# Assessment of the transference of energy from a projectile to a target during a supersonic impact on the metallic lining of an explosive with a 1000000 fps high-speed camera

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## Abstract (nº 22196)

Based upon different Bullet attack and Fragment Impact insensitivity tests conducted in our test centre facilities, a FEM theoretical model adjusted to real data allows us to conclude that when a high energy speed projectile hits the metallic lining of a certain mass of an energetic composition, insensitive or not, the reaction occurs by thermal transference of the fragment's kinetic energy as far as its conic tip touches the item's shell, which happens before the projectile starts penetrating the item. In the case of a fragment impact complying with AOP-4496 Ed.A V.1 at 1860 m/s, we have a Kinetic energy of 32.17 kJ = 0.5*0.0186 kg*$1860^2$$m^2$/$s^2$ applied on a 1*$10^{-6}$ $m^2$ surface, that delivered with a short displacement produces a force that melts any material and starts the reaction of any energetic substance, whatever its insensitive properties. The conclusion of this research is that over the velocity limit that creates a pressure equal to the characteristic energetic threshold of the energetic material in the target, which is a function of the mechanical properties and the chemical composition of the target, any increase in the velocity of the projectile is irrelevant to produce the same reaction in any kind of energetic material. The footage recorded with a 1000000 fps high velocity camera proves that the reaction occurs when the tip of the projectile touches the surface of the target, which is before the penetration begins.

## 1. Introduction

In the current state of the art, according to STANAG 4496 Ed.2 / AOP-4496 Ed.A V.1 and STANAG 4241 Ed.3 / AOP-4241 Ed.A V.1, the way to determine the insensitivity of an explosive or energetic device containing a certain energetic composition must be empirical, and should be performed by means of shooting a standard projectile at a certain velocity against the device that we need to test.

Nevertheless, physics provides the differential equations that govern the energy exchange process, and any commercial code based upon FEM (finite element method) can evaluate the theoretical pressure reached at any point of the device during the penetration of the projectile. This means that we can predict the occurrence of the reaction if we know the energetic threshold of the energetic material in the device we want to test and all the physics of the impact, which encompasses masses, geometries, mechanical properties and chemical composition of the target.

On the other hand, using reversed engineering, it would be possible to evaluate the energetic threshold of an unknown composition if we determine with a convenient test the minimum velocity of the projectile at which the reaction occurs.

If we take into account that conducting a destructive test on an expensive device like a guided missile has an important cost, it would be convenient to run a FEM model beforehand to determine if the reaction of the energetic material is supposed to happen during the test.

It is also a fact that the occurrence of the reaction is not enough to make a proper assessment of the type of response as it is defined in Annex I to AOP-4439 Ed.D V.1 (Type I detonation, Type II partial detonation, Type III Explosion, Type IV deflagration / propulsion, Type V burning, Type VI no reaction), but if we can determine the velocity at which we reach

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the energetic threshold we can successfully predict if we'll be in the domain of burning to no reaction, or in the domain of explosion to detonation when we expose the target to the standard velocities prescribed in AOP-4496 Ed.A V.1 and AOP-4241 Ed.A V.1.

Complying with NATO standards means that at least one test can't be avoided, which is either the one that produces no reaction at the maximum velocity or the one that produces a significant reaction at the lowest velocity.

To get into those upper and lower limits, clients frequently need to perform more than one test, which accounts for a significant cost within the research and development process of a new device.

If we perform a simple and economical FEM analysis before testing, we can determine how close to the standard velocity limits the threshold velocity of the energetic material is, and we can not only choose the best impact velocity, but we can also make a proper assessment of the insensitivity of the new device with a single test.

## 2. Finite Element Analysis

### 2.1. FEM Code

We have used the version of Autodyn included in ANSYS 18.2.

### 2.2. Geometry

We can either define the geometry in a CAD application like CATIA 5 and import the file in ANSYS, or we can directly define the geometry of the parts in the Setup menu of Autodyn.

Whatever the case, we always try to create the most simple geometry that fits the real configuration of the test.

The most simple case is a bare mass of the energetic material exposed to the impact, as shown in figure 1 and figure 2.

