



Development and validation of the JWL Equation of State for PE9 used in blast modelling

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“If I have a thousand ideas and only one turns out to be good, I am satisfied.”

- Alfred Bernhard Nobel

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ABSTRACT

The accumulation of aged and unstable ammunition poses a significant safety and logistical challenge, necessitating controlled disposal methods. Open detonation, a commonly employed technique, requires precise knowledge of the explosive properties to ensure effectiveness and safety. Accurate blast modelling is therefore essential for planning and execution. Central to blast modelling is the Jones-Wilkins-Lee (JWL) Equation of State (EOS), which characterises the pressure-volume relationship during detonation. However, not all commercial explosives have established JWL parameters, limiting their application in simulations and risk assessments.

This dissertation focuses on Plastic Explosive 9 (PE9), for which no parameterised JWL EOS currently at the time of writing exists. These parameters were derived by conducting controlled detonation tests using copper cylinder configurations and were recorded with ultra-high-speed shadowgraph imaging.

Image processing techniques were applied to track the radial expansion of the copper tubes, and the resulting data was used to calibrate the JWL EOS parameters for PE9. The derived parameters were then validated using LS-Dyna simulations and benchmarked against literature data from well-characterised explosives such as Composition B. The results demonstrate strong correlation and consistency with a deviation of only 2.88% for the expansion rate and only 0.004% for the peak pressure, supporting the reliability of the CSIR-developed methodology. Future work with optimized equipment is expected to further enhance the precision of these results.

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KEYWORDS / KEY TERMS

Blast modelling

Equation of State

Explosives

High-Speed Camera

Image analysis

JWL

ABBREVIATIONS

BKW	- Becker-Kistiakowsky-Wilson
BNC	- Bayonet Neill–Concelman
C4	- Composition 4
CH6	- RDX based booster
C-J	- Chapman-Jouguet
Composition B	- Composition B
CSIR	- Council for Scientific and Industrial Research
DBEL	- Detonics, Ballistics and Explosives Laboratory
DNT	- Dinitrotoluene
DoL	- Department of Labour
EBW	- Exploding-Bridgewire detonator
EOS	- Equation of State
FPS	- Frames Per Second
FS43	- Firing System 43
GPa	- Giga Pascal
HE	- High Explosives
HMX	- High Melting eXplosive
JCZ	- Jacobs-Cowperthwaite-Zwisler
JWL	- Jones-Wilkens-lee
KHT	- Kihara-Hikita-Tanaka
LJD	- Lennard-Jones-Devonshire
LS	-Livermore Software
MPa	- Mega Pascal

NC	- Nitrocellulose
NG	- Nitroglycerine
NTP	- Normal Temperature and Pressure
ODE	- Ordinary Differential Equation
OFHC	- Oxygen-free High Thermal Conductivity
PE4	- Plastic Explosive 4
PE9	- Plastic Explosive 9
PETN	- Pentaythritol Tetranitrate
PFV	- Photron FASTCAM Viewer
PMMA	- Polymethylmethacrylate
P-V	- Pressure to Volume
RDX	- Research Department eXplosive
SAP	- Lagrangian finite difference code
SEP	- Spherical/Cylindrical High Explosive
TATB	- Triamino Trinitrobenzene
TMD	- Theoretical Maximum Density
TNT	- Trinitrotoluene
TTL	- Transistor-Transistor Logic
UHSP	- Ultra High-Speed
VOD	- Velocity of Detonation
ZND	- Zeldovich-Von Neumann-Doering

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CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND

The accumulation of aged and unstable munitions poses a significant safety and logistical challenge, necessitating controlled disposal methods. Munitions disposal requires precise knowledge of the explosive properties to ensure effectiveness and safety.

There are two methods of commonly employed munitions disposal, namely Open Detonation and Open Burning. These two methods have been an expedient means of disposal since the banning of dumping. Open Detonation has recently come under increased scrutinization for its potential environmental impact and has been banned in some countries. But it is still a commonly employed method of munitions disposal in most other parts of the world. [1] [2]

Open detonation can be done where the aged munitions are found and is called Blow-In-Place. When the munitions are safe enough to move to another location for open detonation, it is then called Consolidated Detonation. In both cases a donor explosive is placed next to the munitions to initiate a sympathetic detonation to destroy the munitions. [1] The detonation can be controlled to ensure maximum safety and reduce risk as much as possible by characterising the donor explosive.

The JWL EOS helps to characterise the properties of an explosive material and is used in blast modelling which also helps to develop more efficient armours or counter measures. The lack of a parameterised JWL EOS makes it difficult to do any blast modelling and development of protective measures.

1.2 PROBLEM STATEMENT

The general problem is that the parameterised Jones-Wilkins-Lee (JWL) Equation of State (EOS) for many explosives do not exist.

Plastic Explosives 9 (PE9) is amongst the explosive substances that do not have a parameterised JWL EOS available at this moment, while many other more common explosives, like C4 and TNT, have parameterised JWL EOS's already developed and is the explosive that was chosen for completing this research.

1.3 RESEARCH QUESTION

What is the parameterised Jones-Wilkins-Lee Equation of State for Plastic Explosive 9.

1.4 AIM AND OBJECTIVES

The aim of this dissertation is to develop and validate the parameters of the JWL EOS for PE9.

The objectives to achieve the aim are:

- Gather and compile all the remaining scattered information.
- Gain experience in using the Ultra-High-Speed camera.
- Gain experience in using LS-Dyna and fix the simulation model.
- Develop a numerical model to do calculations by using Excel.
- Gather and prepare the necessary materials and equipment.

- Perform mock field tests to gain experience with safety protocols.
- Execute tests to extract data for JWL EOS parameterisation.
- Verify the CSIR method using previous test data.
- Verify the LS-Dyna computer model using previous test data.
- Validate the JWL EOS parameters for PE9 using the LS-Dyna computer model.

1.5 RESEARCH METHODOLOGY

The previously developed CSIR high-speed camera methodology needs to be used to produce and collect the data required to develop and validate the parameters of the JWL EOS for PE9. These tests will be conducted at the specialized facilities of the CSIR in a controlled environment where all the relevant variables can be measured with specialized tools. This CSIR high-speed camera methodology is a very efficient method, comparable to the standard streak-camera method.

The unknown parameters can be determined through curve fitting of the JWL EOS to the Pressure-Volume curve. This is done through the method developed at the CSIR where inputs are converted through multiple steps and plotted on a graph. These inputs are gained from analysing images that are taken from field tests. The images are taken with a Cordin Ultra-High-Speed camera at around 1.5million frames per second (FPS) and are analysed for the expansion rate of a copper cylinder during stable detonation.

The method can be verified by doing a similar test but with another type of explosive, like Composition B which has a lot of data available and comparing the resulting values with those found in literature. This will confirm whether the method and equipment used are valid and

that the results for the main tests will be valid as well. The actual test results can be validated by comparing the test results to the LS-Dyna blast model results.

1.6 LIMITATIONS AND CONCERNS

A concern for this project was the lack of experience regarding the operation of the equipment, since the experienced operators who developed the method have all left the employment of the CSIR. This was in 2017, and all new tests were done using old reports as reference. A risk assessment was done and is added in Appendix C

One of the main concerns was the Ultra-High-Speed camera that needed to be used. It was in an advanced stage of disrepair when the project started and had to be fixed for use. In the end it was discarded for another camera, the Nova S6, which performed the tests satisfactory.

The LS-Dyna computer model that was used was also outdated and had to be updated to the newest version to be ready for use in the simulations. This took a considerable time to address properly due to the steep learning curve of the program.

Budget limitations and expenses were a limiting factor. Everything needed to be planned precisely and executed with little room for error, since each test is expensive to carry out. PE9 is only one of many explosives that can be used and testing every single unparameterised explosive was outside the scope of this dissertation.

CHAPTER 2 - LITERATURE STUDY

2.1 CHAPTER INTRODUCTION

This chapter gives a literature review into the history, background, and the different aspects of explosives. This chapter gives insights into how explosives work and the different types of tests that can be done to determine the explosive power. The methods to quantify explosives as well as the different aspects of the explosive that must be considered for these quantification tests are discussed and explained.

2.2 HISTORY

2.2.1 GENERAL INFORMATION

Most of today's modern explosives are made of multiple chemical substances, or composite mixtures, as opposed to single chemical substance explosives. This is purely for practical purposes since the ingredients of the composite mixtures can be varied in quantity to obtain the preferred properties for each application. [3]

Blackpowder and smokeless powder are examples of early composite explosives. With blackpowder being an intimate mixture of charcoal, sulphur, and potassium nitrate. An interesting feature of blackpowder is that none of its components, on their own, are explosive. [3]

Some explosives have a plastic consistency and are called "Plastic Explosives". This is due to them consisting of a plastic substratum containing a polymeric component such as polysulfides, polybutadiene, acrylic acid, polyurethane, etc. Plastic explosives can also be made from mixtures of RDX and Vaseline or gelatinized liquid nitro compounds and are easy to use. [4]

Some liquid explosives contain liquid oxygen or some other type of liquid oxidizing agent such as nitrogen dioxide. Liquid oxygen explosives are explosives with a combustible absorbent material like wood dust or cork meal impregnated with liquid oxygen. [3] [4]

Finally, there exists a group of explosives with selected components to fulfil selective tasks. These mixtures contain combustible components to increase the heat of explosion by a considerable amount. Components such as aluminium, ferrosilicon, etc utilize the oxygen contained in the explosive to burn. [3]

It is estimated that there are approximately 20000 known molecules that are explosives, but only 600 of them have been studied enough to have been identified for explosive use. [5]

2.2.2 HIGH EXPLOSIVES – PLASTIC EXPLOSIVES

Dynamite is an example of a plastic explosive and contains a high amount of a liquid constituent such as nitroglycerine, usually with dissolved high viscosity polymers. Guhr dynamite, which is no longer in use, is composed of 75% nitroglycerine and 25% kieselguhr. It is the first explosive to have a plastic consistency due to the high proportion of liquid. [3]

Another plastic explosive is blasting gelatine and consists of 92-94% nitroglycerine and 6-8% collodion cotton (high viscosity). This makes blasting gelatine remarkably elastic but loses this elasticity on heating to temperatures over 40°C. This temperature barrier may vary depending on the amount and type of collodion cotton used. [3]

Originally dynamite and blasting gelatine was proposed for use as military explosives, particularly for filling low muzzle velocity shells. This idea was abandoned when it became clear that fillings with nitroglycerine explosives may cause premature detonations inside the

barrel. Now they are only used for civil purposes. During World War 1 the Russian air force used bombs filled with a substance resembling blasting gelatine. [3]

For some time, dynamite was used for military purposes as demolition charges. Their limited chemical stability during extended storage times were a major disadvantage and were therefore replaced by explosives that remained chemically stable and unchanged for longer periods of storage. [3]

An explosive's plasticity can be put to practical use for demolition purposes. The plastic explosive can easily be moulded to fit the shape of the object to be destroyed, objects such as an iron bar, wall, or rock containing ore or that needs to be removed for tunnels or infrastructure. [3]

Blasting gelatine is not entirely safe to handle in this context, being elastic and thus difficult to shape. Attention was directed to developing plastic materials based on other constituents, mixtures comprising a collodion cotton solution in liquid aromatic compounds as plasticizers. If a nitroglycerine rich mixture is used, it can be converted into a plastic mixture by adding collodion cotton. [3]

During World War 2, plastic explosives with cyclonite as main constituent were used extensively since cyclonite detonates easily, even when heavily phlegmatized (desensitized to impact), and has an extremely high rate of detonation. [3]

Plastic explosives originally started with a mixture of 88% cyclonite and 12% lubricating oil. This mixture was not sufficiently plastic and lost its plasticity at high temperatures by easily exuding oil. This mixture was replaced by one named Composition C-3, which consisted of 77% cyclonite and 23% gel made from liquid nitro compounds, such as liquid DNT (dinitrotoluene), and nitrocellulose or of butyl phthalate and nitrocellulose. [3]

Composition C-3 was later improved upon and designated C-4 and contains: [3]

- 91% cyclonite (RDX)
- 2.1% polyisobutylene
- 1.6% motor oil
- 5.3% di-(2-ethylhexyl) sebacate

C-4 is less volatile than C-3, has a density of 1.59, does not harden even at -55°C, and does not exude at 77°C. PE9 is a relatively new explosive developed in South Africa and is reported to be similar to C-4 in performance and contains 90% RDX. [3]

2.3 CLASSIFICATION OF EXPLOSIVES

Explosives have been defined in many ways, with one universally accepted definition being: "An explosive is a chemical or mixture of chemicals which, when suitably initiated, can react so rapidly and with such a liberation of energy that there can be damage to the surroundings."

Explosives are classified in the following two ways: [6]

1. High explosives (HE) otherwise known as detonating explosives (Subdivided into primary and secondary explosives)
2. Low explosives, also known as deflagrating explosives or propellants

Propellants are what propel projectiles from rifles, mortars, cannons, etc. as well as the self-propelled devices such as rockets. All of these fall under low explosives. They deflagrate layer by layer at certain rates creating high amounts of high-pressure hot gasses that propel the device or projectile forward. [6]

Primary explosives are sensitive to mechanical impact, flames or even sparks. Primary explosives are used to initiate secondary explosives due to their sensitivity to outside triggers. This is done because secondary explosives are insensitive to these outside triggers. Secondary explosives detonate with violence and a lot of stored energy creating a high-velocity shock and blast wave, while primary explosives detonate less violently and with less energy, but still with enough to initiate the secondary explosives. [6]

Explosives may also be classified according to their use, i.e., commercial (civil) explosives or military explosives. The cost, properties and use vary between these two categories and is expanded upon in the following subsections. [6]

2.3.1 HIGH VELOCITY DETONATION

The Velocity of Detonation (VOD) is the rate at which an explosive shock wave front travels through any explosive medium and is measured in either kilometres per second or meters per second. This aspect is important in military explosives since it is directly proportional to the shattering effect of an explosive on detonation as well as the velocity of a jet created by a shaped charge. [6]

2.3.2 ABILITY TO WITHSTAND LARGE ACCELERATIONS

The types of ammunition filled with HE need to be able to withstand great amounts of acceleration and deceleration and should not be initiated by such accelerations. Such as when an HE explosive is fired from the barrel of an artillery piece, the accelerations can reach up to 20000 G's. [6]

Commercial explosives generally do not require a high VOD or a high blast effect. In certain commercial applications such as coal mining, a high VOD can prove to be fatal since a high-velocity shock wave might result in adiabatic compression and the resulting initiation of methane present in the coal mines. The composition of the explosive can be adjusted to suit its application as best as possible. [6]

The cost of explosives is a dominant determining factor for commercial use; an expensive explosive will not sell when cheaper alternatives are available that can perform adequately for the same task. [6]

2.3.3 HIGH EXPLOSIVES

High explosives have three categories of importance: [6]

1. High-density, high-VOD explosives with their superior power and volumetric efficiency, can impart great lethality to ammunition of the future.
2. Insensitive explosives are important due to their safety during storage and transportation and their lower risk to accidental initiation during combat.
3. Thermally stable explosives are important when the explosives need to operate in high-temperature environments, and this may affect their performance adversely. An example of such scenarios being a warhead of supersonic missiles in which aerodynamic heating has a big impact, or oil well exploration applications.

For high explosives it is impossible to have all three of these qualities at the same time, thus a compromise must be struck between the different qualities. For an explosive that is less sensitive and thus safer, some of the power will be lost. For a more powerful explosive, the sensitivity of it is increased and more care is needed while handling. This has to do with the

replacement and shuffling of molecule groups to achieve the desired results for specific applications. [6]

High explosives can be further subdivided into classes depending on their Figure of Insensitiveness (F of I). Very sensitive explosives with an F of I of 50 or smaller include both primary and secondary explosives. Primary explosives include but are not limited to Mercury Fulminate, Tetrazene, Lead Styphnate, Lead Azide and Silver Azide. Secondary explosives in this category include Nitrocellulose (dry), Nitroglycerine, PETN, Gunpowder and HMX- α . [7]

The second class is the sensitive explosives with an F of I between 50 and 100 and are made up of secondary explosives such as HMX- β , RDX and Tetryl. [7]

The final class is comparatively insensitive explosives with an F of I of over 100 and is made up of secondary explosives including TATB, Picric Acid, TNT, Nitroguanidine, Amatols and Torpex. [7]

2.4 UNDERSTANDING EXPLOSIVES

2.4.1 EXPLOSIVES: UNDERSTANDING THE BASICS

An explosive has huge potential energy stored, or “bottled-up”, and is kept in a metastable equilibrium ever ready to detonate. The energy produced by the explosive compared to that which is needed to create it can be better explained by an example where a huge boulder is brought to the top of a cliff. [6]

Substantial energy is needed to get the boulder to the top of the cliff where it is kept in a metastable state. When required, a little more energy is spent to push the boulder over the apex of the cliff, and the boulder falls to the ground due to gravity. This potential energy is

converted into kinetic energy as the boulder falls and is dissipated into heat and sound energy as well as fracturing when it hits the ground. [6]

The same applies to explosives. A large amount of energy is packed into an explosive molecule through synthesis; these potential energies are high bond energies, structural strain energies, etc. The explosive is also kept in a metastable state at the cusp of detonation with all the stored potential energy being the energy needed to manufacture the explosive. This energy is also referred to as the heat of formation. The explosive is then detonated through a small initiation energy, and all the stored energy is then released. [6]

A successful explosive synthesis is when the product has a high positive heat of formation (the explosive molecule has a higher level of energy than the elements from which it is made), there is enough internal oxygen for the explosive to react fully without oxygen from outside the explosive and the explosive creates large amounts of gases. The first and second is to ensure that the explosion creates large amounts of heat, called the heat of explosion, increasing the temperature of the exploding products to over 2000°C. [6]

The third will result in many gases at high temperatures creating extremely high pressures. These gases expand rapidly outward to atmospheric pressure, performing a large amount of work in a noticeably short time. This work can be altered to the specific need such as a blast effect of an explosive, accelerating a projectile through a gun barrel or propelling a rocket into orbit. This work can be performed over a time of a few microseconds to a couple of minutes. [6]

Not all explosive reactions need an oxidation reaction even though most chemical explosives involve fast oxidation of its fuel elements. Lead azide is one of these well-known primary explosives and contains no oxygen atoms in its molecule. It does however have a positive heat of formation with the azide groups attached to the lead atom having weak linkages and

themselves being at a higher energy level. This results in the need of a small initiating energy to rupture the linkages and produce more stable products through the explosive reaction. [6]

2.4.2 THERMOCHEMISTRY AND EXPLOSIVE ENERGY

The practical use of an energetic material is often determined by its energy content. The accurate estimation of this energy content is useful in the design of new materials as well as for understanding quantitative detonation tests. Detonation occurs on a microsecond timeframe and any chemical reaction slower than this is not considered relevant when detonation is considered. Energy content is determined by the anticipated release mechanism which can be looked at through thermodynamic cycles. Detonation can be considered a cycle that transforms unreacted explosive into a stable product at the CJ state, with the CJ state being the slowest steady shock state where mass, momentum and energy are conserved. Deflagration is the conversion of unreacted propellant into a product at constant enthalpy and pressure. The nature of the CJ and other thermodynamic states of energetic materials is strongly influenced by the EOS of the stable detonation products. [8]

