried forward in this way can be much larger than the momentum brought in by the bullet. For example, if the bullet weighed 0.1% of the melon weight, and if 10% of the incoming kinetic energy was used to propel 10% of the mass of the melon forward, then the momentum of the jet expelled forward would be $(10)^{1/2}$ times that of the incoming bullet. (I will use subscripts, b for bullet, j for forward moving jet, and m for melon.)

$P_j = (2M_jK_j)^{1/2} = (2 \text{ x } 100M_b \text{ x } 0.1K_b)^{1/2}$

$= (10)^{1/2} (2M_bK_b)^{1/2} = (10)^{1/2}p_b$ *(6)*

since $M_j = 0.1M_m = 100M_b$, $K_j = 0.1K_b$. The melon would then recoil backward with about twice the velocity it would have been expected to go forward, assuming it were made of wood. This is because the melon, acting at first as a ballistic pendulum, acquires a forward velocity equal to $v_m|BP = p_b / M_m$. (The notation $v_m|BP$ means the velocity one would expect the melon to have if it contained all the kinetic energy of the bullet, as a ballistic pendulum does.) But in the center of mass of the system of the melon, which is moving *"forward"* with the expected velocity, a jet moves forward with momentum equal to $(10)^{1/2}p_b$---as we have just seen. It gives the melon an equal and opposite momentum, in the moving *(CM)* system; in that system, $p_m = -(10)^{1/2}p_b$. If we neglect the 10% loss of the mass by the melon to the jet, the recoil velocity of the melon (in the CM system) is $-(10)^{1/2}$ times the expected value. Since velocities add vectorially, the final velocity of the melon (in the laboratory system) is $[1-(10)^{1/2}]v_m|BP$. Since the square root of 10 is close to 3.16, the observed velocity of the melon is about $-2v_m|BP$.

If one wants to know more about the details of the transfer mechanism of kinetic energy from the bullet to kinetic energy of the fragments thrown forward, he will have to ask someone more knowledgeable in the theory of fluid mechanics than I am. My intuitive feeling is that the conical shape of the interaction zone is the key to the nonnegligible efficiency of energy transfer. (It is clear that an appreciable mechanical energy transfer is only possible if the incoming energy can avoid "being thermalized.") The conical region is defined by the small entrance hole and the much larger exit hole in the melon. Transmission lines with tapered internal conductors are efficient transformers of electrical energy, and a tapered bullwhip can smoothly transform the energy given to a large mass, by the flick of the wrist, into roughly the same energy of a much smaller mass at the tip of the whip. The *"crack"* of the whip occurs when the tip of the whip goes supersonic. I believe that in a somewhat analogous manner, but of course in the opposite direction, the kinetic energy of the bullet is given in a *"tapered region"* to a progressively larger mass in the melon, to achieve the modestly efficient energy transfer that is demonstrated in our experiments.

A critique of the jet effect theory as an explanation for John Kennedy's left and rearward head movement when allegedly shot from the right rear

The simple claim of an equal and opposite reaction to the blown out brain matter being similar to the thrust developed in a rocket or jet engine, in response to its exhaust, is deceiving if one does not understand the mechanics involved. How thrust is developed in a rocket or jet engine, and the role the exhaust plays, is shown and explained in the figure and paragraphs below.