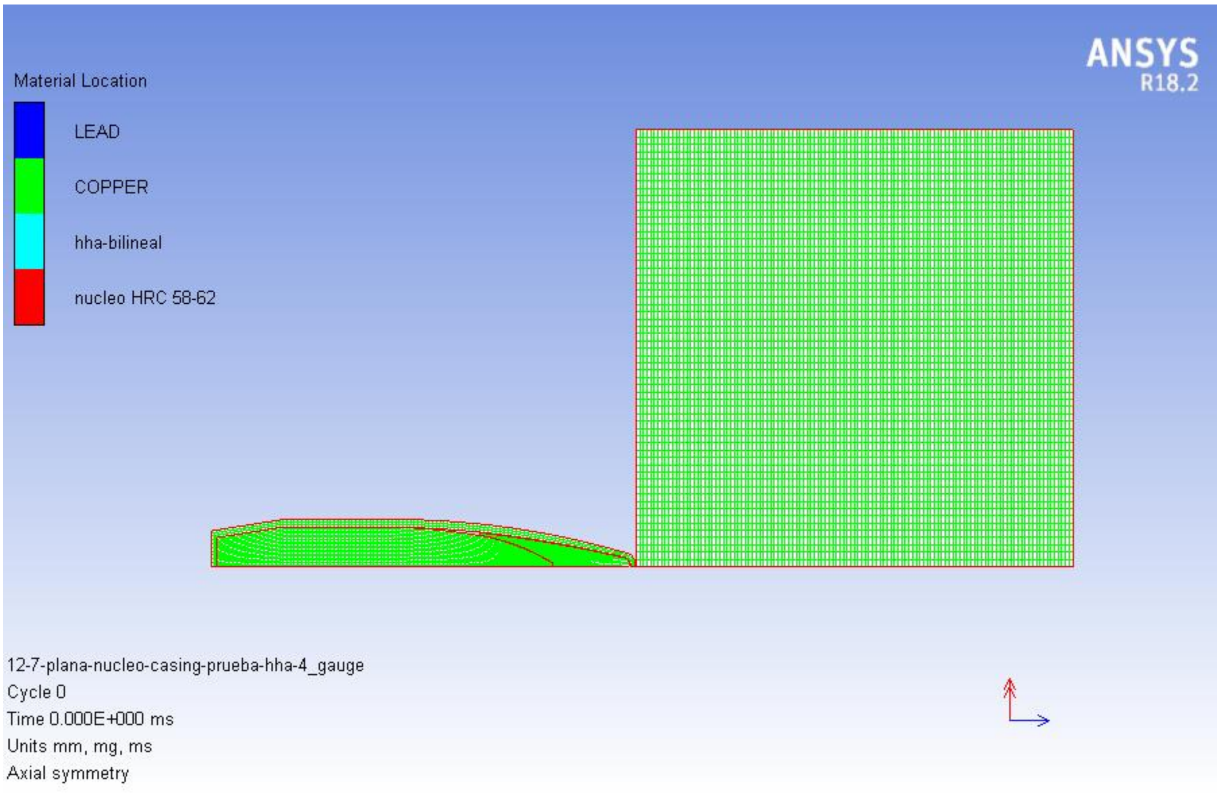


*Figure 1. Nodes in the model of a bare mass of the energetic material.*

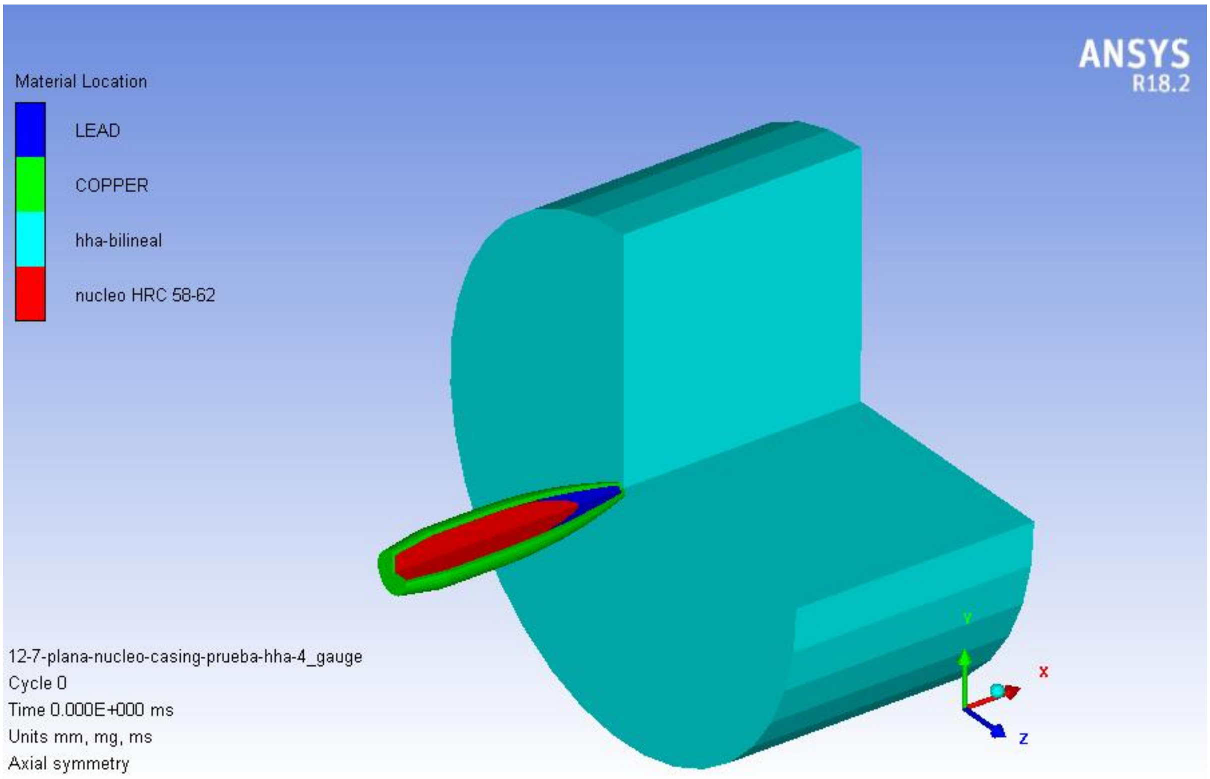


*Figure 2. Materials of the parts of a bare mass of the energetic material.*

However, the most frequent case is the energetic material inside a container or covered with a hard lining, as shown in figure 3.