When energetic materials react, chemical equilibrium is often nearly achieved due to the high temperatures produced by such reactions. Explosives produce product at extreme temperatures and pressures, 6000K and 40 GPa respectively. Shock experimentation has generated sufficient information on a wide range of materials to allow reasonably reliable material modelling. [8]

One attractive feature about thermodynamic modelling is the little amount of information required regarding the unreacted energetic material. The only information needed is the elemental composition, heat of formation, and density. Once the material is specified the

elemental composition is known and only density and heat of formation need to be determined. [8]

CJ detonation theory implies that explosive performance is determined by the CJ state and the connected adiabat. The allowed thermodynamic states behind a shock are intersections of the Rayleigh line and the shock Hugoniot, with the Rayleigh line expressing conservation of mass and momentum and the shock Hugoniot expressing the conservation of energy. CJ theory states that stable detonation occurs where the Rayleigh line is tangent to the shock Hugoniot curve. This point can be determined, assuming the Equation Of State (EOS) $P = P(V, E)$ of the products is known. Thermochemical codes must simultaneously solve for chemical concentrations as well as state variables since the chemical composition of the products change with thermodynamic state. This is not a problem since the EOS of fluid and solid products is known and can be solved relatively straightforward. [8]

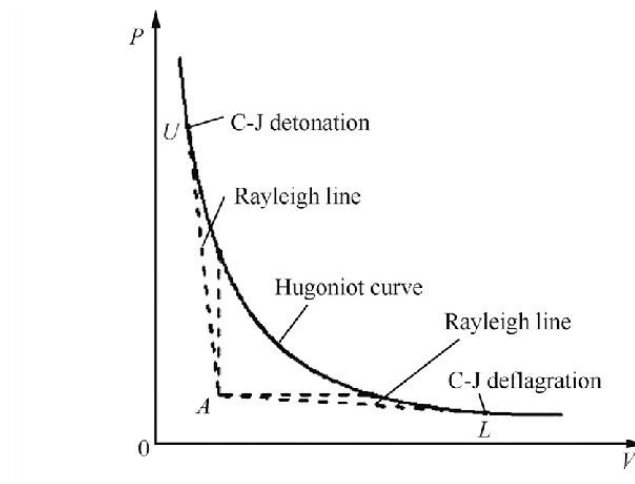


Figure 1: Hugoniot Curve [8]

2.4.2.1 GAS VOLUME

When an explosive is detonated, and undergoes explosive decomposition, it produces high-pressure and high-temperature gaseous products. The high-pressure gasses expand until

they reach atmospheric pressure, and in doing so they do work as they expand. Since the volume of the solid explosive is negligible compared to the volume of the expanded gasses, we can write: [6]

$$PV = nRT \quad (1)$$

Where P, V, n, R and T represent the final pressure, volume, number of moles of gasses, universal gas constant and temperature after expansion, respectively. [6]

Generally, the volume of the expanded gaseous products is calculated at atmospheric pressure (1 bar) and 273K, the normal temperature and pressure (NTP). The volume varies from 700 to 1000 cc/g for most explosives at NTP. [6]

2.4.2.2 PRESSURE OF EXPLOSION

When an explosive undergoes deflagration in a closed container, high-temperature gasses in large amounts produce a high pressure. The total amount of work done by expanding gasses is directly proportional to the pressure produced by the expanding gasses. The pressure of explosion is defined as the maximum static pressure of an explosive that is burned in a closed container with a fixed volume. This is assuming that adiabatic conditions are present. [6]

At such high pressures, a gas is non-ideal, and a correction needs to be made for the volume of gas molecules. The pressure of explosion (P_e) is not the same as detonation pressure, which is the pressure at the detonation front when a shock wave travels through an explosive medium. [6]

2.4.2.3 DENSITY

Density is an important part of explosives and propellant, such that an increase in density results in an increase in VOD and brisance. The actual density, or Theoretical Maximum Density (TMD), can be determined using conventional methods. The density may be slightly less to varying degrees during filling of warheads for example, due to fine voids that may occur during the process. Thus, the goal is to maximize density to as close to TMD as possible when handling explosives. [6]

2.4.2.4 EXPLOSIVE POWER AND POWER INDEX

Explosive power of an explosive is defined as the multiplication of the volume of gas and the heat of explosion. Each of these can be calculated separately since during an explosion both heat and gases are liberated. This explosive power is then compared to the standard explosive power, the explosive power of Picric Acid, to give it as a percentage of standard explosive power. Primary explosives have lower percentages and secondary explosives have higher percentages. [7]

2.4.2.5 MIXED AND ENERGIZED EXPLOSIVES

Most explosives are optimized for certain roles by use of mixing in other components that contribute to one or other attribute of the explosives. Some added components may not contain oxygen and may not contribute to the heat liberated during detonation. Some components contribute to the gaseous products, or the temperature obtained on the detonation of the explosive. [7]

The heat of explosion can be increased by adding a fuel with a high heat of combustion such as beryllium, which has the highest heat of combustion. Other elements include boron and aluminium with aluminium being relatively cheap and useful. Aluminium is used in commercial blasting explosives, most notably the water-based slurry explosives which contain a high percentage of ammonium nitrate. This is to increase the performance of the explosives for maximum usefulness. [7]

2.4.3 EXPLOSION

Explosion is a common word used in life when talking about certain subjects, even though “bursting” and “detonation” are synonymous to explosion. The word “explosion” is loosely used for a vast array of different situations such as “a balloon explodes”, “a bomb explodes”, “a gas cylinder explodes” and so on, even though these situations differ greatly in certain ways, such as: [6]

- Type of energy released
- Quantum of energy released, and
- Rate at which energy is released.

Explosions can be classified in three different types: [6]

- Physical explosions
- Nuclear explosions
- Chemical explosions

Physical explosions are when materials or systems undergo fast physical changes that result in explosions such as an overheated water boiler. Water in its liquid state gets converted to its vapour state at boiling point, no chemical changes take place. Since water vapour occupies a much larger volume than water in its liquid state, the pressure increases to the point where the boiler container ruptures violently. [6]

Nuclear explosions are disastrous because of enormous amounts of energy being released as thermal energy, light, pressure, and radiation. Either the splitting of atomic nuclei (fission) or the joining of atomic nuclei (fusion) triggers this catastrophic release of energy. [6]

A chemical explosion can be subclassified into deflagration and detonation. Most chemical explosions involve rapid chemical reactions where large quantities of heat and high-pressure, high-temperature gasses are formed. This can be explained by the fact that these types of reactions are highly exothermic, releasing large amounts of heat in a noticeably short period of time. This in turn suddenly heats up the surrounding gasses or air and creates high-pressure waves or shock waves. In a few rare cases extraordinarily little to no gasses are formed during a chemical reaction, such as the explosion of copper acetylide. Also, when a hydrogen and oxygen mixture explode, the volume decreases. [6]

The most acceptable definition of an explosion can be given as: "An explosion is a process of rapid physical or chemical transformation of a substance, accompanied by an extremely rapid transition of its potential energy into mechanical work." [6]

2.4.4 DEFLAGRATION AND DETONATION

Explosives are substances with their own supply of oxygen in their molecules. These substances, when initiated, either burn violently (deflagrate), or explode disastrously creating

shock waves (detonate). Substances that deflagrate are generally called propellants and substances that detonate are generally called explosives. [6]

Deflagration has the following characteristics: [6]

1. A propellant burns layer by layer as if stacked on each other.
2. Different zones exist above the burning surface varying in pressure, temperature, concentration, and composition of gaseous products.
3. Hot gaseous products emerge away from the surface that regresses as it burns.
4. The rate of recession or burning of the surface, expressed in millimetres per second, is below the sonic velocity, or velocity of sound through the propellant, of the material.
5. Deflagration of the propellant is sustained by thermal feedback from the flame through conduction, convection, and radiation.
6. The burning rate is heavily dependent on the pressure of the surrounding gasses.

Detonation has the following characteristics: [6]

1. A shock wave accompanies the detonation.
2. The wave front of the shock wave has a high pressure and high temperature gradient called the shock zone. This initiates chemical decomposition of the shocked explosive layer of the undetonated explosive near instantaneously. Right behind the shock zone is the chemical reaction zone where the chemical reaction is completed. The shock zone is very narrow at about 10^{-4} mm, and the chemical reaction zone varies between 1 and 10 mm. These two zones together form the detonation zone.
3. Gaseous product flow in the same direction as the propagation of detonation.

4. The rate of propagation or VOD is more than the sonic velocity of the material. This VOD varies from 1,500 m/s to more than 9,000 m/s, depending on the type of explosive.

2.4.5 EXPLOSIVES/BLAST SCALING

Physical studies and experimentation of blast wave phenomenology are often difficult, take a lot of time, and are very expensive. This is especially true when tests are conducted on a large scale and with a large amount of variations. For this reason, scientific and engineering studies have been conducted by various investigators to attempt to generate scaling laws to widen the applicability of experiments or analyses and make it less expensive. [9]

Using geometrical similarities, the behaviour of any given system can be determined by conducting experiments and tests on a smaller scaled model of that system. The smaller system being called the model and the larger system the prototype. Both model and prototype must be exactly similar in their geometric design. The scaled model is scaled down by a given factor, this scaling factor is applied directly to every dimension of the model, height, width, wall thickness, and time. [10]

Material properties must be similar in both the model and the prototype, especially if these properties influence the behaviours studied. These properties are tensile strength, density, etc. The scaling factor for the areas of the model are the square of the factor used. The volumes and mass of the model are the cube of the scaling factor. The pressure as well as the stresses are the same in the model as in the prototype. [10]

Geometric scaling does have its limits in processes that do not scale such as the spalling of metal plates in contact with explosive material. The type of spalling and its distance from the first free surface of the metal are functions of the slope of the Taylor wave, among other things.

The slope scales for thin explosive charges but only until a few centimetres, then it becomes constant. [10]

Another model that does not scale as required, is in the case of a cylindrical charge. As mentioned earlier the detonation velocity and hence the Chapman-Jouguet (C-J) pressure decreases as the diameter decreases. The explosive properties change with scaling of small diameters, and the model can scale until the diameter scales to below the critical diameter. This is also true from systems with thin sheets of explosive. Being aware of these limitations, one can still obtain excellent results with the scaling technique. [10]

The goal of the scaling technique is to test many ordnance and explosive systems more economically, since the model mass scales as the cube of the scale factor, and materials are purchased by weight, the costs are reduced drastically. [10]

There are various methods of scaling in use, the most common method is the Hopkinson-Cranz scaling law. This law was independently formulated by Hopkinson and then later by Cranz, and states: "Shock waves are produced at identical scaled distances when two explosive charges of similar geometry and the same explosive, but of different size, are detonated in the same atmosphere." [9] [11]

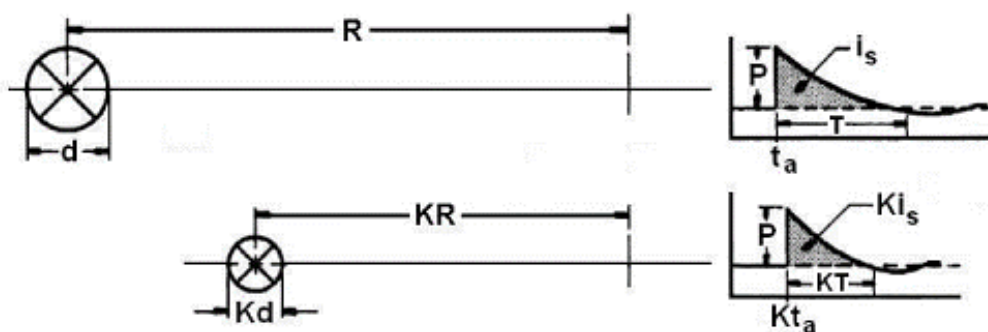


Figure 2: Hopkinson-Cranz scaling law [11]

Another scaling law is Sachs scaling and attempts to consider the effects that altitude or other ambient conditions may have on air blast waves. Sachs's scaling law states that: "Dimensionless groups can be formed that involve pressure, time, impulse, and certain parameters for the ambient air and that these groups are unique functions of a dimensionless distance parameter." [9] [11]

There are other scaling laws and modifications to common scaling laws that attempt to compensate for other parameters. Lutzky and Lehto proposed a modification to Sachs's law to allow for the inclusion of Energy as a parameter, to describe the blast source. The Pi Theorem was used to develop both above-mentioned laws for more specialized cases of a more general blast scaling law. There are even scaling laws for the interaction of explosions with structures as well as many other limitations to blast scaling, but this is not within the scope of this dissertation. The fact that scaling does not influence the data needed for the development of an EOS, scaling and scaling laws will not be taken into consideration for this dissertation. [9] [11]

2.4.6 UNDERSTANDING THE EXPLOSIVE TRAIN

Safety in handling explosives as well as reliability in the use of explosives was ensured by developing a system with which the sensitivity to initiation as well as the output in terms of shock intensity can be controlled by the operators. This is called an explosive train and consists of an initiating explosive with high sensitivity and low output, followed by an intermediary / primary explosive (booster) with medium sensitivity and medium output, finishing with the secondary explosive (main explosive) with low sensitivity and high output. [6]

2.4.6.1 PRIMARY EXPLOSIVES

These explosives start the explosive train and are also known as initiatory explosives and are overly sensitive to shock, heat, friction, electrostatic energy, and impact. This train energy amplification from initiatory explosive to secondary explosive can be in the order of 10 million to 1. Initiatory explosives and primary explosives are frequently combined into a single device or stage. [6]

Compounds most used as primary explosives are lead azide, silver azide, lead styphnate, and lead dinitroresorcinate. This is due to their ease of manufacturing, low cost, sensitivity, compatibility, and output being the most acceptable. They are used in military detonators, commercial blasting caps, and percussion electric primers and can be initiated depending on the environment where they are used. [6]

2.4.6.2 SECONDARY EXPLOSIVES

These explosives are those with low to medium sensitivity to initiation and include High Explosive (HE) charges as well as boosters. They are mostly categorized into three distinct groups: [6]

1. Aliphatic nitrate esters,
2. Aromatic nitro compounds,
3. Nitramines.

Aliphatic nitrate esters are some of the most powerful explosives with high VOD and calorific value, but with less stability than the other types. The most common explosives in this category are NG (Nitro Glycerine), PETN (Pentaythritol Tetranitrate), and NC (Nitrocellulose). [6]

Aromatic nitro compounds are more stable than the previous category of explosives since the aromatic molecules are resonance stabilized. Thus, much more energy is needed to destabilize the compound. These compounds include Triamino Trinitrobenzene (TATB), TNT and picric acid. [6]

Nitramines can be aliphatic, aromatic, or heterocyclic and have a stability of between nitroaromatics and nitric esters and are more powerful with a higher VOD due to their energetic nature. They include nitroguanidine, tetryl, RDX (Research and Development Explosive) or HMX (High Melting Explosive). [6]

2.4.7 THEORETICAL ESTIMATION: VOD AND P_d

Over the past few decades there have been several attempts to theoretically predict the VOD and detonation pressure (P_d) of explosives. There are a few methods like the HOM Equation of State, HOM For Gas Components, the SESAME Equation of State, the Barnes Equation of State, Build-Up of Detonation Equation of State, Grüneisen Equation of State, Stine Method, Becker-Kistiakowsky-Wilson Method, and the Jones-Wilkens-Lee Method. With the last two mentioned being the more popular methods used today. [6] [12]

2.4.7.1 HOM METHOD

The HOM Equation of State is used for a cell of a single component or mixture of explosive and detonation products. For any mixture of explosive and detonation products it is assumed that temperature and pressure is in a state of equilibrium. [12]

$$P = \frac{\left(I - \frac{C}{(3)(23890)(\alpha)} \left(\frac{V}{V_0} - 1 \right) \right) \gamma}{V} \quad (2)$$

$$T = \frac{(I)(23890)}{C} + T_0 \quad (3)$$

where P = pressure (Mbar)

T = temperature (°K)

T₀ = initial temperature (°K)

I = internal energy (Mbar-cc/g)

C = heat capacity of component (cal/g/deg)

V = total volume (cc/g)

V₀ = initial volume (cc/g)

2.4.7.2 BECKER-KISTIAKOWSKY-WILSON METHOD

Ideal gases obey the universal gas equation: PV = nRT. But real gases are non-ideal and at higher pressures and lower temperatures they deviate more from ideal gas behaviour. This is due to the higher intermolecular attraction and the change in volume the molecules occupy. [6] [12]

The situation worsens during a detonation process since the pressure of the product gases in the detonation zone are at extremely high pressures, varying between 2 and 50 GPa. During the past few decades people have tried to develop equations of state that consider the non-ideal behaviour of gases at high pressures, but with little success. [6]

The Becker-Kistiakowsky-Wilson (BKW) method is one of these variations and needs 5 parameters, namely: pressure (P), temperature (T), density (ρ), detonation velocity (D), and internal energy (E). This method also needs two separate sets of data for use in calculations. One set for explosives with positive oxygen balance and one set for explosives with a negative oxygen balance. [6] [12]

The BKW equation of state utilizes thermodynamic and hydrodynamic properties to solve a set of equations, and is given as: [6]

$$P = nRT\rho(1 + xe^{\beta x}) \quad (4)$$

where ρ = density,

$$\beta = 0.3,$$

$$\alpha = 0.25,$$

$$x = b\rho\kappa T^{-\alpha},$$

$$\kappa \approx \text{unity}.$$

This equation makes allowance for compressibility of molecules of the product gases at high pressures. Based on experimental results the values for α , and β are found to be an optimal fit. Due to the iterative nature of this scheme, various computer programs are used to solve the equation. For any type of explosive, the α , β , κ , and θ vary and are arbitrary constants. [6] [12]

Despite its simplicity and lack of rigorous derivation, it is used in many practical energetic material applications. Multiple different parameter sets have been proposed, and some were critically reviewed by Kury and Souers by comparing the predicted values with a database of detonation tests. They concluded that the BKW EOS was inaccurate in modelling the

detonation of a cylindrical charge lined with copper. For this the BKWC parameter set was developed and partially overcame this inaccuracy by more aggressive parameterization techniques but is unreliable when applied to explosives with a very high hydrogen content. [8]

This method along with the Lennard-Jones-Devonshire (LJD) and the Jacobs-Cowperthwaite-Zwisler (JCZ) methods are known as equations of state with explicit chemistry. The LJD free-volume theory was developed and proposed by Fickett in 1962 and 1963 as an attempt to apply a physically based theory. [13]

The JCZ in turn is based on a semi-empirical fit to the LJD and Monte Carlo results for multiple pair potentials. Jacobs found a way, in 1969, to best fit results over the whole range and provide the single-species EOS. In 1976 Cowperthwaite and Zwisler provided mixture rules and incorporated the complete EOS into the TIGER computer code. It was determined in 1976 by Finger that the JCZ method held the most promise of accurately predicting the detonation properties of explosives. [13]

2.4.7.3 KAMLET'S SHORT METHOD

In 1968 Kamlet and Jacobs found an empirical fit to many BKW calculations for a large amount of explosives. The CJ state form was: [13]

$$p_j = k\rho_0^2\Phi \quad (5)$$

$$D = A\Phi^{\frac{1}{2}}(1 + B\rho_0) \quad (6)$$

$$\Phi = NM^{\frac{1}{2}}q^{\frac{1}{2}} \quad (7)$$

where $k = 0.762$

$A = 22.3$

$B = 0.0013$

ρ = density

q = heat of reaction per kg of explosive

N = number of moles of gas per kg of explosive

M = average molecular weight of the gas

2.4.7.4 STINE METHOD

The Stine method is a relatively accurate method of estimating the detonation velocities for CHNO explosives. It uses the atomic composition of pure or mixed explosives as well as the density and heat of formation. The explosive is defined as $C_aH_bN_cO_d$, where the subscripts are the atomic fraction. The equation is then given by: [6]

$$D = 3.69 + (-13.85a + 3.95b + 37.74c + 68.11d + 0.6917\Delta H_f)\left(\frac{\rho}{M}\right) \quad (8)$$

where ρ is the initial explosive density, ΔH_f is the heat of formation, and M is the molecular weight of the explosive. [6]

2.4.7.5 JONES-WILKENS-LEE METHOD

An equation of state that can be easily recalibrated is needed for the design of high explosives. This method is a constant β equation of state where $\omega = \beta^{-1} = \Gamma$, the Grüneisen coefficient. It is also known as an EOS without explicit chemistry, unlike the previously mentioned methods

from 2.5.7.1 to 2.5.7.4. This equation of state has been calibrated down to 0.1GPa and is widely used in practical calculations. The equation is given as: [5] [13]

$$P = A \exp(-R_1 V) + B \exp(-R_2 V) + C V^{-(\omega+1)} \quad (9)$$

This is the equation to be used in this dissertation due to it being accurate and practical. Below in Figure 3 is a typical comparison of two different TNT isentropes compared to HMX when using the JWL method.