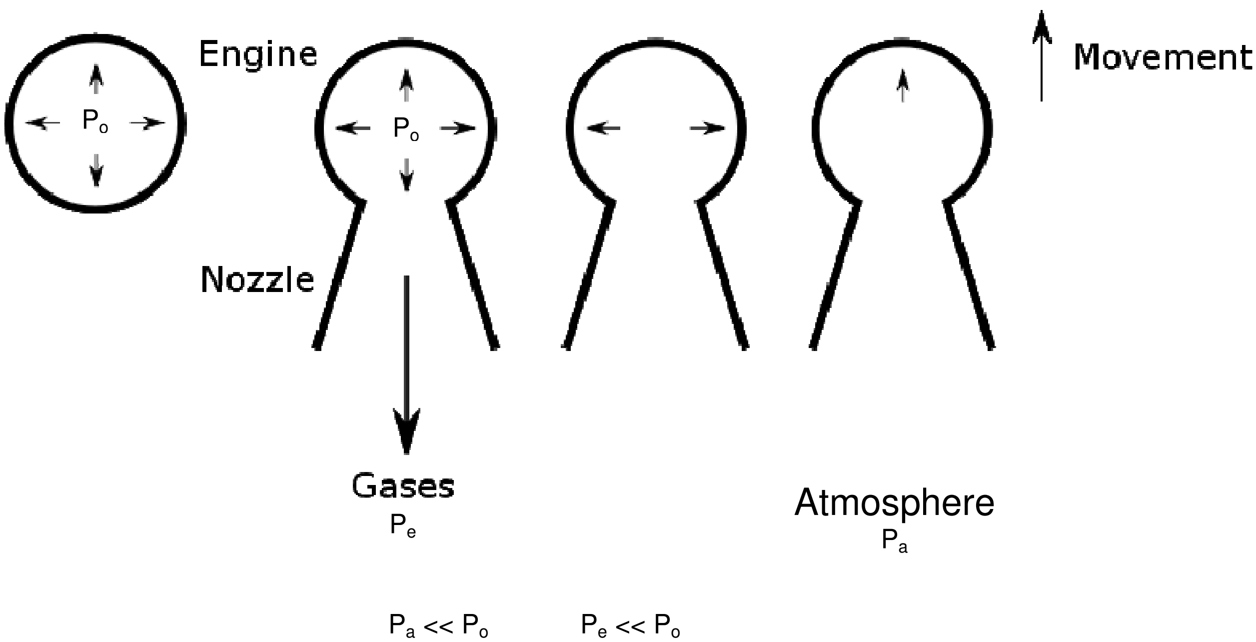

Figure 1. Rocket engine thrust diagram

In the above figure *Po* stands for combustion chamber pressure, *Pe* for exhaust or exit pressure, and *Pa* for atmospheric pressure. The high pressure *Po* of the combustion by-products inside the combustion chamber of the rocket or jet engine pushes in all directions to form balanced pairs of opposing forces that nullify one another, except where the hole in the system for the exhaust nozzle is placed. Here the pressure escapes at very high velocity, causing an unbalanced force at the opposite side of the combustion chamber that pushes the rocket or jet in the opposite direction to that of the exhaust. The role of the exhaust is to create a lower pressure side allowing the forward pushing opposite component of the originally equal pair to be at a higher pressure, thus causing a forward reaction, which we call thrust. The purpose of the exhaust is not to push on anything to create thrust; it is simply to relieve the pressure on one side allowing the opposite side to dominate. If it did not operate in this fashion a rocket would not work in space. Both rocket and jet engines are based on the same principle that causes a pressurized toy balloon to move forward and away when let go with its end untied. Thus one of the operating requirements of a rocket or jet engine is the generation of a high gas pressure in all directions in its combustion chamber, which can then be relieved at one side to gain an unbalanced force at the opposite side. With the above having been said, to ensure the reader understands how a rocket or jet actually propels itself forward, we can now get to a sort of cross examination of what Dr. Alvarez said in his article.

Dr. Alvarez claims that President Kennedy's head recoiled the way a rocket recoils when its jet exhaust is ejected. However, he does not explain any mechanism for putting an opposite force on the head when the jet was expelled forward. He simply makes the case for the potential of the jet taking out more momentum than that brought in by the bullet. In order for a jet effect to have occurred a pressure would have to be built up inside the head, acting at least rearward as well as forward, which was then relieved on the forward side allowing the rearward pressure to dominate and create an unbalanced force in that direction. This is usually done with either a combustion process or having a pressure on tap in a sealed volume. The thrust in a jet or rocket engine can be computed based on the change in momentum of the exhaust gases with respect to time. However, this change in momentum is directly related to the forward acting pressure opposite that of the exhaust gases, since their initial pressure values are the same but one is allowed to escape.