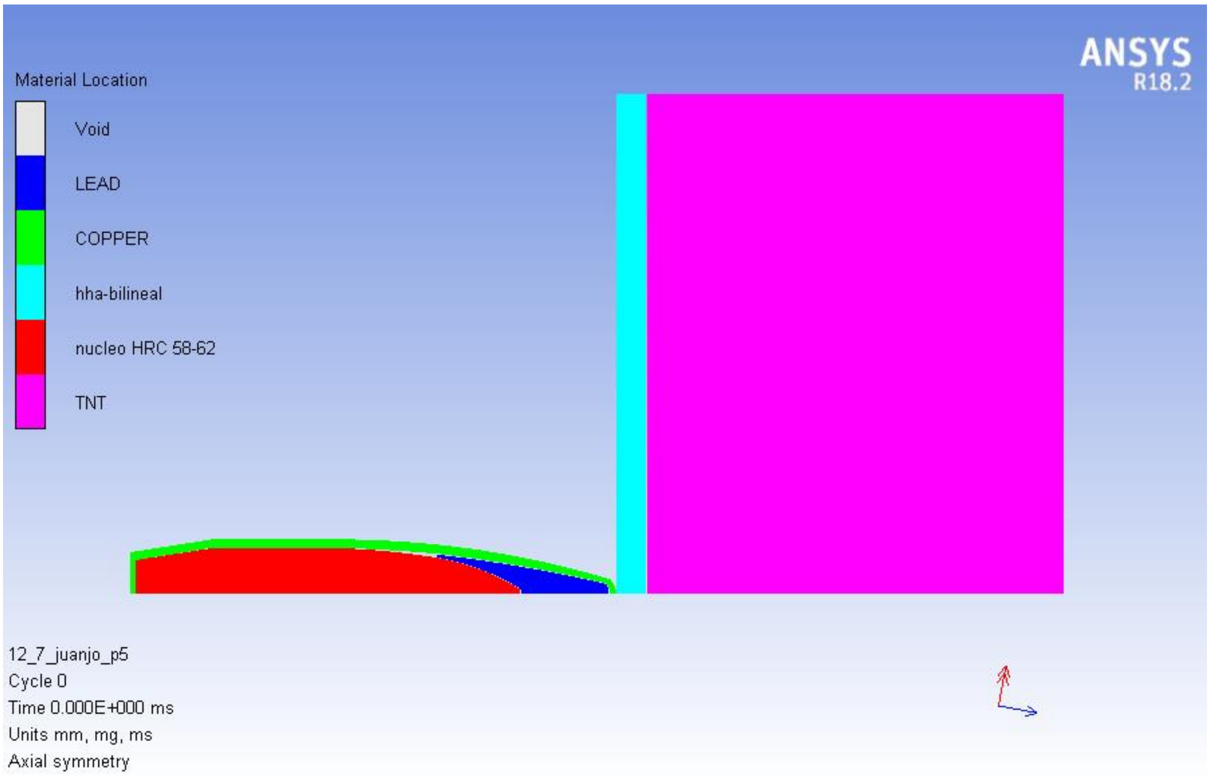


*Figure 3. Model of the energetic material inside a case.*

## 2.3. FEM fomulation

We normally use a Lagrangian formulation for all the parts, but sometimes it's useful to combine both Lagrange and Euler using an ALE formulation (Arbitrary Lagrangian-Eulerian), where the mesh and material deformations are uncoupled. In this case we use Lagrange for the projectile and the shell of the target, and Euler for the explosive composition inside the target, as shown in figure 4.