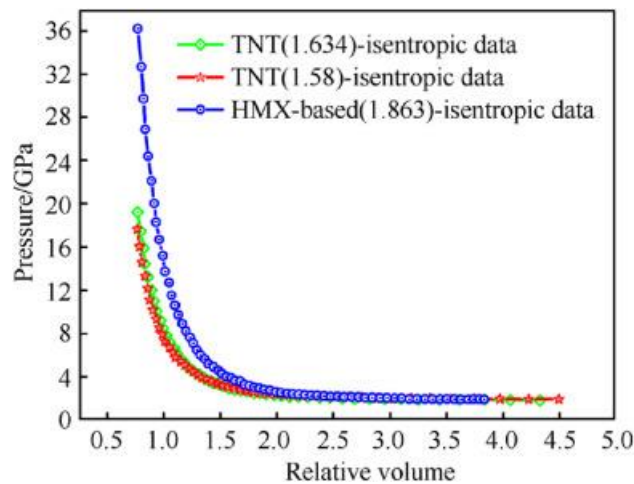


Figure 3: Typical expectation of JWL P-V curve results comparing TNT and HMX [14]

2.4.7.6 ZELDOVICH-VON NEUMANN-DOERING MODEL

If the previous methods are expanded to include a finite reaction rate, it becomes what is called the Zeldovich-Von Neumann-Doering (ZND) model. It is assumed that the shock wave is thinner than the chemical reaction zone and considers the shock a discontinuous jump. The detonation front is imagined as a shock wave initiating a thin zone of chemical reactions right behind it. Other assumptions are: [13]

1. One dimensional flow.

2. Shock jump discontinuity (transport effects like radiation, diffusion, heat conduction, and viscosity are neglected).
3. The reaction is irreversible with a reaction rate of zero ahead of the shock and finite behind.
4. Thermodynamic equilibrium exists everywhere locally for all thermodynamic variables except for the chemical composition.

Under these assumptions the flow equation solutions are steady/stable throughout the region in which reaction takes place. This means that the ZND model is one-dimensional and does not accommodate unstable or multi-dimensional detonation waves and does not consider spinning detonation or pulsating detonation. An unstable detonation occurs when there is breakdown in the detonation wave and stable when no breakdown occurs. Breakdown occurs almost exclusively among liquid explosives with only a few solid explosives that experience breakdown. [13] [15]

2.4.8 TWO ASPECTS OF EXPLOSIVE PERFORMANCE

2.4.8.1 PARTITION OF EXPLOSIVE ENERGY

When an explosive is detonated it causes damage to its surroundings through shock waves as well as gas expansion and grouped together is known as explosive energy. The effects of both energies on the surrounding can be described by looking at when a rock formation is blown up. The shock wave leads by producing a very intense compression as it travels through the rock. A rarefaction wave follows and is below the atmospheric pressure, creating tension in the rock formation. The compression and tension that follow in quick succession causes

plastic deformation of the rock material and it cracks or shatters. The expanding gases then follow pushing the pieces outward in all directions. [6]

No more than 50% of the explosive energy occurs through the shock wave, the same applies to high VOD explosives. In certain cases, it is better to utilize the shock energy more, as with shaped charge explosives, and in other cases the gas expansion energy is utilized to heave out large chunks of material such as coal in coal mining. No matter what type of explosive is used, both effects will always be present in explosions. [6]

2.4.8.2 DETONATION WAVES

The first detonation studies were performed in 1881 by detonation of an explosive mixture of gases by igniting it at one end in a long uniform cylinder. The initial subsonic combustion wave accelerated rapidly to a high constant speed, defined as the Velocity of Detonation (VOD). [6]

The VOD was found to mainly depend on the composition of the explosive mixture and not the material of the cylinder, the diameter (over a certain minimum), nor the method of initiation. Typical detonation velocities, pressures, and temperatures of the gas mixtures are in the range of 2000m/s, 2MPa, and 3000K, respectively. [6]

The Hugoniot curve (Figure 4) passes smoothly, from its initial state, for a shock wave without a chemical reaction. This is not the case for detonation, which can be thought of a two-step process. First a chemical reaction releases energy in a constant-volume explosion and the reaction products are then shock-compressed to a final state. The velocity of the final state is proportional to the slope of the line passing through the initial and final states on a graph. [6]

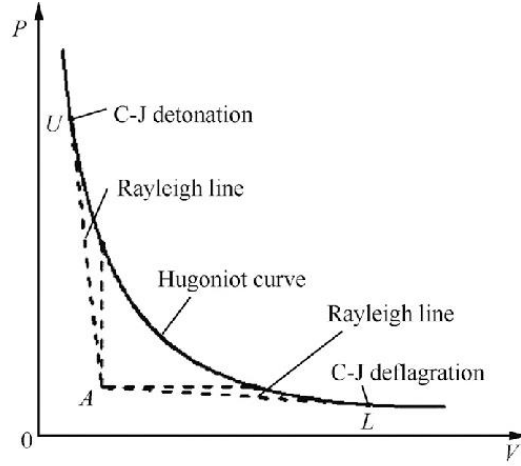


Figure 4: Hugoniot curve [6]

This is called the Rayleigh line and can be obtained by eliminating the U_0 between equation (10) and (11): [6]

$$U_s = V_0 \left(\frac{P - P_0^{\frac{1}{2}}}{V_0 - V} \right) \quad (10)$$

The Rayleigh equations cannot predict which of the Rayleigh lines, UA, or AL, corresponds to the detonation velocity. Chapman-Jouguet (C-J) theory assumes: [6]

$$D = C + U_p \quad (11)$$

where D = velocity of the detonation front,

C = velocity of sound in the medium,

U_p = velocity of the detonation products.

This is done by drawing a tangent line from the initial state to the Hugoniot curve (UA) with point U being called the C-J point. The application of C-J theory to solid explosives becomes

more complex. At the C-J point the product form a very dense gas and thus the computed properties become more difficult to predict accurately. [6]

A detonation wave is a shock wave in an explosive material where there is a chemical reaction taking place in the shock front. This chemical reaction continuously adds energy to the shock front as it progresses and thus compensates for energy loss due to normal shock progression. [10]

When the energy added to the shock front is equal to the energy lost due to work and expansion of rear-flowing product gases, an equilibrium is achieved, and the velocity of the shock wave has constant velocity. This type of detonation is called a 'steady-state detonation' and does not attenuate. It retains its structure and detonation state values if there is explosive material to be consumed during the detonation process. [10]

The detonation wave structure is more complicated than the previous waves described. This is due to the ongoing exothermic chemical reaction taking place. The front of the wave is travelling at a certain velocity. There is a spike at the front end, called the Von Neumann spike, where the explosive reaction is initiated. The zone created by the spike is the reaction zone where the chemical reaction takes place and energy, or heat of detonation, is released. [10]

In most explosives this zone is approximately 1 mm thick. This zone ends in the (C-J) plane, and its state is characteristic of the explosive material at a given initial unreacted density. Behind this plane the high-pressure gases, with high temperatures, expand in a manner dictated by the boundary conditions. The area behind the C-J plane of decreasing pressure due to gas expansion is called the Taylor wave. [10]

Energy is lost to the rear of the wave where the gases expand backwards, only being balanced out by the addition of chemical energy at the wave front as is the case with steady-state detonation. If the explosive is in the form of a cylinder, the gases can also expand sideways if

the explosive is detonated along its axis. The energy losses are negligible with large-diameter explosives. [10]

As the diameter decreases the effects of energy loss at the sides becomes increasingly prevalent until a diameter is reached at which the detonation velocity decreases so much that detonation fails to propagate and is called the critical or failure diameter. The velocity of detonation falls linearly with the reciprocal of the diameter and drops rapidly as the failure diameter is approached from about less than 150% of the critical diameter for most explosives. [10]

This is relevant for the manufacturing of the copper cylinder for high-speed camera testing in the development of the JWL EOS. The copper cylinder will be filled with explosives and if the diameter is smaller than the critical diameter the tests will fail.

2.4.8.3 VELOCITY OF DETONATION

VOD is the rate at which a detonation propagates through an explosive, thus being a serious index of explosive performance. The detonation velocity is a characteristic of any given explosive when the density is at its maximum, the theoretical maximum density (TMD). The VOD depends on four major factors: loading density, charge diameter, degree of confinement, and strength of initiation. [6]

1. Loading density (Δ)

Loading density is defined as the amount of explosive mass placed within a certain volume in which it is detonated expressed in grams per cubic centimetre, or g/cc. The higher the density, the higher the VOD for the simple reason that in a volume there is more explosive material that can sustain a detonation wave through the evolved energy. [6]

2. Charge diameter

When using a cylindrical column of explosive, the VOD changes with a change in the diameter of the explosive cylinder. The VOD decreases with a decrease in diameter and increases with an increase in the diameter. This is due to energy losses to the peripheral sides of the explosive. With a large diameter the losses are small compared to the produced wave front but becomes much more significant with smaller diameters. [6]

3. Degree of confinement

The VOD increases the more an explosive is confined in a defined space. [6]

4. Strength of initiation

The VOD increases with higher strengths of initiation and decreases with weaker initiators. Industrial explosives are initiated with weak initiators to achieve lower order VOD's. [6]

2.4.8.4 RATE OF DETONATION AND CRITICAL DIAMETER

Detonation is not propagated below a certain critical diameter, defined as follows: "The critical diameter is larger when the cartridges detonate in the open, and smaller when confined in metal tubes." Thus, the rate of detonation is dependent on the confinement of the charges. [16] [17] [15]

An increase in diameter of the explosive brings about an increase of detonation velocity. This relation ends at a certain maximum diameter where an equilibrium is reached, and the amount of energy released by the reaction is equal to the amount of energy lost on the boundaries of the expanding gasses. [7]

Similarly, an increase in density brings about an increase in detonation velocity. This relation scales to the maximum density that can be achieved with compressing the explosive. For certain heterogeneous, commercial explosives the velocity of detonation can even decrease after the initial increase as the density is increased further. [7]

The critical diameter is also dependent on other physical parameters besides the chemistry of the explosive such as confinement, density, initial temperature, presence of additives and particle size. This critical diameter varies between 0.5 mm for lead azide initiators, to 100 mm for less sensitive explosives such as ammonium nitrate. [6] [10]

The critical diameter of an explosive inside a confined space like a cylinder can be determined by doing a simple set of tests. First the critical diameter needs to be approximated by filling a conical cylinder with explosives. The conical cylinder has a large change in diameter and is very long. The explosive is detonated from the end with a bigger diameter, and the progress of the explosion is monitored. At the point where the critical diameter is reached the explosive will stop to progress and this diameter is taken as a point to work from. Similar diameters of tubes are used in follow up tests, with slightly smaller and bigger varying diameters. The explosive is tested, and it is recorded at which diameters the explosion propagates or not. [17]

Soloukhin and Mitrofanov and later Edwards et al. determined that the critical diameter of a confined explosive can be determined by the empirical calculation of $D_c \approx 13\lambda$ where D_c is the critical diameter and λ is the cell height. But determining the cell height is a complex and time-consuming venture and as such the simpler tests of using a conical cylinder to approximate the critical diameter is used more often. The critical diameter is also influenced by the initial pressure of the explosive with a higher pressure decreasing the critical diameter. [17]

2.4.8.5 GAS EXPANSION

As with the shock effect, so too is the expansion work done by explosive gases an indication of the power, strength, or energy of an explosive. The specific energy (f) is defined as “the working performance per kg of explosive”. It can be calculated using the equation of state of gases: [6]

$$f = PV = nRT \quad (12)$$

This work performance parameter can be determined experimentally for any explosive, using the reliable Trauzl Lead Block Test and is measured in units of cm^3/g . When this value of “ f ” is plotted against the “ nRT ” value as determined for every different explosive, a near linear plot is obtained. The slight non-linearity of the curve may be due to our assumption that the high-pressure gases behave ideally, which they do not. [6]

Picric acid is used as a reference to compare the power of other explosives and expressed as a “Power Index” as a percentage. Since $n \propto V$ (the volume of gases produced per gram of explosive) and $T \propto Q$ (the calorific value of the explosive), then $nRT \propto QV$, with QV being the characteristic product of an explosive indicating its power. [6]

2.4.9 PERFORMANCE PARAMETERS OF MILITARY EXPLOSIVES

Blast is a phenomenon where rapid expansion is caused by high pressure, and high temperature gasses during an explosion. In World War 2 it was found that much more damage can potentially be caused by the blast effect than with fragmentation. This is since during fragmentation, damage is done only at points of fragment impact whereas a blast wave “balloons out” in a spherical fashion causing damage over a larger area. This can damage walls, propel equipment, and kill people within the lethal overpressure region. [6]

When an HE composition undergoes detonation in a confined space, such as a shell or a bomb, the detonation develops pressures and temperatures in the order of 10^5 atm and 3000-4000°C respectively. The casing gives way to these conditions and about half of the explosive energy is used to shatter the casing and propel the created fragments. The rest of the energy is used in compressing the surrounding air to create a shock front. This shock wave expands spherically from the detonation point followed by the gaseous products, and within a few milliseconds the pressure falls back to ambient. [6]

The positive pressure is followed by a negative pressure phase as shown in Figure 5 where the air moves in the opposite direction from the shock front. Most of the damage is done by the peak overpressure of the shock front and the following positive phase, also known as the impulse of the blast wave. This represents the work done by the overpressure in “pushing” an object. During the negative phase, the object experiences a “pulling” force due to the gasses moving in the opposite direction. This can have the effect of shattered glass from a window being found outside a house and not inside as is expected during an external detonation. [6]

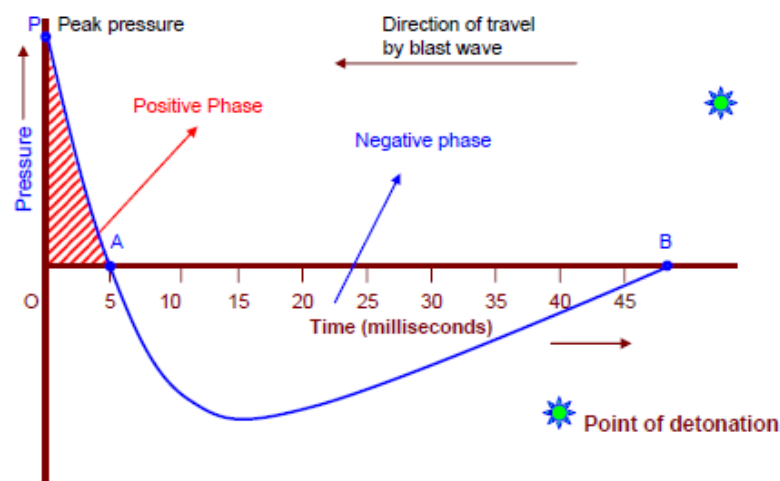


Figure 5: Two phases of a blast wave [6]

Even though both peak over pressure as well as impulse cause damage, the damage potential depends on the type of target. A high peak pressure is needed to destroy a light but strong target, like a window, while a low peak pressure and relatively higher impulse is needed to destroy a heavy but weak target, like a brick wall. An overpressure of $0.07\text{--}0.7\text{kg/cm}^2$ is enough to destroy a windowpane, while an overpressure of 6kg/cm^2 is needed to kill a person by fatal compression of his/her vital organs. [6]

The blast effect is dependent on the medium as well as the surroundings. The blast wave attenuates quickly in an open space and is severely reduced in a less dense atmosphere. The blast wave becomes more powerful when confined to smaller spaces due to multiple reflections and is enhanced in denser mediums such as water. This is the reason for larger quantities of HE composition being needed for efficient blast effect from warheads used in anti-aircraft missiles at high altitudes. [6]

2.5 EXPLOSIVE OUTPUT TESTS

Explosive output can be classified according to Chapman-Jouguet pressure, heat of detonation, or detonation velocity (VOD). Heat of detonation is the measurement that quantifies the chemical energy in a detonation reaction. Explosive output is classified empirically by various system tests, tests that measure “brisance”, “relative blast” or “relative effectiveness”. “Brisance” is a French term that describes the ability of an explosive to cause shattering and relates to the C-J pressure. “Relative blast” and “relative effectiveness” relates to the power generated by an explosive. The following sections are the different tests that are used to classify the output of explosives empirically. [10]

2.5.1 SAND TEST

The sand test is used to measure the quantity of sand that gets crushed during an explosion of the selected explosive material. This test is carried out inside a thick-walled containment unit to keep the sand contained. A mesh is chosen through which the coarse sand will not pass and after the explosive test all the sand in the containment unit is filtered through the same mesh and the amount of sand that passes through is weighed with all results reported in grams. [4] [10]

The larger the quantity of sand that filters through the mesh, the higher the brisance or shattering power of the explosive is. Usually, 0.4 g of explosive is placed on top of 200 g of sand and detonated. These tests can be performed for liquid explosives as well, only needing a suitable container to hold the liquid in place so that it does not spread through the sand. This test is used to measure brisance and thus will not be used for this dissertation. [4] [10]

2.5.2 BALLISTIC MORTAR TEST

In a ballistic mortar test a heavy steel mortar is loaded with an amount of selected explosive material, in a small cylinder in the mortar. This mortar hangs from a pendulum mounted a certain distance above the mortar. The opening of the mortar with explosives is aimed at a pile of dirt or sand. The hole is plugged with a steel cylinder, called the projectile. [4] [10]

The explosive is fired, and the projectile is shot into the sand while kicking the mortar backwards. The maximum height and angle the mortar pendulum reaches is recorded. The amount of explosive in grams needed to make the mortar pendulum reach the same angle as 10g of TNT is recorded as a “percent TNT equivalent”. This test is prone to experimental variables that are hard to remove or account for and makes it less reliable than the other methods and will not be used for this dissertation. [4] [10]

2.5.3 TRAUZL TEST

This tests the strength of an explosive relative to the strength of TNT. With this test 10g of the selected explosive (2) is loaded into a cavity in a thick-walled lead cylinder (3). The dimensions of the cylinder are 200mm x 200mm, with the cavity centred in the upper face with dimensions being 25mm diameter x 125mm deep. The mouth of the cavity being smaller as the diameter of the cavity body to try and transfer as much of the explosive energy into the lead cylinder and is then filled with sand (1). [4] [10]