A bullet moving through a fluid creates a high pressure conical shock wave in front of it and leaves a residual pressure in its wake in what is known as the temporary cavity as shown in Figure 2 below.

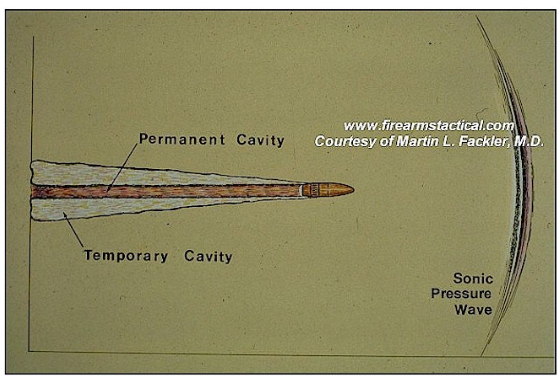

Figure 2. Bullet pressure generation rendition

The U.S. Army Wound Ballistics Research program has measured the pressure of the shock wave forward of the projectile as up to 100 atmospheres (approximately 1500 psi) in experiments, by shooting through tissue replicating matter. The frontal shock wave leaves some residual pressure behind it, but it is orders of magnitude lower than that in front of the projectile. This residual pressure, in what is known as the temporary cavity, has been measured by the Wound Ballistics Research program as 4 atmospheres (59 psi). Thus the change in momentum axiom is not valid in a jet effect caused by a projectile moving through an encased fluid filled object, as the pressure of the forward acting shock wave is not the same in all directions.

Since a jet effect requires a pressure opposite that of the exhaust it would have to be caused by the operation of the relatively low temporary cavity pressure, when the high pressure shock wave exits, although it would not be related to the change in momentum with respect to time of the exhausting material.

While it is true that a jet effect can certainly occur when a projectile strikes and passes through a fluid filled object, it is only one of the forces acting on the object. The other force involved is that due to shearing through the casing of the object, and this force is in the direction of the projectile. For his tests Dr. Alvarez used a taped up melon, rather than an object with a shear strength and thickness close to that of a human skull. This was misleading, as the force required for a 6.5 millimeter (0.256 inch) diameter projectile to shear through the skin of even a taped up melon is orders of magnitude lower than it is for that same projectile to shear through a human cranium. The shear strength of a melon rind is approximately 70 psi. In comparison, the shear strength of live human bone is approximately 17,000 psi perpendicular to its grain and 7,100 psi parallel to its grain.[1] For dead bone these figures are 8,500 psi and 3,550 psi respectively, as it is approximately half the strength of live bone, although still much stronger than melon rind.[1] Thus the force required for the same object to penetrate and shear through the same thickness of live human bone vs. that required for a melon rind, is at least 100 times greater, and 50 times greater even for dead human bone.

The direction the object takes after the projectile passes through it is dependent upon the **net force,** or the sum of all of the forces involved. The Wound Ballistics Research program puts the temporary cavity size as about 12 times the diameter of the projectile. For the case of a 6.5 millimeter projectile, the temporary cavity would be approximately 3 inches in diameter giving a circular area of about 7 square inches. If the 4 atmosphere (59 psi) temporary cavity pressure acted on the entire area of this diameter it would generate a force to the back and towards the shooter of 413 pounds. This is a significant amount. However, this force is competing with the shear forces that act in the opposite direction and away from the shooter. The shear force for a 6.5 millimeter projectile passing through a 0.300" thick melon rind is only 17 pounds. Since the projectile passes through both sides of the melon the shear force is experienced twice. If the coordinate system is chosen so that the direction of the projectile motion is positive, then for the case of the melon the net resulting force is

-413 pounds + 34 pounds = -379 pound

showing that the **net force** on the melon is in the direction of and back towards the shooter.