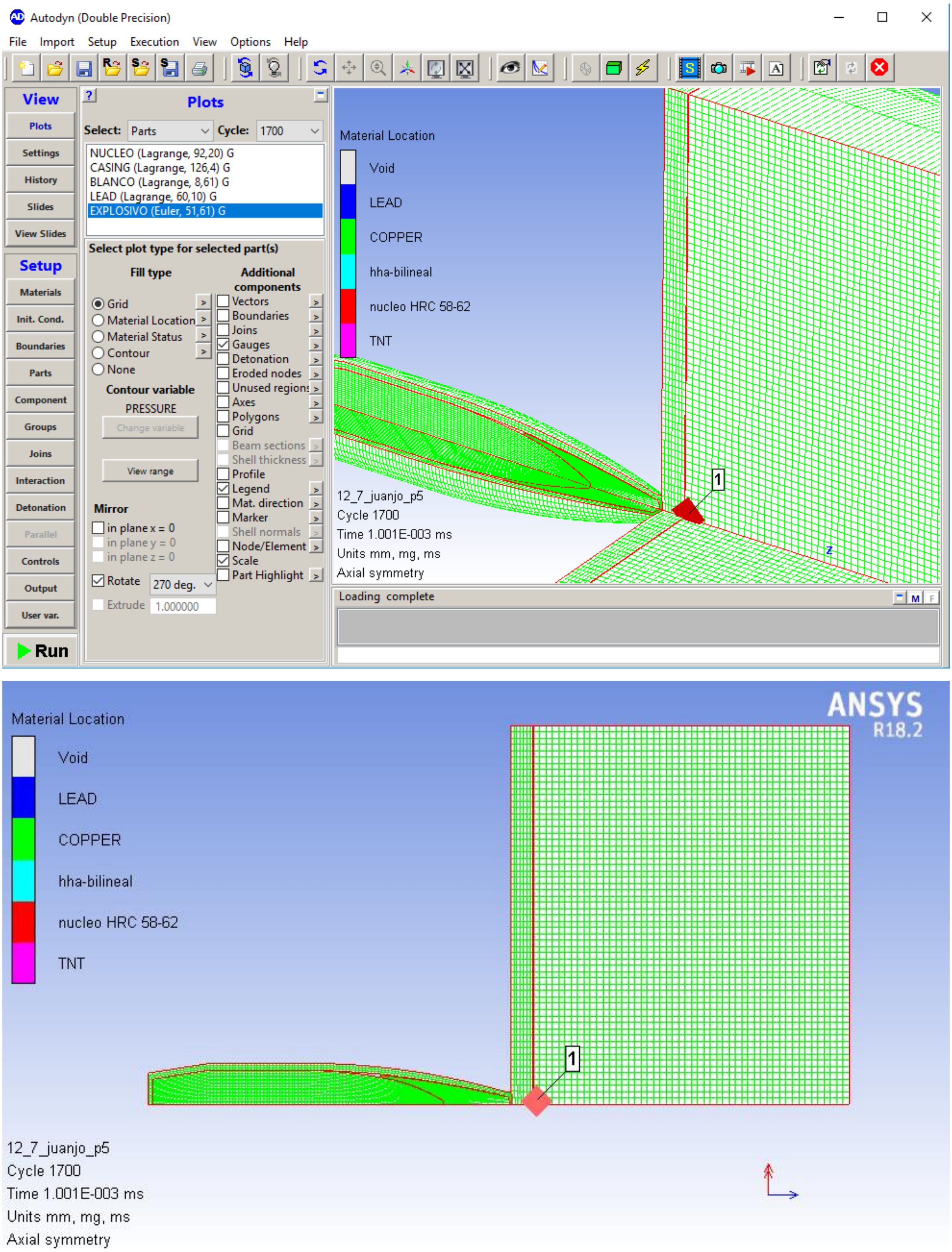


*Figure 4. Model in ALE formulation.*

### 2.4. Materials

The characterization of the physical and chemical properties of the energetic compositions is key, but when it is a new composition it must be the client who provides us with the data.

We've run the model changing the compositions included in the repository of Autodyn and in the data base of MSIAC, and we have concluded that the FEM model is more sensitive to the geometry and the velocity of the threat than to the accurate properties of the energetic composition. Actually, what really makes the difference is the energetic threshold of the chemical reaction.

Most propellants deflagrate the same, and most insensitive compositions react on the basis on a type V (burning) or a Type VI (no reaction).

### 2.5. Post-processing

In the case shown in section 2.3 we are running the simulation of the impact of a 12.7 mm AP projectile at an average velocity of 850 m/s with a gauge in the first Eulerian node in contact with the last Lagrangian node of the explosive's casing, that has a thickness of 3.5 mm.

At time = 1 ms, as shown in figure 5, we already have maximum pressure of $8 \cdot 10^9$ Pa in the Eulerinan domain measured with gauge 1 (figure 6) due to the conversion of the kinetic energy of the projectile into dynamic pressure when hitting a steel sheet 3.5 mm thick. Without the steel shell, the bullet would just pass through the explosive composition with a minimum pressure, which equals to no reaction at all.