After the explosion is fired, the expansion in the cavity volume is compared to the expansion of the cavity volume due to 10g of TNT loaded into a similar cylinder. This is recorded as “percent TNT equivalent”. The Trauzl test is now seldomly used due to the power of modern explosives that can rupture the lead block leaving no intact cavity to measure. This is the reason why it cannot be used for this dissertation. [4] [10]

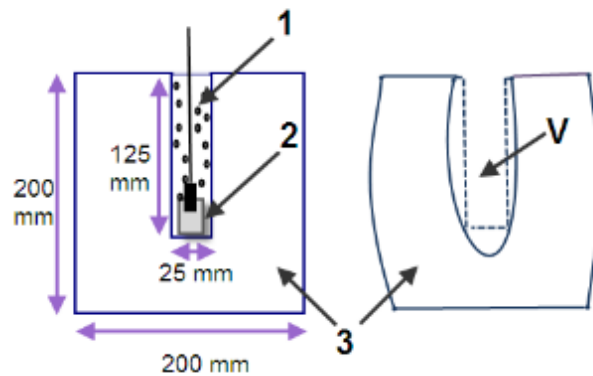


Figure 6: Trauzl test [4]

2.5.4 UPSETTING TEST

This type of test is to measure the brisance of an explosive with the setup demonstrated in Figure 7 below. A 40mm diameter lead cylinder, 60mm in length, is placed in an upright position. Atop this cylinder two 6mm thick steel discs are placed to protect the lead cylinder. Atop the steel discs an unconfined sample of the explosive with similar diameter than the lead cylinder is placed and detonated to upset the lead cylinder. The lead cylinder is pressed down into a mushroom shape, and the total deformation is a measurement of the explosive's power. With some sensitized gelatines the lead cylinder can be destroyed. This test will not be used for this dissertation due to the limited information that can be obtained. [4]

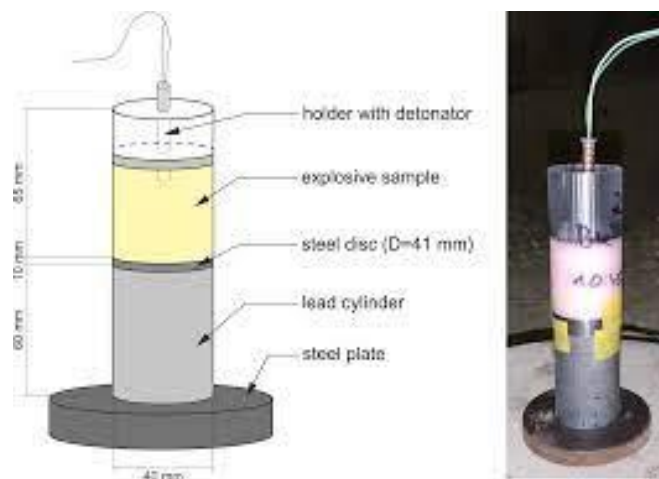


Figure 7: Upsetting test setup [4]

2.5.5 CRATER TEST

An explosive with a large critical diameter is placed at a certain depth underground and detonated. The resulting volume of ground displaced and the depth and diameter of the crater created is used to compare explosive power. This test is very inaccurate due to differing ground conditions and large scatter. This along with the large critical diameter prerequisite is why this test will not be used for this dissertation. [4]

2.5.6 AQUARIUM TEST

An explosive sample is exploded underwater in a reservoir or man-made pool. Lead or copper membranes are used to measure the pressure of the resulting impact wave. This only gives the pressure generated by the explosive and thus the information obtainable is too few to be useful in this dissertation and will not be used. [4]

2.5.7 PLATE DENT TEST

This test is straight forward in that a charge of a given size is set up against a thick steel plate and fired. After the shot, the depth of the dent is recorded and compared to a dent made by the same weight of TNT. Again, the results are recorded as “percent TNT equivalent”. This type of testing is extremely popular in the explosives industry due to its simplicity. This test will not be used for this dissertation. [4] [10] [12]

2.5.8 FRAGMENTATION TEST

The fragmentation test tests the explosives’ ability to create fragments from a standard bomb casing. The casing is loaded with a given amount of explosive and buried approximately one meter in a sand catcher pit. After detonation, the sand is screened through four-mesh screening to filter out and classify the fragments. All fragments are counted for totals. The results are recorded as “number of fragments”. [4] [10]

This test is more to determine the perfect type of explosive that will create the greatest number of lethal fragments for obvious military reasons. This is not the aim for this dissertation and will not be used to conduct tests for this dissertation. [4] [10]

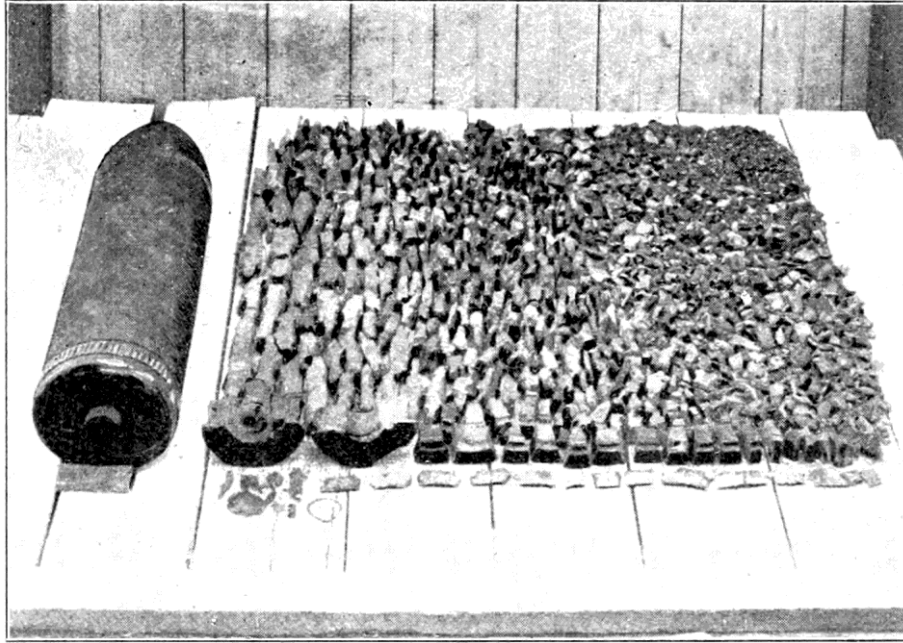


Figure 8: Fragmentation test (before and after detonation) [4]

2.5.9 CYLINDER TEST

This test uses a copper cylinder with known dimensions and filled with an explosive substance for the entire length of the copper cylinder. Care must be given to the loading technique to reduce the number of inconsistencies in the density of explosive. A high-speed streak camera is set up, from the side of the cylinder, to record the cylinder as it expands during detonation of the explosive. The velocity of the expanding copper cylinder is determined through reference points along the cylinder length. [10]

An x-ray flash camera setup can also be used to acquire the relevant images for data processing. By use of special x-ray tubes and ultra-fast voltage circuitry, ultrashort x-ray flashes are generated, down to the microsecond range, in tune with the duration of an explosion. This is a very important means of short-time photography when set up in conjunction with ultra-high-speed cameras allowing for the verification of data. [4]

Measurements allow the data acquired to be reduced to yield output energy “head-on” and “tangential” to the detonation direction. These results are recorded and compared to cylinder tests of known explosives. This method also yields data required to determine the parameters of the JWL EOS of any given explosive used in the testing. The JWL EOS was developed specifically to characterise explosives and gives the most accurate results while being relatively simplistic. This is the method to be used for this dissertation. [10]

2.6 DETERMINISATION OF JWL EOS PARAMETERS OF EXPLOSIVES

2.6.1 USEFULNESS OF THE JWL EOS

Ralph states that the JWL EOS is used frequently for the products, and sometimes reactants, of high explosives (HE). In his article he reviews and systematically derives important properties. The JWL EOS is of the Mie-Grüneisen form with a constant Grüneisen coefficient as well as a constant specific heat and is thus thermodynamically consistent to specify the temperature at a reference state. [18]

The EOS domain in the (V, e) -plane of phase space becomes restricted with an increase in reference state temperature. This is due to the conditions that $P \geq 0$, $T \geq 0$, and the isothermal bulk modulus being positive. This limits the low temperature regime in expansion and the application to HE heat of detonation is discussed. Ralph uses examples to illustrate the restriction on the domain of the EOS. [18]

2.6.2 FUNCTIONAL FORM FOR JWL PRESSURE

Ralph states the function for the pressure for the Jones-Wilkens-Lee (JWL) equation of state (EOS) can be defined as: [Kury et al., 1965; Lee et al., 1968] [18]

$$P(V, e) = A \left(1 - \frac{\omega V_0}{V R_1} \right) \exp\left(-\frac{R_1 V}{V_0}\right) + B \left(1 - \frac{\omega V_0}{V R_2} \right) \exp\left(-\frac{R_2 V}{V_0}\right) + \frac{\omega}{V} (e + \Delta e) \quad (13)$$

Where $\rho_0 = 1/V_0$ is the initial density, ω is the Grüneisen coefficient $V(\delta_e P)_v$, and A, B, R_1, R_2 are parameters. The parameters A and B have dimensions of pressure, while R_1, R_2 and ω are dimensionless. He furthermore states that $R_1 > R_2 > 0$ and $\omega > 0$ and for explosive products $A > B > 0$, but for reactants $A > -B > 0$. [18]

Δe is an offset in the origin of specific internal energy. For explosive reactants, Δe can be chosen such that for the ambient state specified by (V_0, P_0, T_0) , the specific energy $e_0 = 0$. For products, Δe corresponds to the heat of detonation when the initial state of the reactants is such that $e_0 = 0$ and $P_0 = 0$. [18]

2.6.3 ISENTROPES

The isentrope through the C-J state, for HE products, is important for applications and simulations. They play an important role in the construction of the thermal JWL EOS component and are determined by the integral curves of the Ordinary Differential Equation (ODE) [18]

$$\frac{de}{dV} = -P(V, e) \quad (14)$$

It can be verified that the isentropes are given by: [18]

$$P_C(V) = A \cdot \exp(-R_1 v) + B \cdot \exp(-R_2 v) + C v^{-\omega-1} \quad (15)$$

$$e_C(V) = -\Delta e + V_0 \left[\left(\frac{A}{R_1} \right) \exp(-R_1 v) + \left(\frac{B}{R_2} \right) \exp(-R_2 v) + \left(\frac{C}{\omega} \right) v^{-\omega} \right] \quad (16)$$

Where $v = V/V_0$ and C is the integration constant with dimensions of pressure that serves to label the specific isentrope. Later Ralph will relate C to the value of the entropy. [18]

The JWL parameters are fit to data for the isentrope from the detonation state for explosive products and fit to data for the shock locus through the initial state (V_0, e_0) for explosive reactants. [18]

2.6.4 HIGH EXPLOSIVE EQUATION OF STATE DESCRIPTION

The Jones-Wilkins-Lee (JWL) equation of state (EOS) is used to accurately describe the pressure-volume-energy behaviour of detonation products of explosives used in metal acceleration applications. The JWL EOS: [19]

$$P = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E}{V} \quad (17)$$

P as a function of V at constant entropy, the isentrope, is: [19]

$$P_S = A e^{-R_1 V} + B e^{-R_2 V} + C V^{-(\omega+1)} \quad (18)$$

Where:

V = (volume of detonation products)/ (volume of undetonated explosive)

P = pressure in megabars

E = energy in Mb cc/cc

Only a limited number of explosives have been subjected to a rigorous comparison, in which coefficients are determined by matching the equation with the experimental C-J conditions, calorimetric data, and expansion behaviour (cylinder test data). [19]

This method has proven useful to estimate coefficients for explosives for which only a limited amount of data is available. Where cylinder test data is available for explosives the estimates are at their best. [19]

2.6.5 ACCELERATING METAL WITH EXPLOSIVES

A simple technique for predicting the expansion rate of cylindrical bomb casings during detonation was first proposed by R. W. Gurney. This method predicts the velocity to which materials, placed in close contact with explosives, can be accelerated. J. E. Kennedy extended upon this method by applying additional geometries. [10]

The only inputs needed are as follows:

1. The Gurney velocity.
2. The weight of the metal piece to be moved.
3. The weight of the explosive.
4. The weight of a tamper (sheet or metal placed at the rear of the explosive).

2.6.6 UNDERWATER EXPLOSION TEST (CASE STUDY)

The authors of the article "*Determinisation of JWL parameters from underwater explosion test*" obtained the JWL EOS parameters through a method of characteristics they applied to the configurations of underwater shock waves by cylindrical high explosives. They compared the numerical results with the experimental results and confirmed a good agreement between the two sets of results. [20]

2.6.6.1 EXPERIMENTS

The authors used both the cylindrical as well as the spherical high explosives SEP with density of 1310kg/m^3 , and detonation velocity of 6970m/s in their experiments. They placed a sample of each explosive in an aquarium made of Polymethylmethacrylate (PMMA) and initiated the sample explosives with No. 6 electric detonators. Streak photographs and framing photographs were taken by a high-speed camera using a conventional shadowgraph system. [20]

The streak photographs were used to obtain the underwater shock waves. The cylindrical high explosive SEP experimental device is shown in Figure 9 and the spherical high explosive SEP experimental device in Figure 10. In both figures the slit shows the optical slit for taking the photographs. [20]

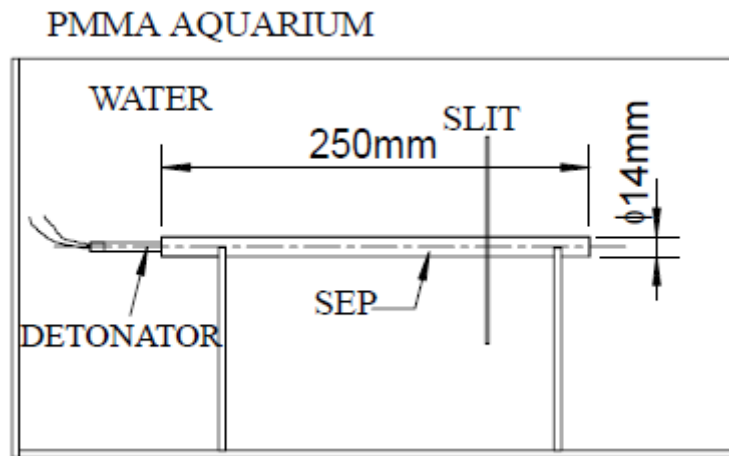


Figure 9: Cylindrical high explosive SEP [20]

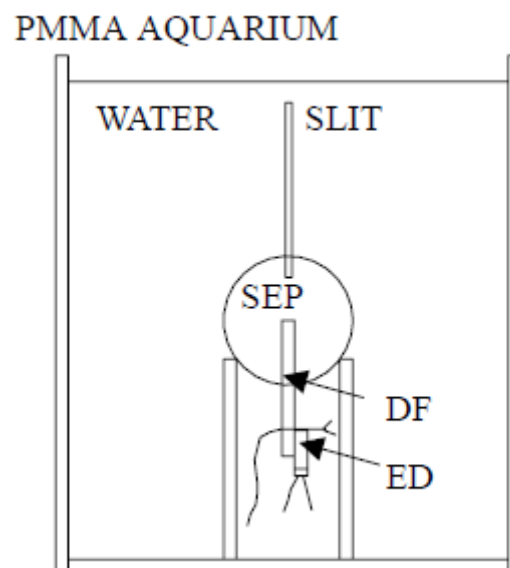


Figure 10: Spherical high explosive SEP [20]

2.6.6.2 NUMERICAL SIMULATION

The numerical simulation of the cylindrical high explosive underwater explosion was conducted by the Arbitrary-Lagrangian-Eulerian method, using C-J Volume Burn Technique as well as the laws of conservation of mass, momentum, energy, and EOS. [20]

The numerical simulation of the spherical high explosive underwater explosion was conducted with the help of one-dimensional hydrodynamic code of FORTRAN SIN, by using C-J Volume Burn Technique, JWL EOS as well as Mie-Grüneisen EOS. [20]

The JWL EOS with new parameters was obtained with the use of the proposed method for the detonation products. [20]

2.6.6.3 RESULTS AND DISCUSSION

Figure 11 shows the P-V curves that were obtained from the underwater expansion test and the Kihara-Hikita-Tanaka (KHT) calculation. This indicates that the detonation products pressure estimated for the underwater expansion test was lower than the KHT calculation estimation at a high expansion region. [20]

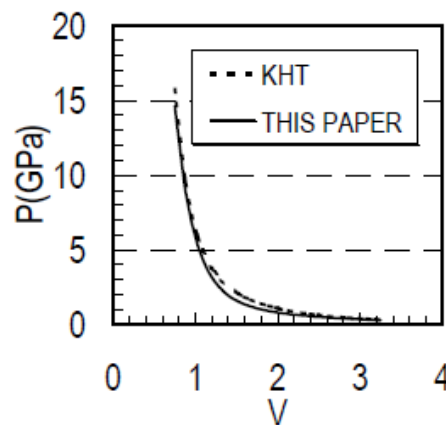


Figure 11: P-V curves for KHT and case study paper [20]

The cylindrical explosive used for the test was 14mm in diameter and 250mm long with the detonation front moving in the horizontal axis. A good agreement was confirmed between the numerical and experimental results for both cases of underwater shock wave as well as the boundary between detonation products and water. [20]

The spherical explosive charge had a diameter of 54mm, and a good agreement was also found between both the numerical and experimental results as shown in Figure 12. [20]