However, as the shear strength of human bone is so much greater than that of the melon rind, the shear forces on the skull are much greater. The shear force required for a 6.5 millimeter projectile to penetrate and pass through a live human skull (the average thickness of a human skull is ¾ of a centimeter or about 0.300 of an inch), even using the lower parallel to the grain bone shear strength, is about 1,700 pounds at both entrance and exit, or 3,400 pounds total. Since the same diameter projectile is used and the same size temporary cavity should occur, the jet effect will produce a similar amount of force toward the shooter of 413 pounds. The **net force** equation for shooting through a live human skull with a jet effect occurring is then

-413 pounds + 3,400 pounds = + 2,987 pounds

showing the **net force** on the skull is resoundingly in the direction of the projectile's motion. The trick with the use of the melon, to show the jet effect could cause it to move towards the shooter, was that the force required to shear through its skin was so low that it allowed the jet effect generated force to dominate. This situation is not true when a human skull is involved.

The fact that it takes about 1,700 pounds to shear a 6.5 millimeter diameter through a 0.300 inch thick item with a shear strength of at least 7,100 psi (live human skull) is indisputable. How a 10 gram (0.022 pound) bullet can do this due to a high velocity collision needs to be explained. The force generated in the collision is a function of the change in momentum per unit of time of the impacting projectile. This is essentially the derivative of the momentum with respect to time and results in Isaac Newton's classic equation F = ma as shown below

$$F = \frac{(W/g)\,(V_{initial} - V_{final})}{\text{Impulse duration}}$$

so

$$F = m\frac{dv}{dt} = ma$$

Note: $g = 32.174\ ft/sec^2$

A projectile traveling at 2,000 ft/sec covers a 0.300 inch distance over a duration of just 0.0125 milliseconds, or 1/80,000th of a second, and this explains why a 0.022 pound item moving at 2,000 ft/sec and impacting a rigid item can generate a force of 1,700 pounds.

In his article, Dr. Alvarez discusses what occurs with both the conservation of momentum and conservation of energy in a ballistic pendulum. He goes through the equations to show how much of the kinetic energy is transformed to internal energy in the pendulum, and how little of it is conserved as mechanical energy. With the 10 gram bullet and 10 kilogram wooden block he chooses the amount of kinetic energy transformed to internal energy by friction is over 99%. He then states that the mechanism of retrograde recoil is rather simple, if one remembers that 99.9% of the incoming energy must be accounted for. It appears that he is implying that the energy involved as friction in the ballistic pendulum should be accounted for in the matter which is blown out as a jet in the head shot, and that the jet would contain a very large amount of the energy of the bullet. As with earlier points this implication made by Dr. Alvarez is also misleading. In the real world, the jet would only absorb as much energy from the bullet as its reactive forces would allow. The amount of energy ultimately contained in the jet is equal to the reaction its matter exerted upon the bullet over the distance the reaction forces were applied. The wooden block of the ballistic pendulum was able to exert enough friction to stop the bullet, whereas it is obvious, due to the escaping bullet and jet, that the encased fluid filled volume of a melon or skull did not perform this feat.

There are many who believe that the jet effect is a result of Newton's third law of motion at work, with the head being blown back due to the exiting material in the jet pushing against the air. This was shown not to be the case in the beginning of this discussion. However, Newton's third law is at work here, as it is when any force is applied, but not the way those who believe the above think. Newton's third law states that ***"for every reaction there is an equal but opposite reaction"***. Once it exits, the forward moving jet is not pushing against anything in relation to the skull or melon, but since it is relieved it allows the rearward component of the pressure to act on the skull. The skull applies an equal and opposite reaction by absorbing the rearward acting component of the pressure over a specific area, which is a force, but since it is ultimately not restrained it accelerates in the direction of the force. The forces imparted by the projectile to the skull or melon, when shearing through it, are equal to and only as great as the skull or melon's resistance to the shearing action, no matter how much force the projectile is capable of applying.