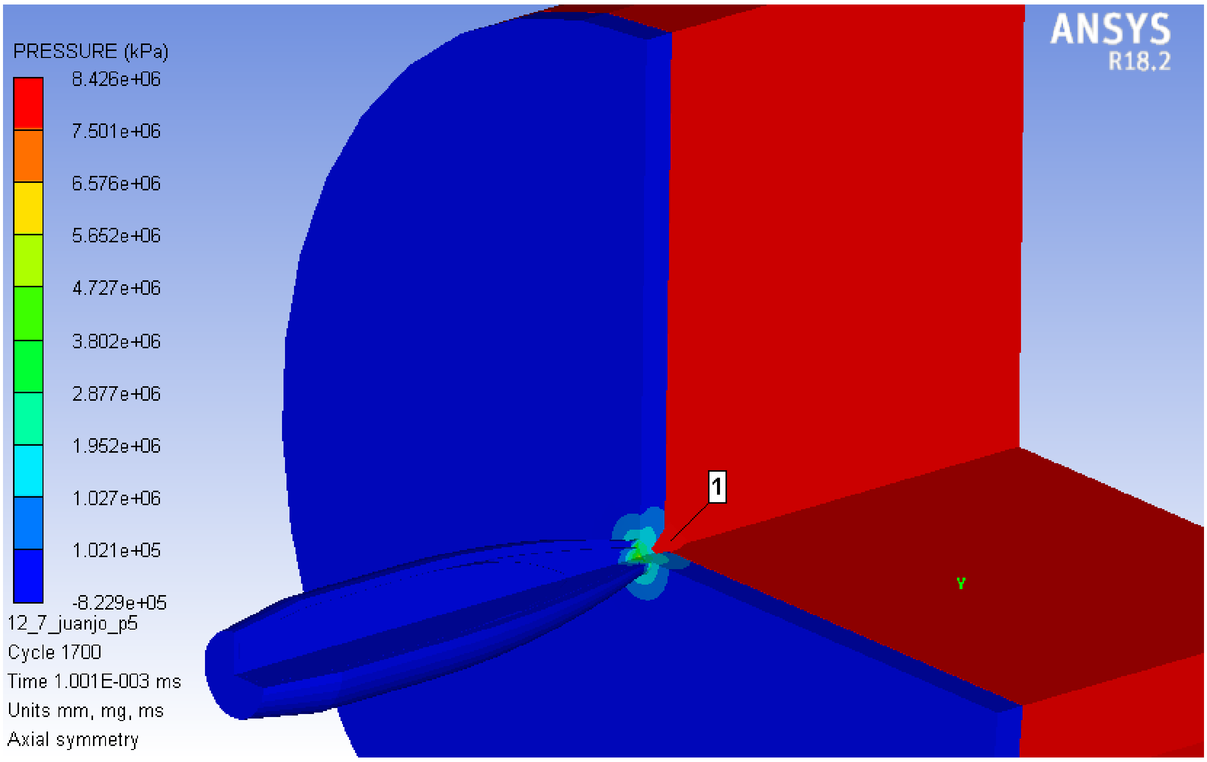


*Figure 5. Pressure field in the Lagrangian and Eulerian domain.*

This means that if we want to avoid the reaction of the explosive, we either need an energetic composition with a $8 \cdot 10^9$ Pa energetic threshold, or we should significantly reduce the thickness of the lining to reduce the pressure. If we change the material in the lining avoiding metals, we can get a significant reduction in the pressure achieved in the explosive mass. If we eliminate the lining, as shown in the chart in figure 7, we have a much lower peak pressure at the impact and pressure disappears as the bullet passes through the energetic mass.

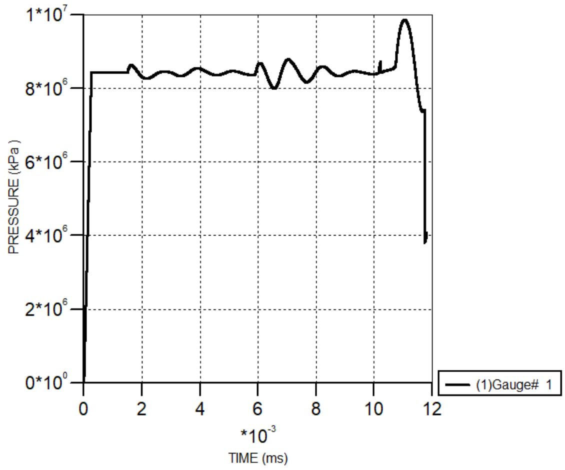


Figure 6. Pressure with a 3.5 mm shell.

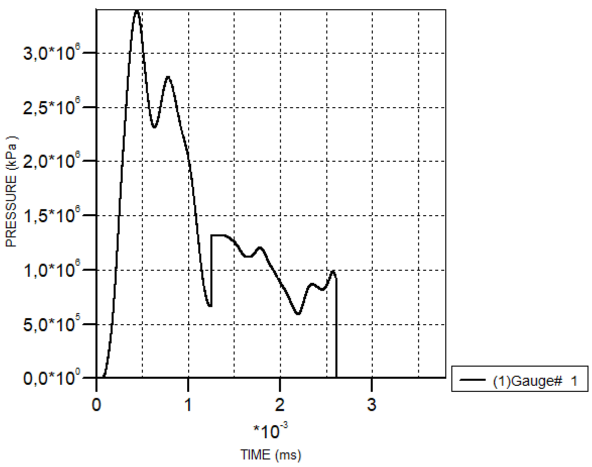


Figure 7. Pressure with a bare target.

If we have a propellant inside the lining instead of an explosive composition, as the reaction energetic threshold of the item is at least 3 orders of magnitude lower, we'll have propulsion. This is what happens to most rocket engines or gas generators in modern missiles. In this case, the immediate reaction of the energetic material prevents the projectile from following the course of a normal penetration in a non-reactive mass with the same mechanical properties, as we can see in figure 8.

If we change the 12.7 mm AP projectile for an AOP-4496 Ed.A V.1 fragment at maximum speed (2530 ± 90 m/s), pressures grow much more, but the reaction type is the same.

This is the reason why we recommend clients not to start their tests with fragment impacts if any type of significant reaction is expected, because if we start with bullet attacks according to AOP-4241 Ed.A V.1, we'll already get the most adverse reaction possible. Fragment impact, in our experience, never increases the adversity of the reaction in these cases.