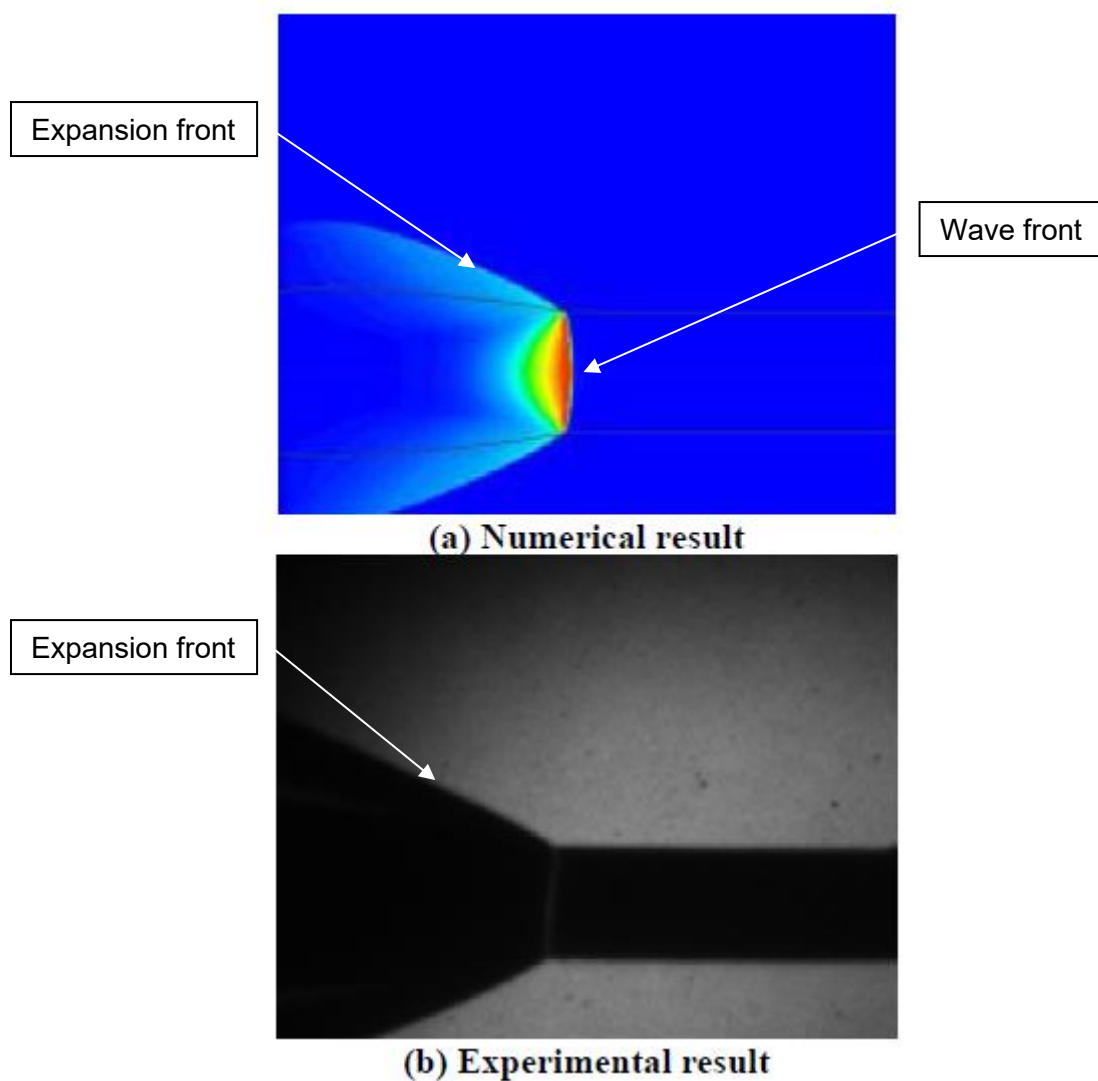


Figure 12: Results of underwater shock wave for cylindrical high explosive SEP [20]

2.6.6.4 CONCLUSION

This case study paper proposed a new technique in determining the JWL parameters of detonation products. A strong correlation was confirmed between an underwater shock wave and an expansion wave in underwater experiments with expanding detonation products. The relation between pressure and volume of the expanded region of detonation products was estimated and allowed for the generation of parameters for the JWL EOS. The propagation of the underwater shock wave was well estimated by the numerical calculation for both the cylindrical charge as well as the spherical charge. [20]

2.7 VERIFICATION AND VALIDATION USING SIMULATION SOFTWARE

In an exercise using the simulation software Altair Radioss [21], a Euler model using the copper cylinder expansion test was set out as an example. In this exercise a copper cylinder Euler was set up, and the simulation results were then compared to the real data extracted using the streak camera method to validate the model and method. The detonation was initiated from the bottom, which is on the left in Figure 13, meaning that the explosion propagated to the right.

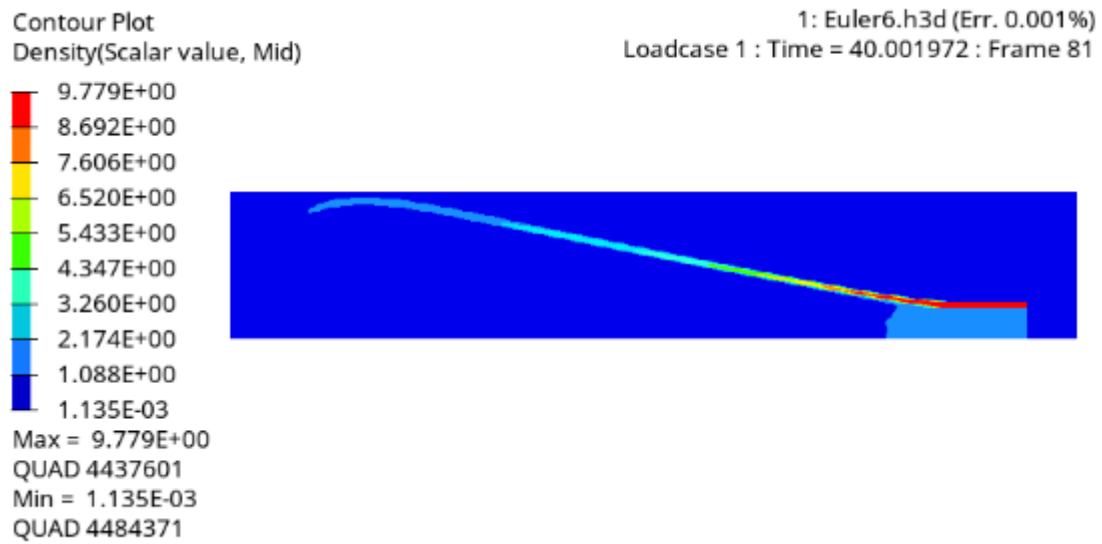


Figure 13: Altair Radioss model [21]

The model used was an OFHC copper cylinder with dimensions as can be seen in Figure 14. They measured the radial expansion at a point that was eight times the diameter of the cylinder. Measuring at least four times the diameter down along the copper cylinder is standard practice and is generally accepted that the detonation wave becomes stable at this distance from the detonation initiation point.

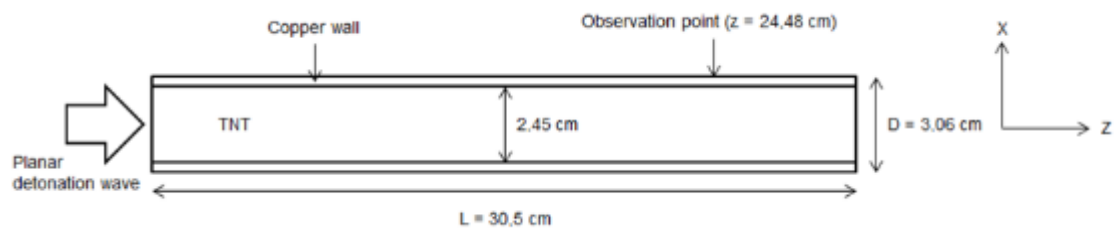


Figure 14: Copper cylinder dimensions [21]

Brick elements were used to create a 3D mesh with element size for the copper cylinder being approximately 0.035x0.035x0.035cm. The mesh was dragged along the z-axis and no discontinuity in element volume was needed to ensure a good detonation and shock wave propagation.

Figure 15 shows the results that they were able to produce and shows the variation in density and pressure in the cylinder, explosive and air. It was overlaid with the energy balance of the explosive propagation.

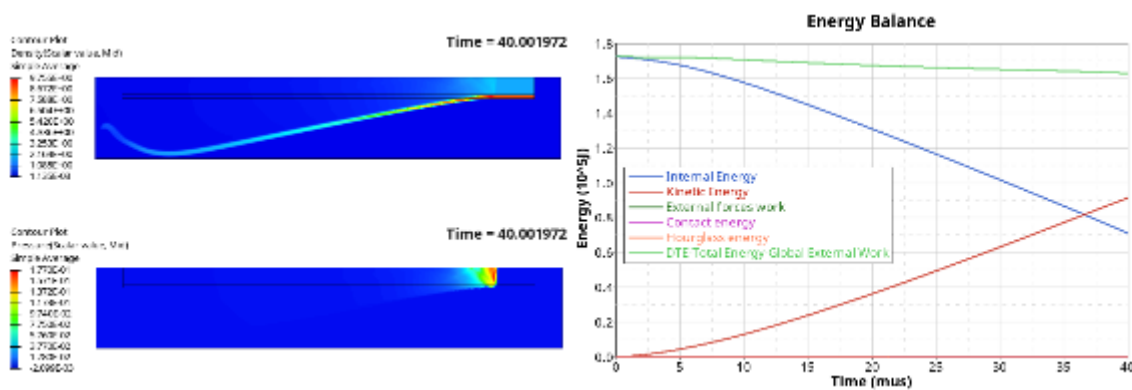


Figure 15: Radioss simulation results [21]

In Figure 16 the radial expansion results of the simulation were compared to the experimental results. The displacement values were estimated on the animations using the density contour. In conclusion, the correlation between experimental and simulation results were very good, validating the model, and it was suggested that by using a finer mesh the correlation could be improved further.

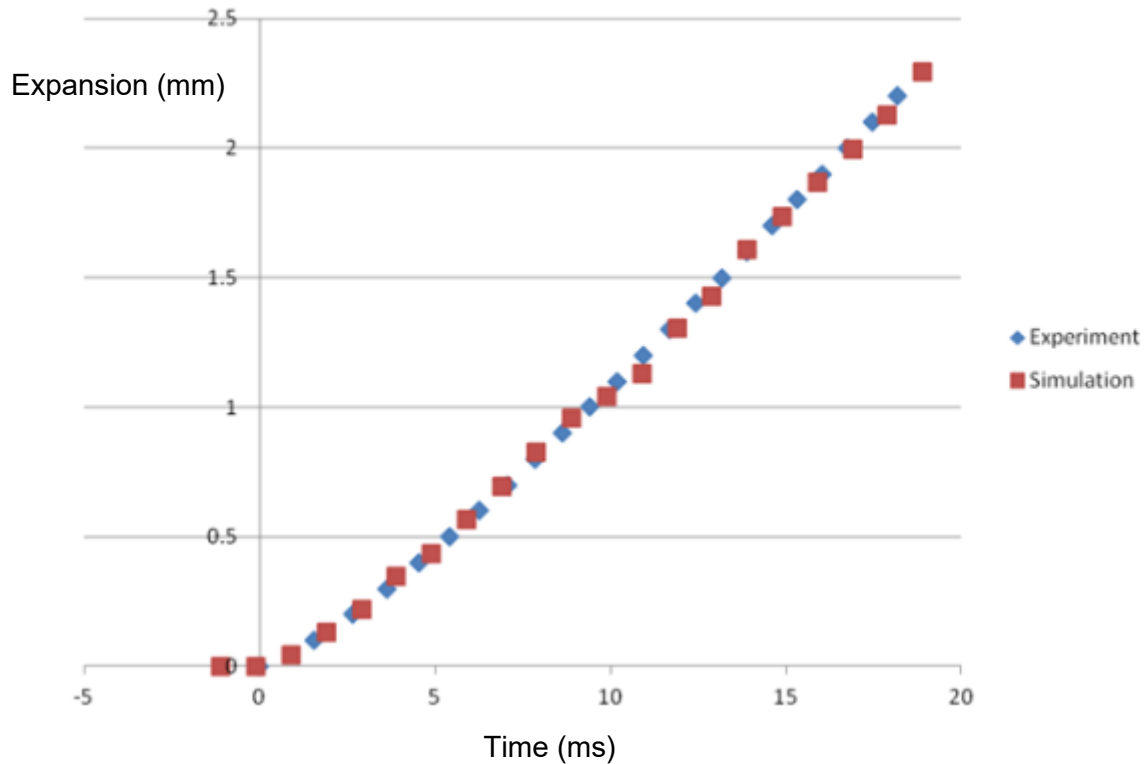


Figure 16: Comparison of radial expansion results [21]

2.8 CHAPTER SUMMARY

This chapter gave a short summary of the history of explosives as well as their broad application by using diverse types of explosives tailored for specific applications.

The safety of explosives was discussed and how they have been improved to make them safer to operate. The basics of explosives, how they work, how they can be utilized, how they react to the environment, and how to control them for specific situations were discussed.

Different tests to determine the strength and power output of explosives was discussed. The idea behind the development of Equation of States for explosives and the advantages that this brings was discussed in detail.

A simulation model used as an example by Altair Radioss and how they were able to verify their method and validate their results using simulation software was also investigated.

CHAPTER 3 – JWL EOS PARAMETERISATION METHODOLOGY

3.1 BACKGROUND

The JWL EOS parameterisation methodology was developed at the CSIR to develop a new method of determining the JWL EOS parameters by using an in-house test at CSIR owned facilities rather than using outside facilities to do tests. The CSIR method attempted to simplify the parameterisation method and to give the CSIR the ability to do their own tests as well as generating an income by making these test facilities available to potential clients.

The CSIR method also had a LS-Dyna simulation model developed in parallel to the parameterisation methodology to run simulations with the determined JWL EOS parameters. This helps to validate the results obtained from the CSIR method by comparing the expansion results obtained from tests with the expansion results obtained from the LS-Dyna simulation model. Both the CSIR method as well as the CSIR LS-Dyna simulation model and how they interact with each other will be discussed in this chapter.

3.2 DESCRIPTION OF TESTS

3.2.1 TEST SETUP

The primary diagnostic tool used to quantify the expansion of the copper cylinder were the two Nova S6 cameras at the T7 firing range at Detonics, Ballistics and Explosives Laboratory (DBEL). The conceptual layout for the Cordin Ultra-High-Speed (UHSP) camera test was used as the basis to work from and was modified for use with the Nova S6's as shown in Figure 17.

[22]

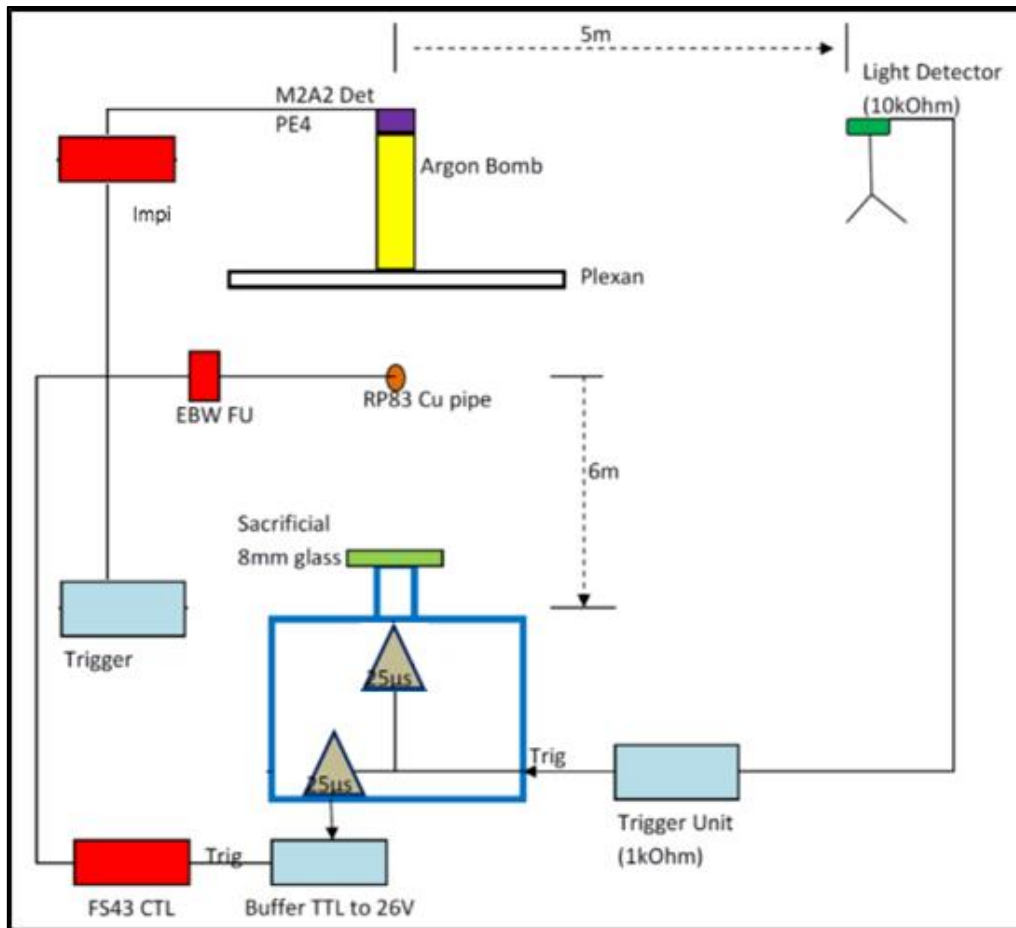


Figure 17: Conceptual layout of the cylinder test setup in front of the camera

The cameras were installed in a steel shelter with a viewing port, with the viewing axis of the camera on a fixed height of approximately 1.5 m above ground height. The viewing port of the cameras must be covered with a laminated piece of glass at least 50 mm thick that protects the direct line of sight to the camera. Due to the complexity of introducing geometric aberrations with non-optically flat mirrors, (optically flat mirrors are expensive items to write off on every test) it was decided to view the event directly into the line of sight. This naturally introduces a serious hazard of fragments that can impact, penetrate, and possibly perforate the glass and cause damage to the camera.

By firing the copper cylinder in the downward direction on the same level as the view port and approximately 7 m away, the hit probability of the main fragment spray can be drastically reduced. However, there is still a distinct chance of a fragment hit on the glass frame from the top section of the copper cylinder. Estimated maximum velocity of the fragments from the top section can be 1700 m/s or more, depending on the type of explosive used. Mass of the fragments are difficult to estimate because of the uncertain metallurgical condition of the cylinder, but 2-4 g are typical estimates. The penetration of a 4 g fragment at 1700 m/s initial velocity is estimated to be 12 mm of steel at a 7 m standoff distance. Scaling up with the density ratio to glass, approximately 33 mm penetration capability is expected. This implies that the fragment will be stopped by the glass protection in the event of a hit on the view port.

A close-up schematic description of the line-of-sight view on the camera plane of the setup is shown in Figure 18.

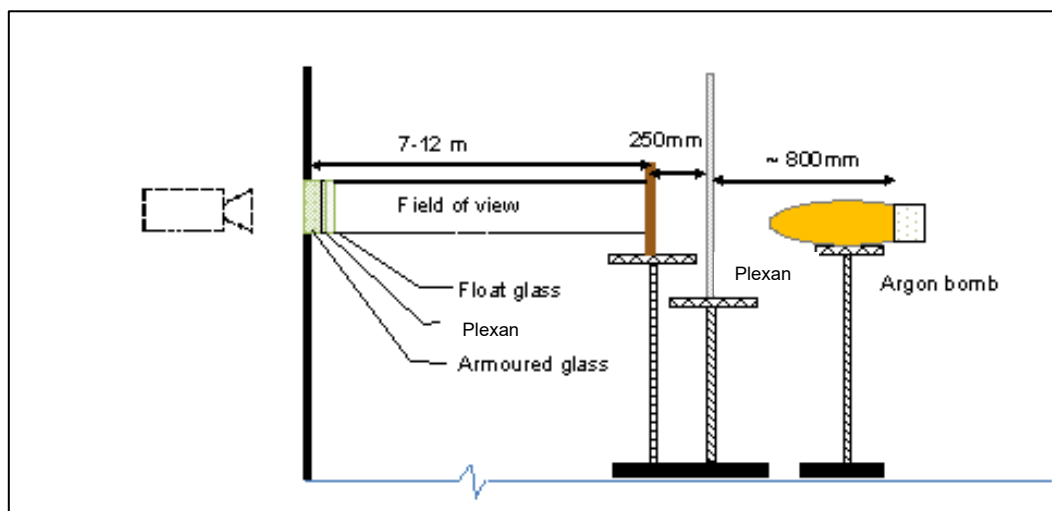


Figure 18: Schematic representation of the setup, line of sight in the camera plane

Figure 19 shows a typical test set-up of the Argon bomb, diffusing Plexan screen, and the copper cylinder with its reference frame. Detonation of the copper cylinder in the image is from the top down to direct the flying fragments downwards.