It is with the use of an energy equation that Dr. Alvarez attempts to show that more momentum can be carried out by the jet than that which is brought in by the bullet. He correctly states that the momentum associated with a given amount of kinetic energy varies as the square root of the mass of the object carrying that kinetic energy. However, his use of this rule, with assumed numbers for the masses of the bullet, melon, and the jet, has no basis, nor does he provide one. He has simply provided assumed masses that work with the equation in the direction that supports his theory. To show how easy it is to manipulate the equation he uses, we can insert lower values for the kinetic energy absorbed by the jet, and the mass of the jet. Then using the same equation as the one shown by Dr. Alvarez, we see that the momentum carried forward by the jet, with these figures, is less than the momentum brought in by the bullet. For example, if the bullet weighed 0.1% of the melon weight, and if 2.5% of its incoming kinetic energy was used to propel 2.5% of the mass of the melon forward, then the momentum of the jet expelled forward would be $(0.625)^{1/2}$ times that of the incoming bullet. (again subscripts, **b** for bullet**, j** for forward moving jet, and **m** for melon are used.)

$$P_j = (2M_jK_j)^{1/2} = (2 \times 25M_b \times 0.025K_b)^{1/2}$$

$$= (.625)^{1/2} (2M_bK_b)^{1/2} = (.625)^{1/2} p_b$$

since $M_j = 0.025M_m = 25M_b$, $K_j = 0.025K_b$. The result with these assumed values shows the jet to have less momentum than the bullet. Although these values are still probably a little high for the mass of the jet and its kinetic energy, one can now see that the simple use of this equation does not necessarily show the jet to have more momentum than the bullet. By using the words "*if 10% of the incoming kinetic energy were used to propel 10% of the mass of the melon forward"* Dr. Alvarez shows that he simply assumed the values he needed to make the equation work in the direction he wanted it to go. If he had proof of what he was saying he would have provided it. Since he did testing, which he says validated his theory, he could have simply weighed the melon beforehand and the remaining melon after the shooting tests, to find the actual mass of the jet displaced from the melon. He doesn't mention anything of the sort. However, the amount of matter blown forward is actually inconsequential in the formation of a jet effect generated by shooting a projectile through an encased fluid filled volume. The jet effect in this situation is strictly dependent on the magnitude of the rearward acting temporary cavity pressure and the area that pressure impinges upon. The temporary cavity pressure generated in the wake of a projectile's path through an encased fluid filled volume is not directly related to the shock wave momentum forward of the projectile in the way the forward acting pressure of a jet engine is related to the momentum of its exhaust.

As we have seen, the potential for a residual pressure behind the projectile does exist, but for it to cause a movement in the opposite direction of the projectile's motion it requires: the sealing of the permanent cavity at the entrance, a shear force through the skin of the impacted object lower than the jet effect force it generates, and a temporary cavity that occurs early enough in the projectile's path to matter.

It should be noted here that Dr. Alvarez did not see a jet effect in the melon with copper jacketed ammunition, which was what would have been used with a 6.5 millimeter Mannlicher-Carcano rifle. He only speaks of having used soft nosed lead tipped hunting ammunition. As seen in Figures 3 and 4 below, the U.S. Army Wound Ballistics Lab's wound profiles for unjacketed lead hunting projectiles show they have a tendency to mushroom on entrance and create a large temporary cavity almost immediately. On the other hand, the copper jacketed military ammunition does not generate much of a temporary cavity until it has penetrated over 17 centimeters. The human head is approximately 17 centimeters in diameter and most melons are not much larger. Thus a skull or melon shot with jacketed ammunition would not begin to build much of a temporary cavity pressure diameter until near exit, if at all. This would explain why others who have also performed the experiment on melons did not see a jet effect with jacketed ammunition, but did with unjacketed lead hunting ammunition.