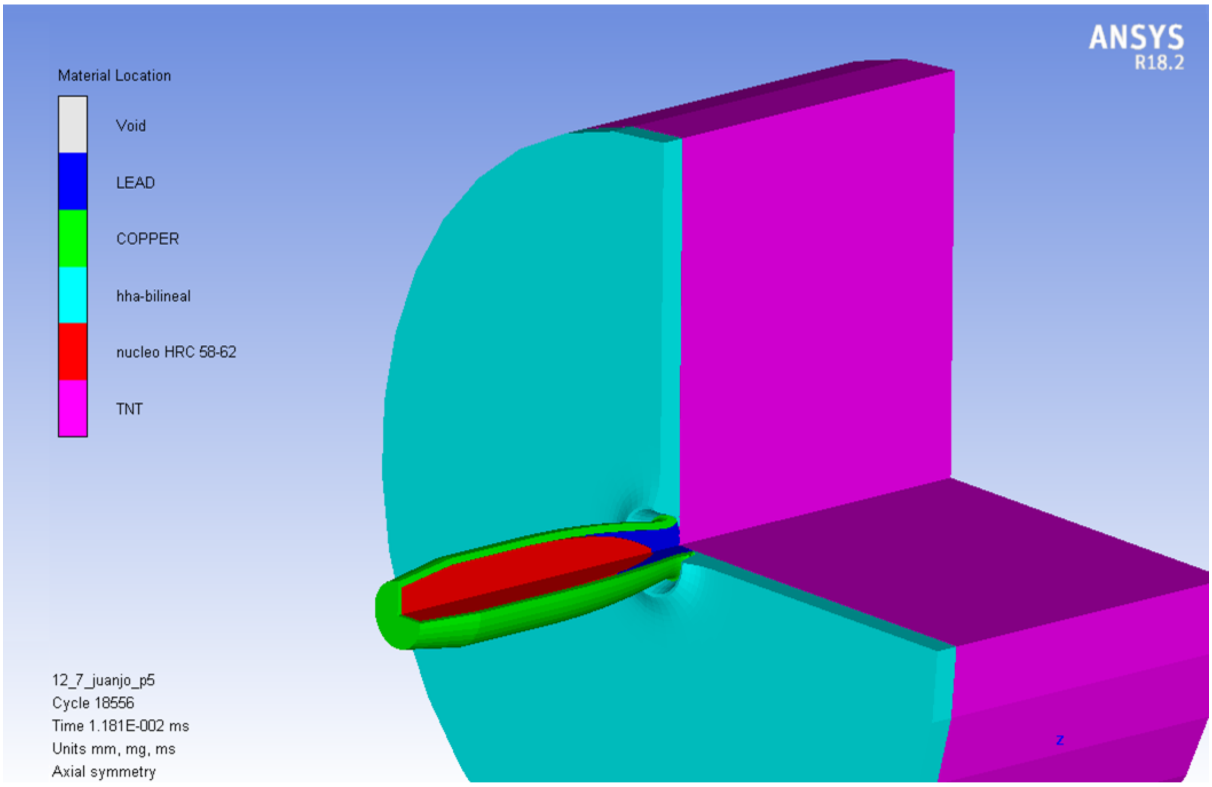


*Figure 8. Shell and reaction of the propellant containing the penetration of the projectile.*

## 3. Real test

A bullet impact test according to AOP-4241 Ed.A V.1 was performed on the surface of a rocket engine in our testing facilities in San Martín de la Vega, Madrid, so that the physics of the impact was perfectly coincident to the specifications in the FEM model in section 2.

The test was recorded with a 1,000,000 fps high speed camera, and we could see that the reaction in the energetic material of the rocket engine stated 0,00001 s after the tip of the bullet touched the surface of the rocket engine, as shown in figure 9, just before the bullet started penetrating the target as it was predicted in the theoretical FME model runned with Autodyn, which delivers a post-processed image identical to the real event, as shown in figure 10.