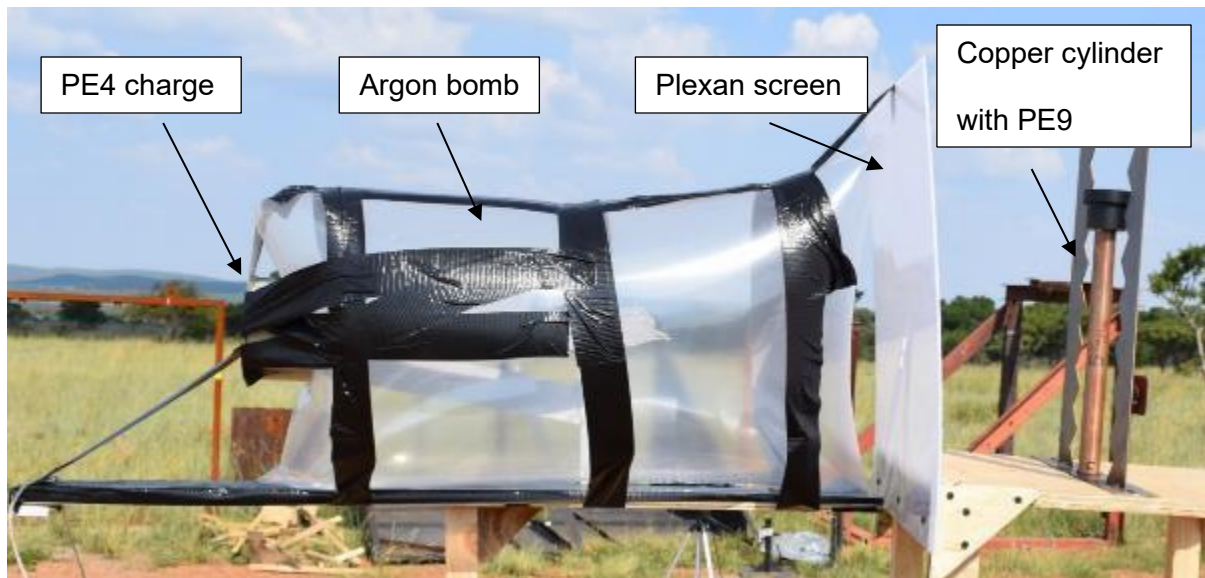


Figure 19: Test set-up showing the Argon bomb and Copper cylinder

The Plexan screen between the argon bomb arrangement and the copper cylinder is aimed at reducing direct luminosity into the camera recording but simultaneously providing adequate contrast lighting for a clear definition of the cylinder shadow. The time of the event is approximately $25\ \mu\text{s}$ which implies that an effective lighting time for the argon bomb should be between $20\text{-}30\ \mu\text{s}$ of uniform illumination. The preferred arrangement is a cylindrical argon bomb balloon with a restricted illumination signature that does not extend beyond the Plexan screen. The explosive charge used was PE4 but with a mass not exceeding $0.5\ \text{kg}$, this is to impart enough energy into the trapped Argon to excite the Argon molecules enough to produce adequate light as required. The argon bomb must be as close as possible to the Plexan screen, but the explosive charge cannot be closer than $200\ \text{mm}$ since the shock may then interfere with the last phase of the cylinder expansion.

3.2.2 FIRING SEQUENCE AND TRIGGERING EVENTS

After activation of the two Nova Cameras to start, the operator plays one further role by triggering the Impi firing unit that delivers enough current to fire the M2A2 detonator ($I > 2A$). This specific detonator was used because the accuracy of the delay is not a driving factor in the capturing of the images; the driving factor is the light intensity sensor.

The M2A2 detonator initiates the PE4, which delivers a shockwave into the trapped Argon inside the Argon Bomb bag (plastic bag cut to 1m length, 300mm diameter and sealed using a bag sealer to contain the Argon gas), resulting in a very bright flash of light. This light is required to illuminate the copper cylinder object from the rear during very high-speed imaging. The white opaque Plexan diffuses the bright light from the Argon Bomb onto the object (copper cylinder), resulting in “shadowgraph photography”.

The Light Detector (at 5-meter distance from the Argon Bomb) monitors the level of the emitted light from the Argon Bomb, and when it exceeds ca 1.5V, sends a trigger signal to the camera via the Trigger Unit. This ensures two prerequisites:

1. The Argon Bomb has activated, and enough light is available for high-speed imaging.
2. If the Argon Bomb did not perform as required, then the main event (detonation of the copper cylinder) does not take place.

Upon reception of the trigger signal, the delay generator starts two timers (or independent delays):

1. One for the detonation of the copper cylinder ($37\mu s$ after trigger – this ensures that the lighting has grown to the maximum).
2. One for the actual image capturing ($54\mu s$ after trigger – this ensures that the expansion of the copper cylinder is within the field of view of the camera).

Upon lapse of the first timer, a TTL 5V signal is issued by the delay generator to the FS43 EBW Firing Control Unit via a TTL-26V Buffer Interface. The FS43 is manually pre-primed by the responsible person and fires the RP83 EBW detonator into the copper cylinder. This causes the copper cylinder to detonate in a downwards direction into the field of view of the camera (so chosen to avoid the flash of the booster into the camera images). This specific detonator is used for this application for its dependability in accuracy of time delay, which is important to get the timing of the sequence correct for efficient data extraction.

Upon lapse of the second timer, the two Nova cameras are triggered to start capturing a video of the expanding copper cylinder event. This video is saved on the Nova internal memory and then transferred over to a laptop for storage. This is also the end of the sequence of events for a particular shot. Important timing events can be recorded by a digital oscilloscope if so required.

From the firing of the M2A2 detonator (initiation of the Argon Bomb PE4 charge), a delay of $37\ \mu\text{s}$ is generated after light detection by the delay generator for proper light build-up. From Figure 20, the total delay from the RP83 detonator being fired to the 100 mm Copper cylinder station varies from $17.4\ \mu\text{s}$ to $19.1\ \mu\text{s}$, thus the delay in the delay generator was chosen to be about $17\ \mu\text{s}$. This value can be adapted to move the captured video upwards or downwards in the field of view of the camera. The timeline below explains the sequence of events graphically:

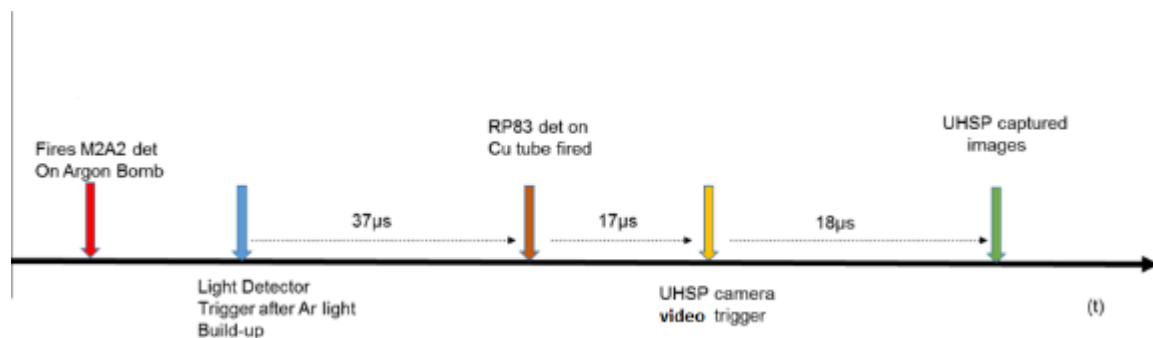


Figure 20: Timeline of events for detonation into Copper cylinder for JWL Tests

3.2.3 COPPER TUBES

Oxygen-Free High thermal Conductivity (OFHC) copper tubes were procured from a relevant supplier and machined to specification. Managing the tolerances when machining tubes from copper while achieving a suitable finish is difficult and time consuming. As the tubes are machined the copper heats up and expands and must be cooled down to keep the tolerances the same throughout the entire length of the cylinder. The process took one week to machine the tubes to adequate specifications and at great expense. Figure 21 shows an example of three explosive filled tubes as well as the top of one of the copper tubes filled with explosive.

The type of explosive may vary as required for testing and a minimum of three tests must be done with the same explosive material to get repeatable results. The OFHC copper tubes have a 1-inch outer diameter, $\frac{3}{4}$ -inch inner diameter and a length of 12 inches. The tubes were press-filled with the explosive, but the density of the explosive was not controlled due to time constraints and must be taken into consideration for future tests.



Figure 21: OFHC cylinder filled with explosive charges

3.2.4 COPPER CYLINDER EXPLOSIVE INITIATION

It is required to have a stable planar detonation wave in the cylinder for optimum equation of state parameter extraction. Each detonation initiation was boosted with a CH6 booster, a pressed RDX-based cylindrical pellet that is 30 mm x 38 mm diameter to the explosive fill. The tests were initiated with an RP83 detonator, and both the booster and initiators were located outside of the copper cylinder.

Figure 22 shows the design of such a device and how the booster fits snug into the holder; it must be perfectly in line with the copper cylinder as illustrated. The device shown in Figure 22 also doubles as the detonator holder for the explosive cylinder. The detonator holder and CH6 booster pellets used during the tests are shown in Figure 23.

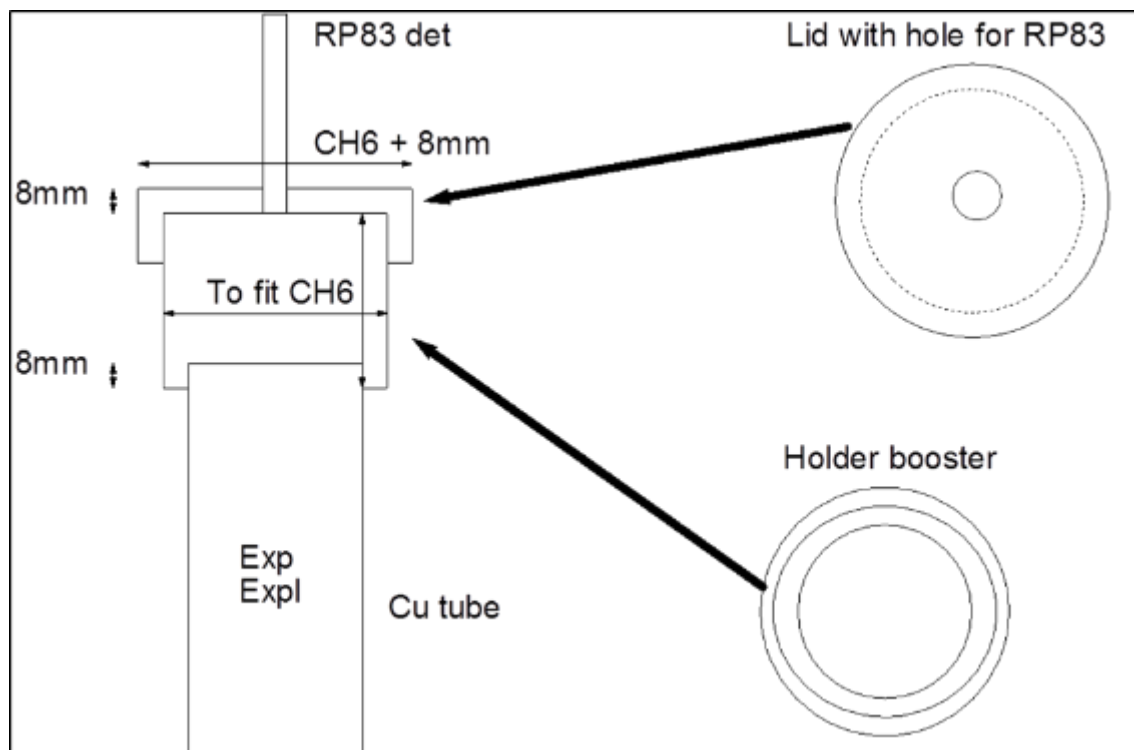


Figure 22: Arranged planar initiation device for the copper explosive cylinder

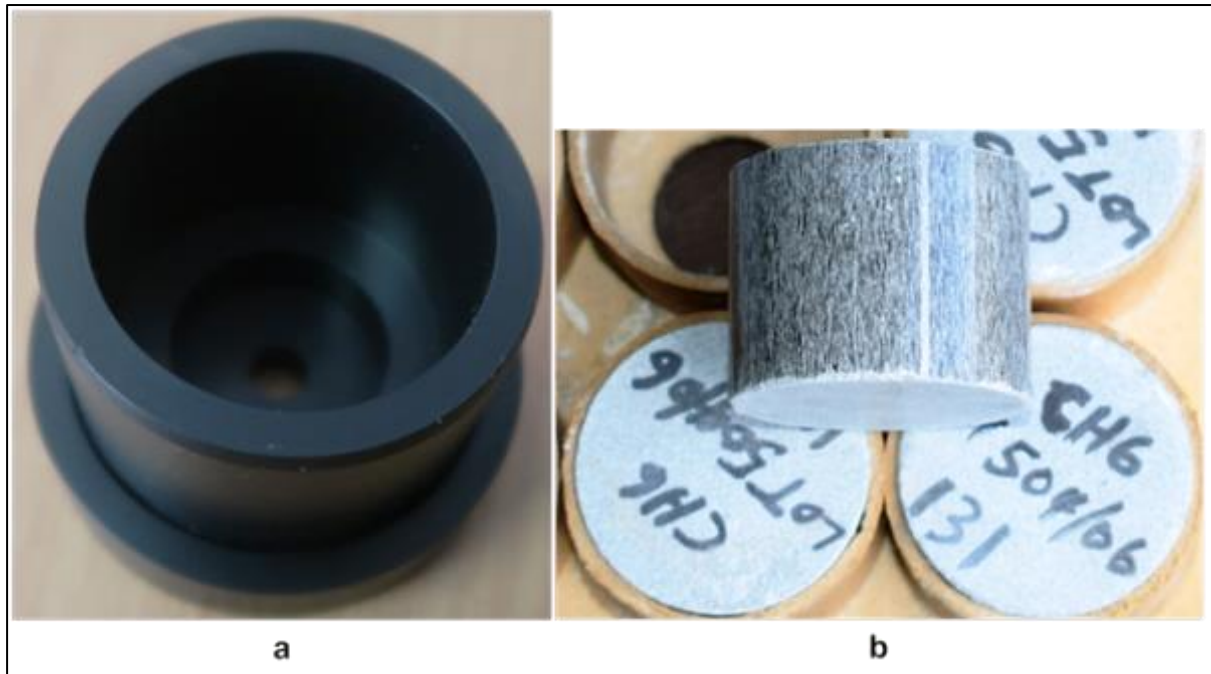


Figure 23: a) Detonator/booster holder b) CH6 booster

3.3 PROCESSING THE IMAGES OF THE NOVA

A discussion of the tests and how they were carried out, along with all the complications and everything that was discovered can be found in Appendix A. The Nova cameras recorded videos of the detonation and the expansions of explosive charges within the cylinder. The average time between each frame was approximately 3.3 and 8 microseconds for each camera respectively. The shutter speed is a tenth of this time, which is approximately 0.33 and 0.8 microseconds respectively, and is the length of time when the digital sensor inside the camera is exposed to light. The Photron Nova S6's captured the expansion of the cylinder in videos at a frame rate of 125 000 and 300 000 frames per second respectively. Figure 24 shows the copper cylinder as viewed by the Nova's.

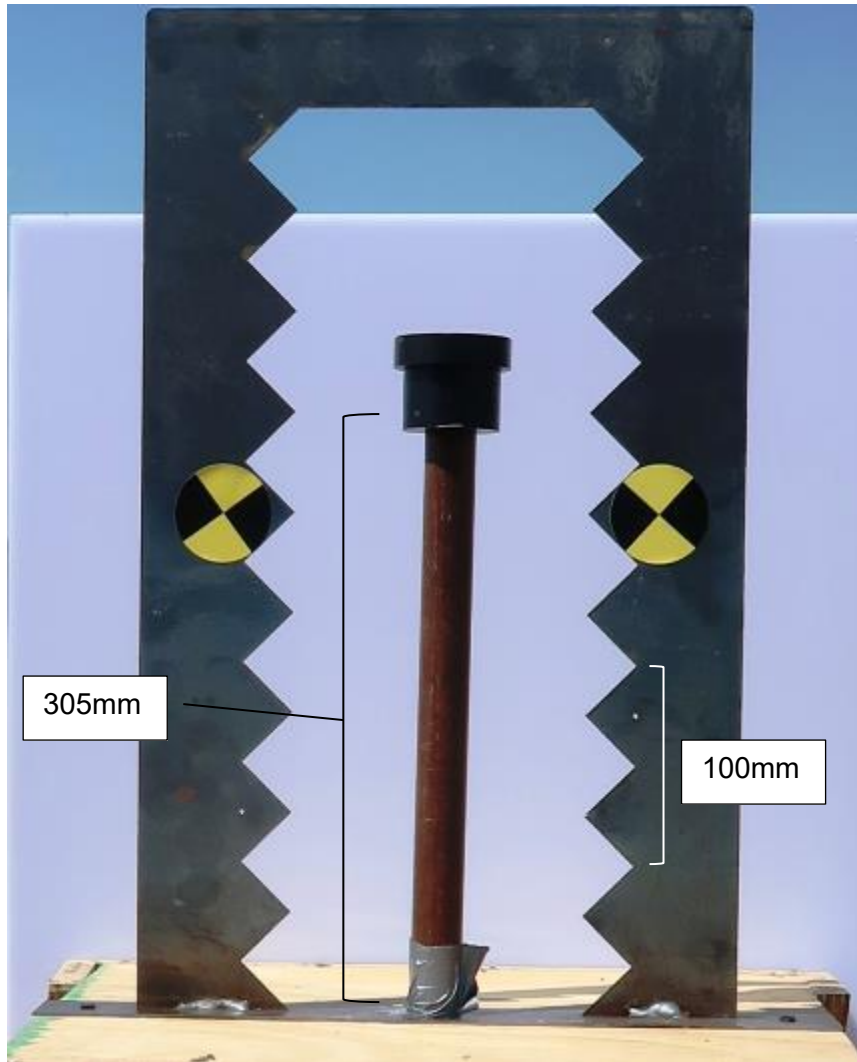


Figure 24: The view of the Copper cylinder from the Nova's

The expansion of the cylinder is estimated by viewing each image and the expansion position at specific locations, using the PFV software from Photron. The expansion is measured in pixels horizontally, noting the vertical pixel position. This horizontal measurement is converted to millimetre and divided by two to obtain the radial expansion. The vertical pixel position is converted to millimetre and used as the axial position of the expansion.

3.4 PROCEDURE OF DETERMINING THE JWEL PARAMETERS

Figure 25 shows a sequence of images as they are typically captured by the Cordin UHSP camera. There is a total of 32 images that are captured during a single test, this is why the timing needs to be accurate, a few microseconds earlier or later and the image sequence misses the event. Figure 26 on the left shows a single frame from the image sequence with dimensions and markers that are used for image analysis and on the right a sketch of the event with assigned variables that will be used for further calculations as in Table 1.