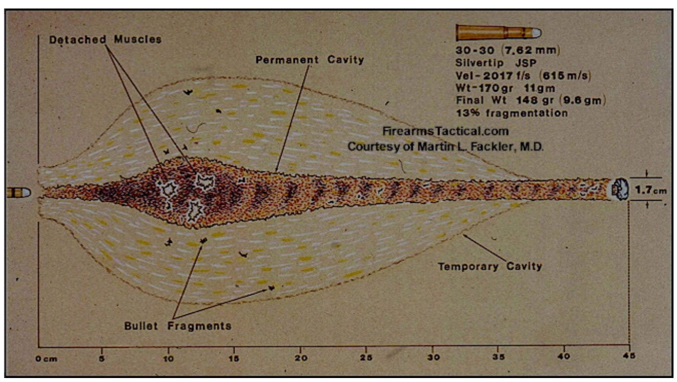

Figure 3. Lead hunting ammunition wound profile showing early generation of temporary cavity

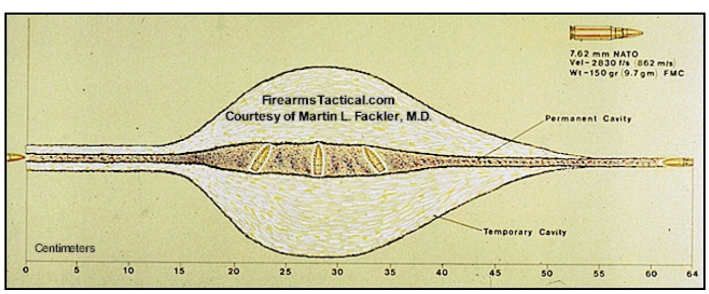

Figure 4. Copper jacketed ammunition wound profile showing late generation of temporary cavity

While Dr. Alvarez's experiments on tape bound melons could certainly have shown a jet effect, it would not be due to his hypothesis of more momentum in the forward moving jet than that brought in by the bullet, but to the residual pressure behind the projectile in the temporary cavity. With this pressure, and a cooperating permanent cavity simultaneously sealing for the moment, an unbalanced force could be generated opposite the direction of the projectile when the frontal pressure is relieved. However, there is a misleading element to the use of a melon for the tests, and that is that a melon is an object with a soft skin or casing, which would severely reduce the shear force. While the taping of the melon rind helped mock up the tensile strength of the human cranium, it did not help to replicate the shear strength of the human skull, and it is the shear strength of the human skull which would have been the significant parameter to replicate. The shear forces generated by the bullet penetrating through the much higher shear strength of the President's skull would have precluded the appearance of a jet effect induced motion in the assassination. This was actually demonstrated in testing at the U.S. Army's Edgewood Arsenal. Ten human skulls, filled with the same tissue replicating material as that used by the Army Wound Ballistics Research program, were shot with 6.5 millimeter ammunition. All ten skulls went forward, in the direction of the bullet, with none moving backward towards the shooter.

The backwards movement of a melon struck by a bullet may be possible with the use of soft nosed unjacketed lead hunting ammunition, but it is not possible, even in a melon, with jacketed ammunition, and finally it is not possible at all, with any type of ammunition, in the case of a human skull. It is clear that the melon tests were misleading, and the jet effect seen on the soft cased melons, with the use of unjacketed lead hunting ammunition, really has no place in attempting to explain away the back and to the left head motion of President John Kennedy as being possible if hit from the rear.

References:

1. Harris, "Shock and Vibration Handbook", 3rd Edition, Chapter 44, page 10, Table 44.2.

2. "Wound Ballistics", Firearms Tactical Laboratory article, Wound Profile Illustrations. http://www.firearmstactical.com/wound.htm