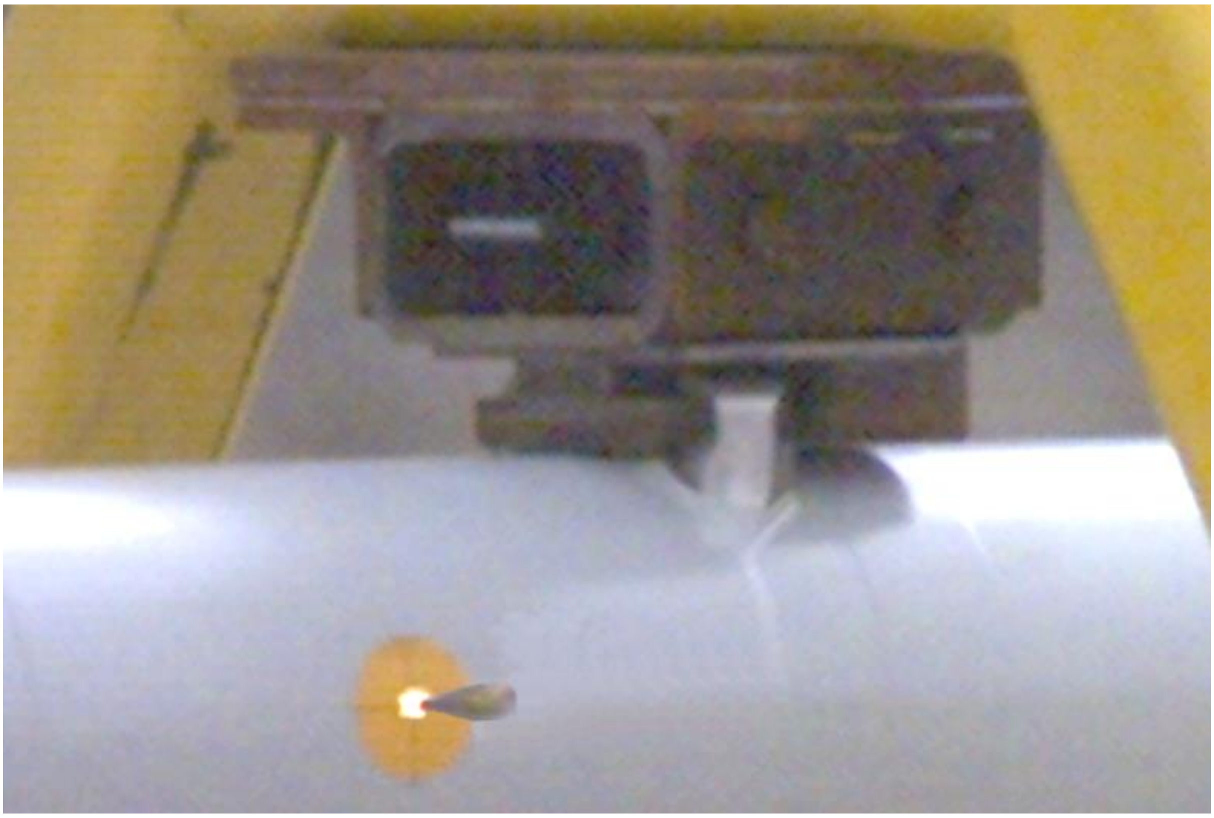

*Figure 9. Initiation of the reaction when the tip of the projectile hits the surface of the motor.*

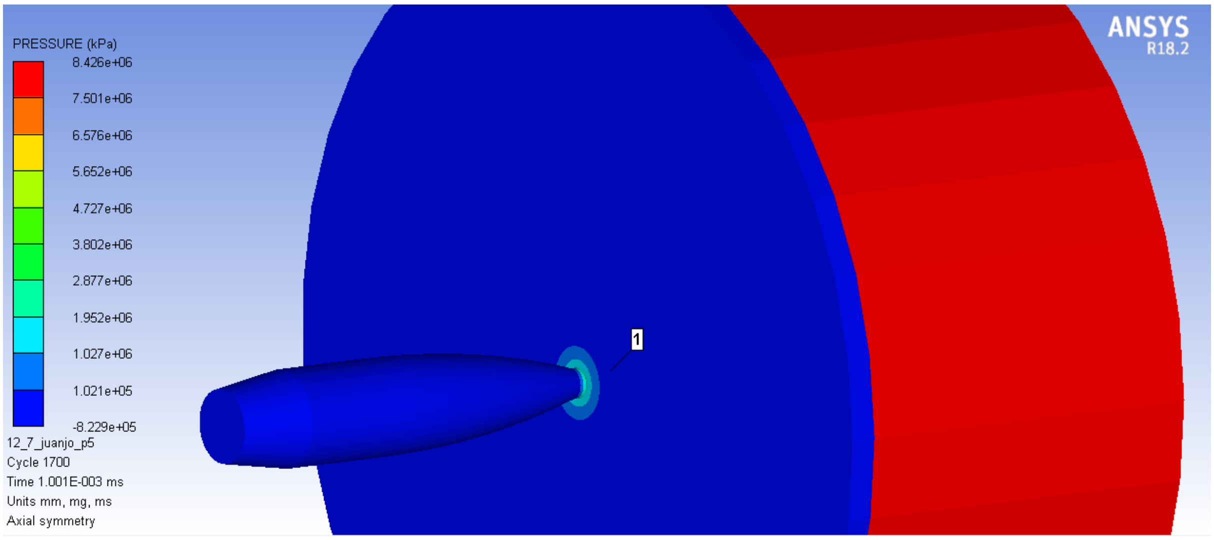


*Figure 10. Initiation of the reaction according to a FEM model processed with Autodyn.*

A second test with a fragment according to AOP-4496 Ed.A V.1 was performed in a second item of the same rocket engine, and the same reaction happened exactly the same way, when the conical tip of the fragment touched the surface of the rocket engine. The whole sequence is shown in figure 11 with a red dotted line showing the trajectory of the fragment in every slate.