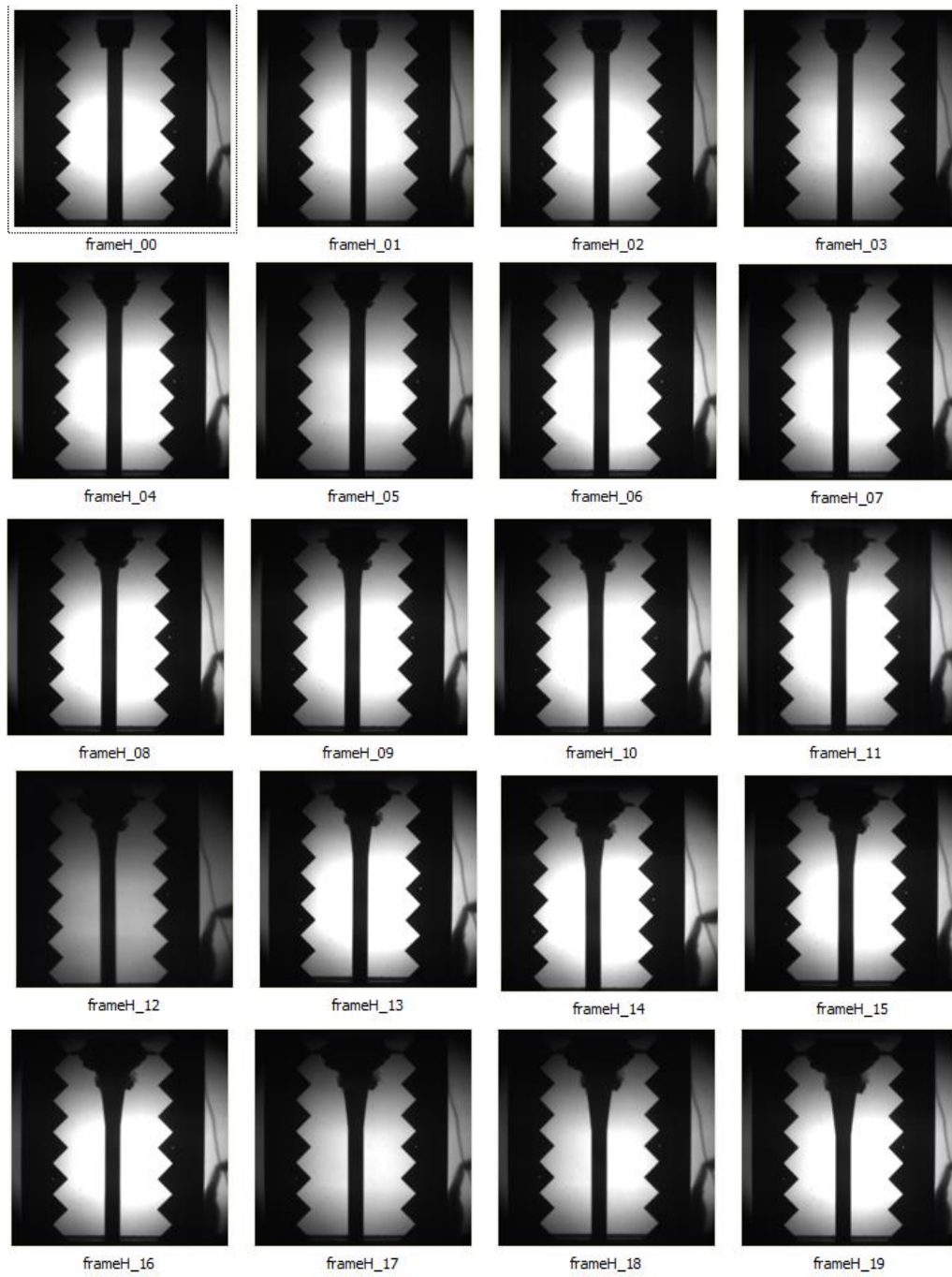


Figure 25: Sequence of images captured, each to be analysed [23]

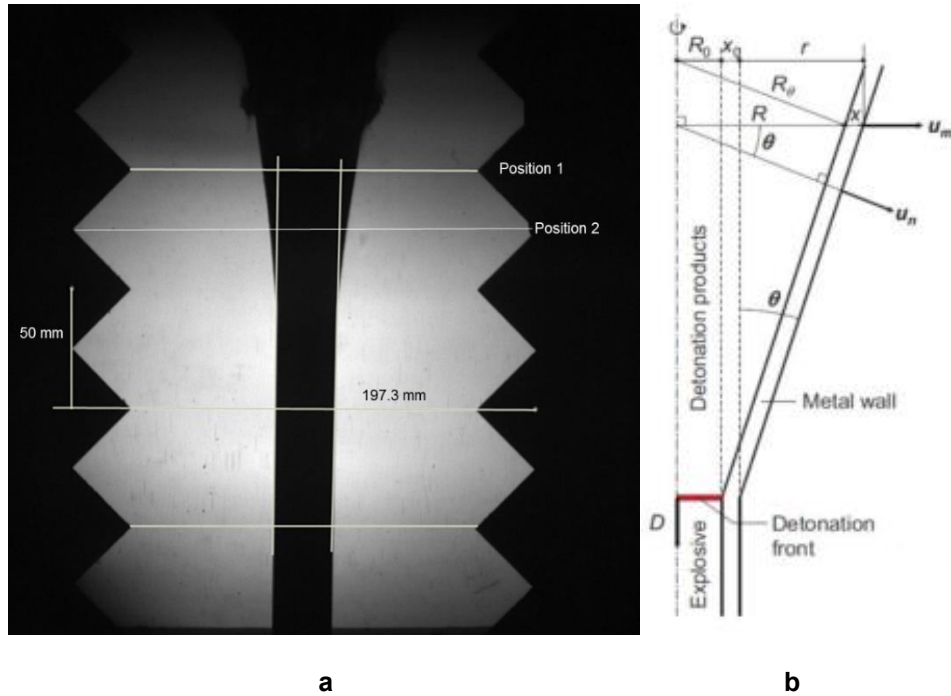


Figure 26: Processed Cordin image showing positions for data extraction (a) with assigned variables for further calculations (b) [23]

The procedure for determination of JWL equation of state parameters from the cylinder test data is collated in Table 1, this procedure was described by Dr Mostert [23] and was derived from Elek et al [24] and Sanchidrián et al [25]. The method of analysing a single copper cylinder image, such as in Figure 26, and to obtain expansion data is as follows:

- A fixed radial plane relatively far away from the initiation point is chosen.
- The diameter of the cylinder in every photograph at fixed known times at that radial plane is measured (the radius is half the diameter).
- The approximate position of the detonation front was measured by choosing the first point where one can see that the cylinder has not yet moved.
- The detonation velocity (i.e., average of the difference in detonation position between successive photographs, divided by the time between photographs, or plot a graph of position with time and get the slope) is calculated.

Table 1: Procedure to analyse the expansion data

Step Number	Action	Result
1	Obtain the cylinder test photographic recordings	Expansion photographs
2	Obtain radial positions of the cylinder in 0.5μs steps very accurately	Series r
3	Convert r to r_c through $r^2 - r_c^2 = r_c^2 - R^2 = \frac{1}{2}((R_0 + x_0)^2 - R_0^2) = R_0 x_0 + \frac{1}{2} x_0^2$	Series r_c
4	Fit $a(t - t_0) + \frac{1}{b}(u_0 - a)(1 - e^{-b(t-t_0)})$ on r_c	Constants a, b, u_0 and t_0
5	Obtain velocity u_m by differentiation of $a(t - t_0) + \frac{1}{b}(u_0 - a)(1 - e^{-b(t-t_0)})$	Series u_m
6	Calculate the angle on every data point by $u_m = D \tan \theta$	Series θ
7	Convert u_m to u_n by $u_n = 2D \sin \frac{\theta}{2}$	Series u_n
8	Obtain acceleration by second differentiation of $a(t - t_0) + \frac{1}{b}(u_0 - a)(1 - e^{-b(t-t_0)})$ and convert to a_{true}	Series a_m , a_{true}

Step Number	Action	Result
9	Calculate the relative expansion ratio via $V = \frac{R^2}{R_0^2 \cos \theta} = \frac{(R_0 + r)^2 + 2xr}{R_0^2 \cos \theta}$	V
10	Calculate the pressure via $P = \frac{Ma}{2\pi R} - \sigma_f \left(\frac{r}{R} - 1\right)$	P
11	Plot P as a function of V	Hugoniot
12	Fit constants in $P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega}{V}E_0$ to the graph	A, B, C, R1, R2, ω

R_0 - initial radius,

x_0 - an initial thickness,

r - is a measured expansion radius that corresponds to an inner radius R plus the effective thickness x (which changes with time), at a specific axial coordinate,

u_n -is the normal velocity of the wall,

u_m - is the component in the radial direction,

a and b - are fitting parameters,

u_0 - is the initial velocity of the cylinder,

t_0 - is a finite time before the cylinder starts to move after the detonation front has reached that specific axial location,

M - is the cylinder mass per unit length,

D - is the velocity of detonation,

θ – cylinder inclination angle,

$A, B, C, R1, R2$ and ω – parameters in JWL equation of state ($\omega = \gamma - 1$),

γ - is the polytropic expansion constant for an ideal gas,

p – pressure of detonation products,

E_0 - is the internal energy,

V – expansion ratio of detonation products

σ_f – flow stress of cylinder material

Temperature and humidity are not considered in these tests. This process is repeated for each successive image captured as can be seen in Figure 25. The number of images typically range from 25 to 32 images for the Cordin UHSP camera and 4 to 9 images for the Nova S6 cameras due to the slower capturing speeds. Typically, two to three points along both sides of the lower two thirds of the copper cylinder is chosen. Only three tests are necessary since there are multiple reference points from which the horizontal data extraction can take place for each test. This process results in six data sets extracted from one single test and with three tests in total, this results in a total of 18 data sets from which an average can be calculated.

3.5 LS-DYNA MODEL

The computational model uses axial symmetry (2D axisymmetric), the ALE solver models the air and explosive while the Lagrange solver models the copper cylinder with outer diameter 25.4 mm, inner diameter 18.9 mm and length 305 mm. The mesh resolution is 0.5 mm for both solvers, and the boundaries of the ALE mesh use non-reflecting boundaries. The dimension of the Euler mesh is 100 mm in the radial direction and 400 mm in the axial direction with a mesh resolution of 0.5 mm.

3.5.1 MATERIAL PROPERTIES

The material models and parameter values are shown in Table 2. The units employed in the model are mm, g and ms.

Table 2: Material models and parameter sets

Material	EOS model	Material model	Parameters
Air	Linear polynomial	Null	Table 3
Composition B	JWL	Explosive Burn	Table 4
OFHC Copper	Gruneisen	Elastic -Plastic- Hydro	Table 5

The parameter sets as they appear in the input keywords for LS-Dyna are given in Table 3 to Table 5 and are obtained from previous test data as used by the CSIR for Composition B. [26] The keywords of the full model can be found in Appendix B.

Table 3: Material parameters for air [19]

*MAT_NULL									
mid	ro	pc	mu	terod	cerod	ym	pr		
4	1.29000E-6	-0.101	0	0	0	0	0		
*EOS_LINEAR_POLYNOMIAL									
eosid	c0	c1	c2	c3	c4	c5	c6	e0	v0
3	0	0	0	0	0.4	0.4	0	0.2525	1.0

Table 4: Material parameters for Composition B [19]

*MAT_HIGH_EXPLOSIVE_BURN							
mid	ro	d	pcj	beta	k	g	sigy
1	0.00171	7980	29500	0	0	0	0
*EOS_JWL							
eosid	a	b	r1	r2	omeg	e0	vo
1	524230	7678	4.2	1.1	0.34	8500	1

Table 5: Material parameters for OFHC copper [19]

MAT_ELASTIC_PLASTIC_HYDRO								
mid	ro	g	sigy	beta	eh	gama	sigm	
7	0.00893	46000	90	0	0.5	0	0	
*EOS_GRUNEISEN								
eosid	c	s1	s2	s3	gamao	a	e0	v0
2	3940	1.49	0	0	2.02	0	0	1

3.5.2 SIMULATION MODEL PROBLEMS

In Figure 27 the LS-Dyna model can be seen and is the final model after many iterations to get the model to work and give accurate results. The original model was received from the CSIR as set up by the previous scientists, Mostert, Snyman and Olivier, who developed the CSIR method. [22] [23] [27]

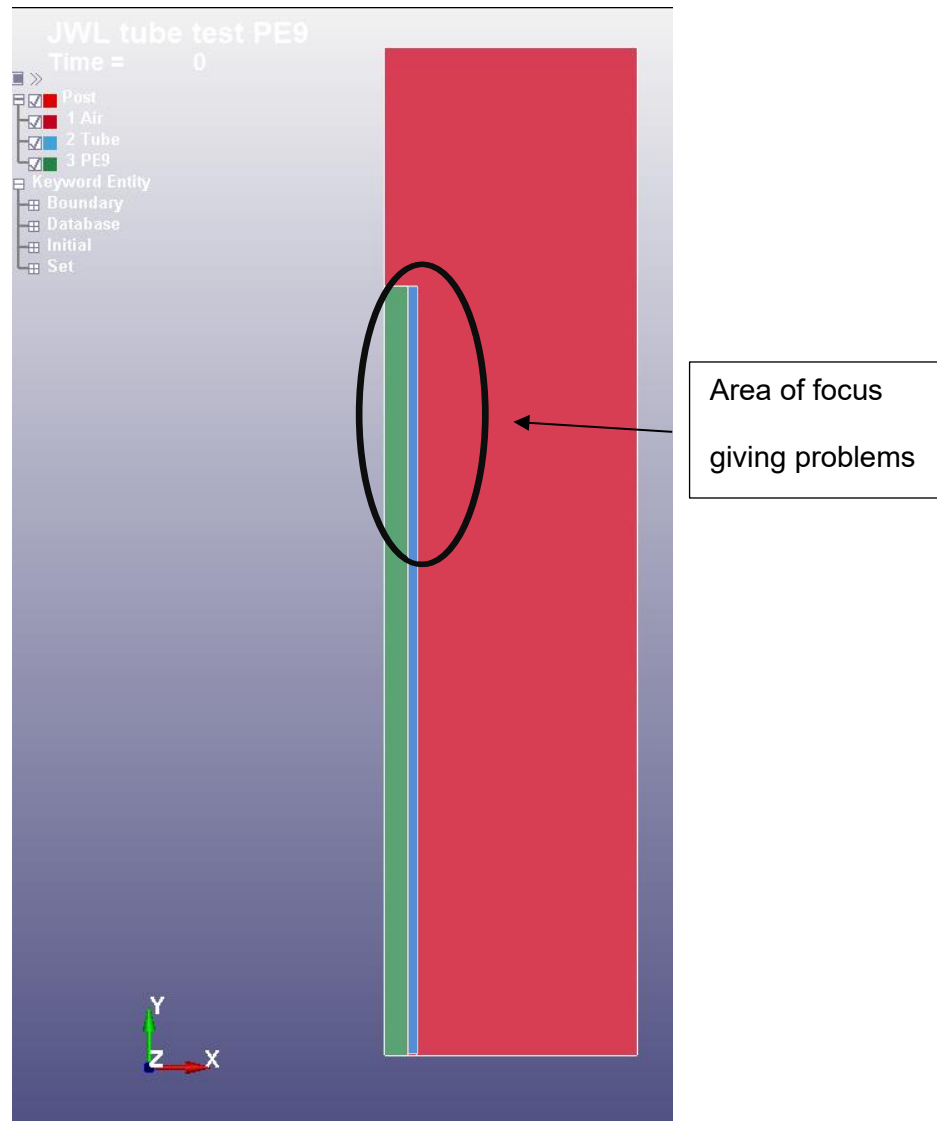


Figure 27: LS-Dyna model

There were a few concerns regarding the accuracy of the model as can be seen in Figure 28, revealing the main concern. The outer cells of the model copper cylinder wall became elongated during simulated detonation. It was first thought to be a mesh problem, that the cylinder mesh was too coarse and thus could not simulate correctly. The mesh size was decreased from 0.5mm to 0.15mm but still produced similar results with cylinder outer wall element elongation and severe distortion of the elements lower down on the cylinder mesh as

can be seen in Figure 29 and Figure 30. The mesh was then transformed from a square mesh to a triangular mesh but produced even worse results with elongation and wall mesh deformation combined as can be seen in Figure 31.