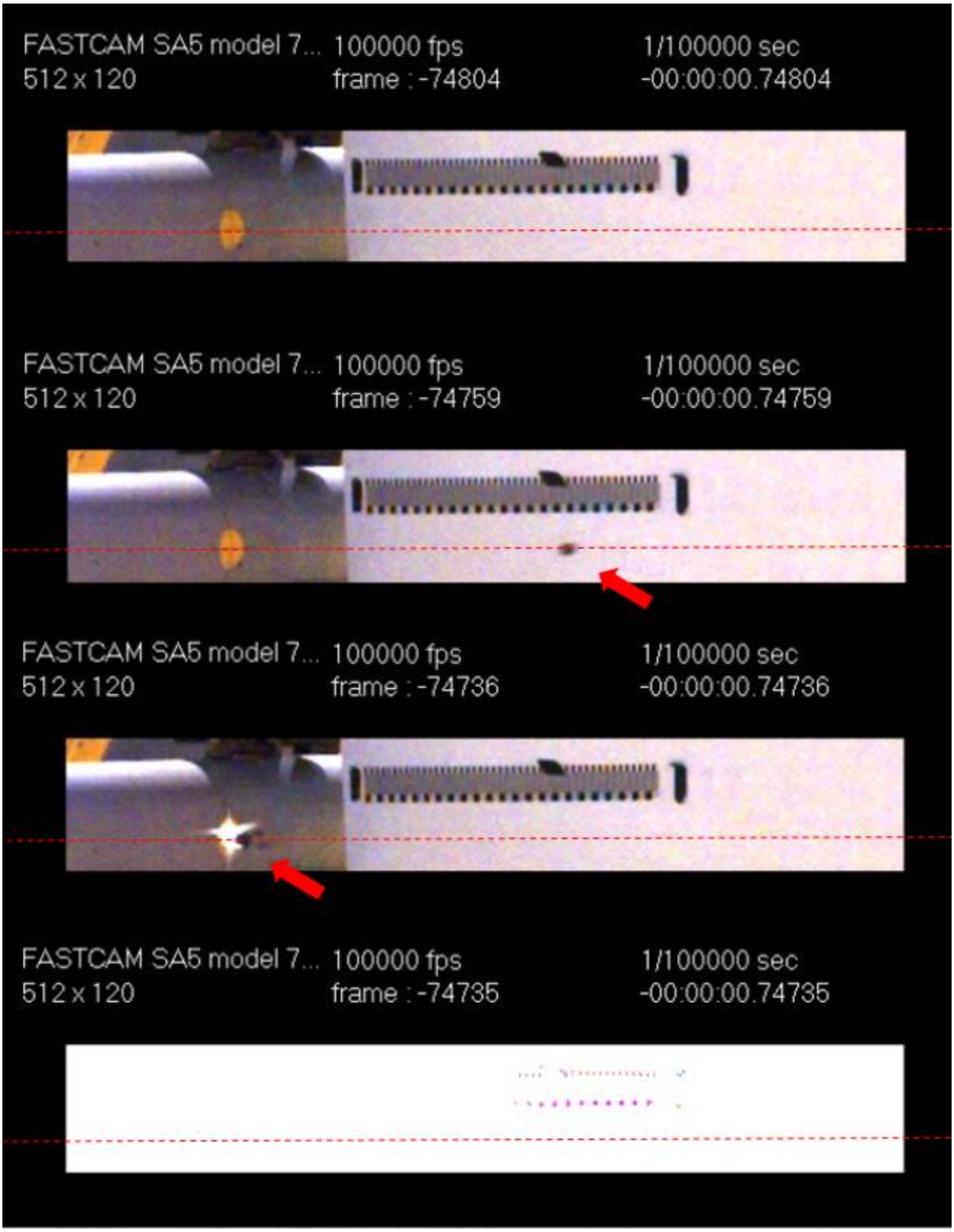


*Figure 11. Fragment impact on the surface of a rocket motor.*

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The fragment impact test was made with a 50 mm powder cannon (figure 12) shooting a 14.3 mm mild-steel right-circular cylindrical fragment with a conical nose inside a four-piece polycarbonate sabot, according to AOP-4496 Ed.A V.1.

*Figure 12. 50 mm powder cannon used in the fragment impact test.*

*Figure 13. Reaction of an item after a fragment impact test.*

## 4. Insensitivity tests in INTA

INTA can perform insensitivity tests on items up to 25 kg Explosive at La Marañosa Facilities on a flat and unobstructed 120 m diameter test area (figures 12, 13 and 14). Items with more explosive quantity can be tested at Las Bardenas Firing Range. All insensitivity tests are available:

- Fragment impact tests according to STANAG 4496 Ed.3 / AOP-4496 Ed.A V.1.
- Bullet impact tests according to STANAG 4241 Ed.3 / AOP-4241 Ed.A V.1.
- Fast cook-off tests according to STANAG 4240 Ed.3 / AOP-4240 Ed.A V.1.
- Slow cook-off tests according to STANAG 4382 Ed.2.
- Shaped charge jet tests according to STANAG 4526 Ed.3 / AOP-4526 Ed.A V.1.
- Sympathetic reaction tests according to STANAG 4396 Ed.2.

## 5. Conclusions

The conclusion of this research putting together the results of real tests with the prediction obtained with a FEM model processed with Autodyn code inside ANSYS 18.2 simulation suit is that the reaction in a certain energetic composition, either explosive or propellant, occurs when an infinitesimal fraction of its mass is excited with a mechanical pressure above its energetic threshold.

## 6. References

[1] STANAG 4439 Ed.4 “Policy for introduction and assessment of insensitive munitions”.

[2] AOP-39 Ed.D V.1 “Policy for introduction and assessment of insensitive munitions”.

[3] STANAG 4496 Ed.2 “Fragment impact test procedures for munitions”.

[4] AOP-4496 Ed.A V.1 “Fragment impact test procedures for munitions”.

[5] STANAG 4241 Ed.3 “Bullet impact munition test procedures”.

[6] AOP-4241 Ed.A V.1 “Bullet impact munition test procedures”.

[7] STANAG 4240 Ed.3 “Fast heating munition test procedures”.

[8] AOP-4240 Ed.A V.1 “Fast heating munition test procedures”.

[9] STANAG 4382 Ed.2 “Slow heating, munitions test procedures”.

[10] STANAG 4526 Ed.3 “Shaped charge jet munition test procedure”.

[11] AOP-4526 Ed.A V.1 “Shaped charge jet munition test procedure”.

[12] STANAG 4396 Ed.2 “Sympathetic reaction, munition test procedures”.

[13] Different INTA’s test plans and test reports.