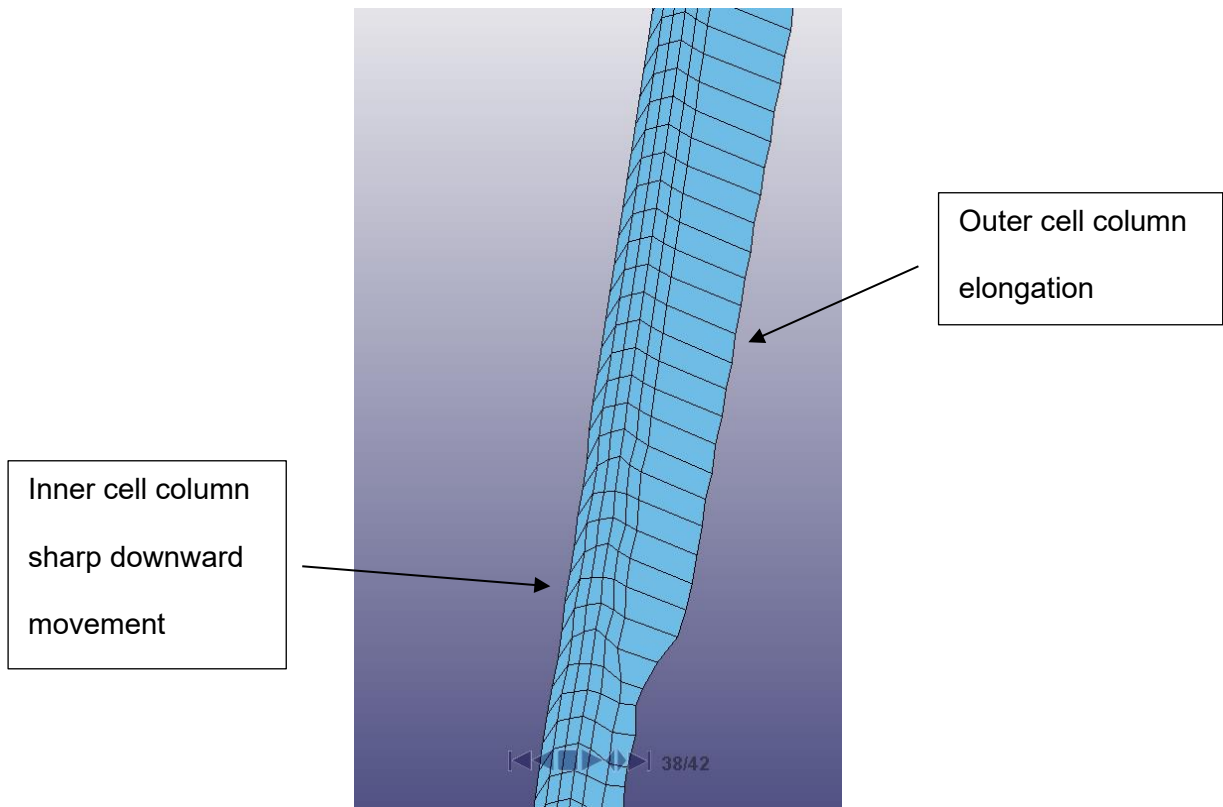


Figure 28: Model problems and concerns with Johnson-Cook material model

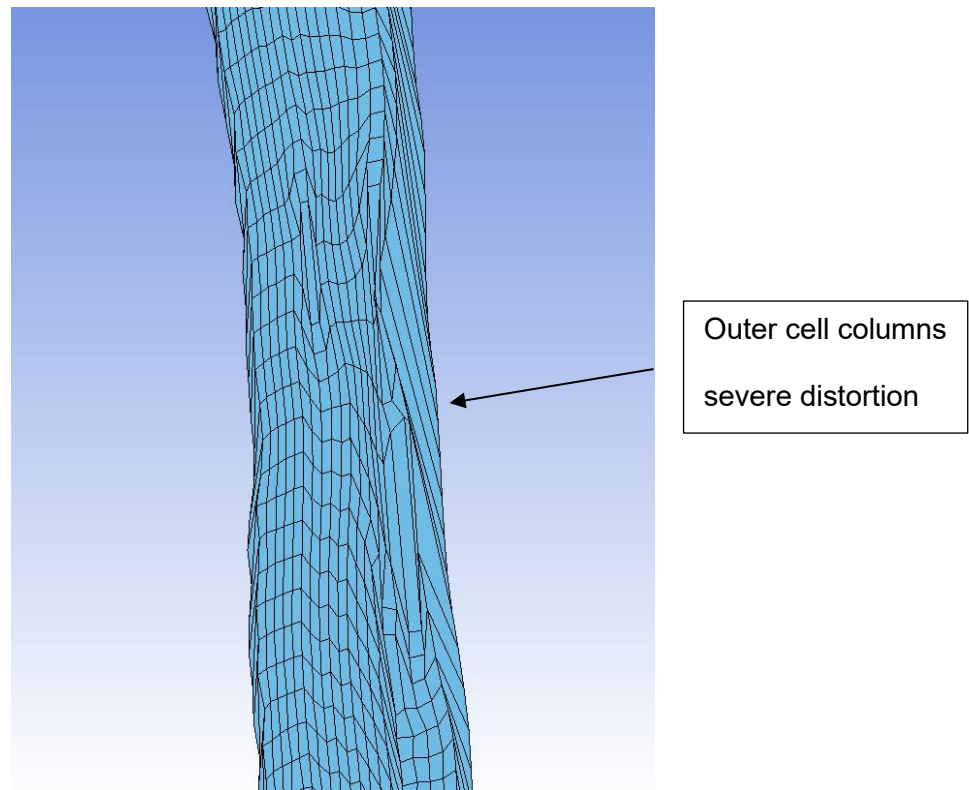


Figure 29: Finer mesh element distortion

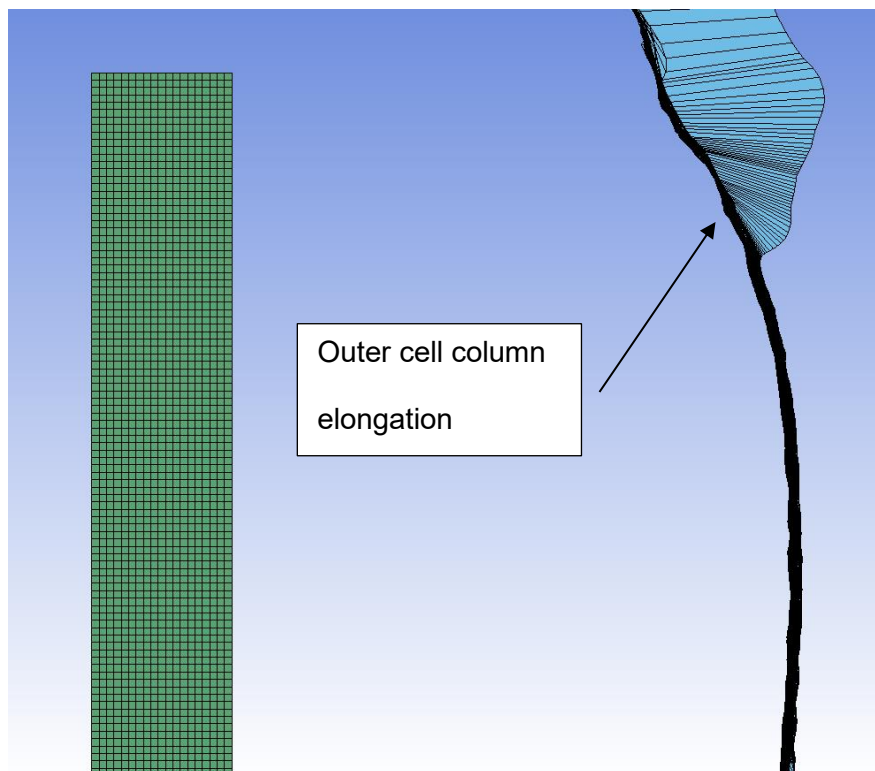


Figure 30: Finer mesh outer wall elongation

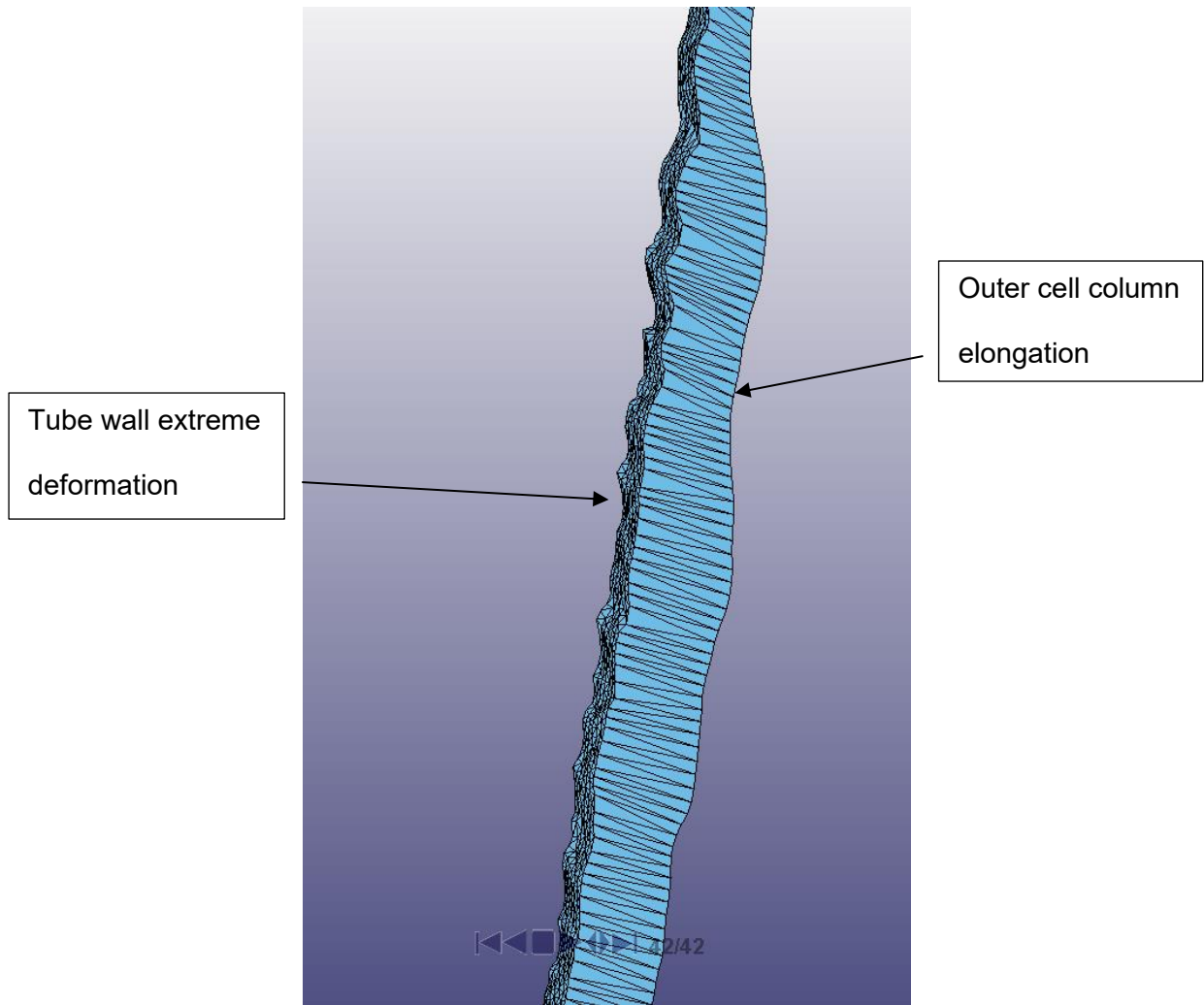


Figure 31: Triangular mesh elongation and wall deformation

With the final iteration, the model was fixed by changing the copper material model from a normal Johnson-Cook to an Elastic-Plastic-Hydro material model that is specifically used for high-strain / high-acceleration simulations and adding the Flanagan-Belytschko stiffness form in the Hourglass keycard. This material model was chosen because the copper cylinder wall under such immense pressures and speeds essentially acts like a jet as is the case with copper lined EFP's in a similar situation.

The result of this change can be seen in Figure 32 where the outer cells of the copper cylinder wall no longer elongate during simulated detonation and the entire length of the cylinder is smooth without any irregularities and minimal unwanted deformation on the inside of the copper cylinder wall. The final image of the simulation can be seen in Figure 33 and is the expected result.

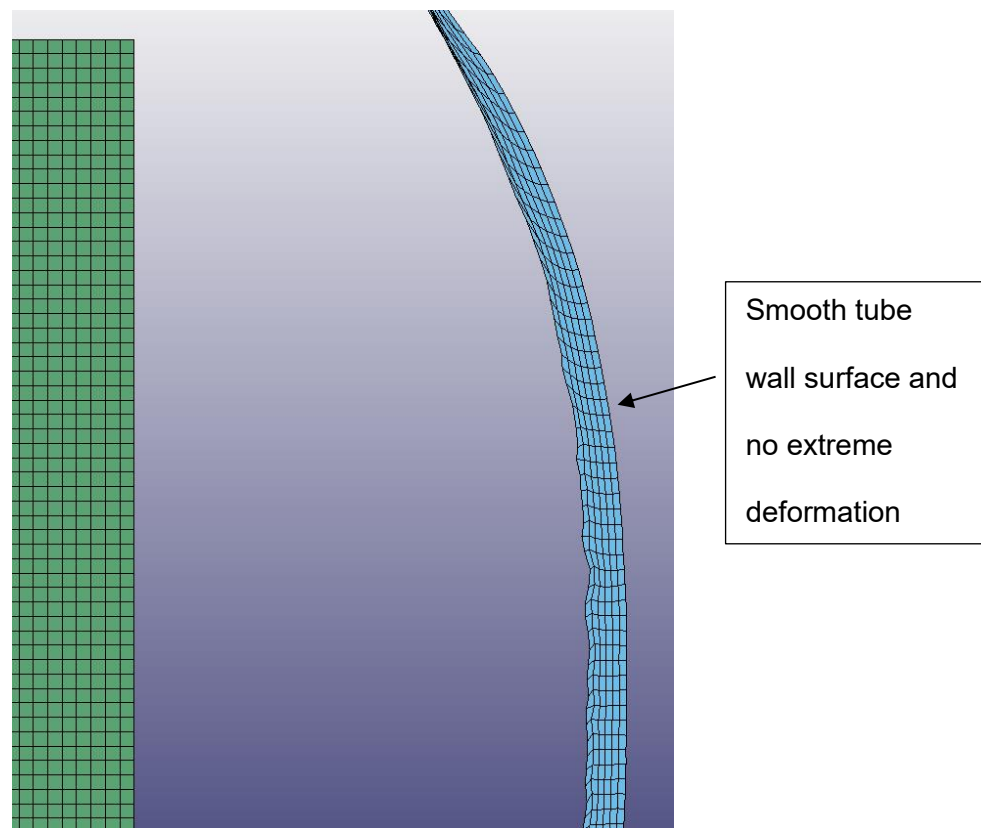


Figure 32: Model fixed with Elastic-Plastic-Hydro model

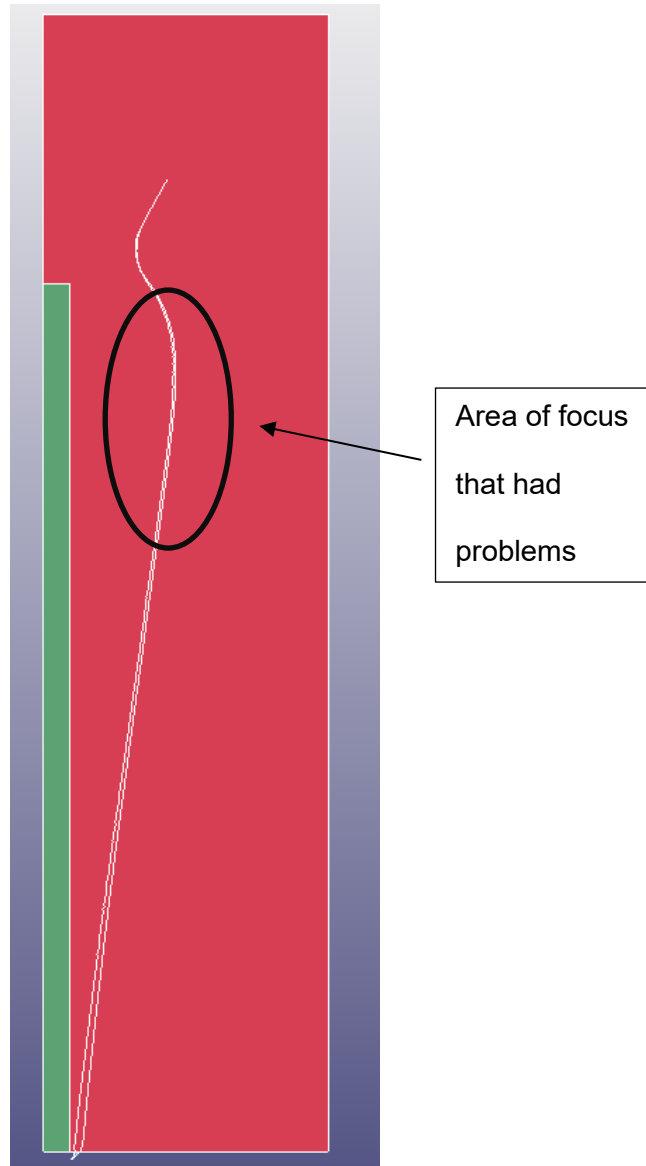


Figure 33: Simulation final image at Timestep 42

3.5.3 MESH CONVERGENCE

The mesh size of the simulation model copper cylinder was varied to determine the mesh convergence at which the best results could be obtained while not sacrificing on simulation time. The cylinder wall radial expansion results ($x_displacement$) for each one of the mesh

sizes of 0.5mm, 0.33mm, 0.25mm, 0.15mm, 0.1mm and 0.05mm were compared with one another to determine the most effective mesh size and can be seen in Figure 34.

The 0.5mm mesh ran for 22 minutes, while the 0.1mm mesh ran for 5 hours and 16 minutes. This time difference shows that a finer mesh takes longer to solve, but since the time for the smaller mesh was not very long, considering only 8 runs needed to be solved, the time constraint was regarded to be irrelevant.

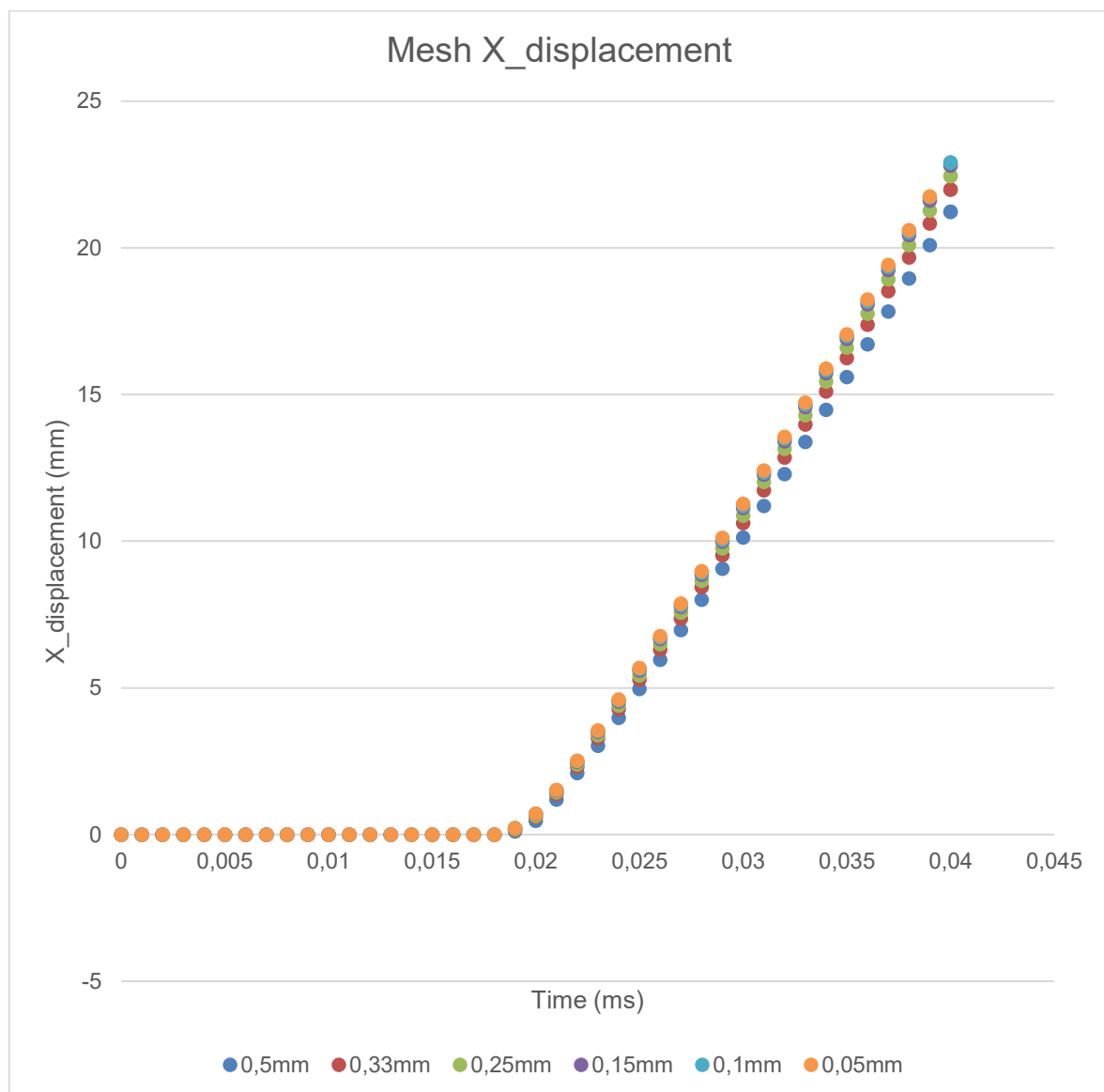


Figure 34: X displacement for each mesh size

As can be seen in Figure 35, the expansion value converged at just below 21.78mm when decreasing the mesh size. It was observed that the 0.1mm mesh size gave nearly the same value as the 0.05mm mesh size of 21.74mm, while the 0.1mm mesh size ran for 5 hours and 16 minutes and the 0.05mm mesh ran for 11 hours and 57 minutes while also failing at the final time step due to errors as can be seen in Figure 36 and Figure 37. This meant that the mesh size can be accepted to have converged at 0.1mm and this is the mesh size that was used for all 8 simulations.

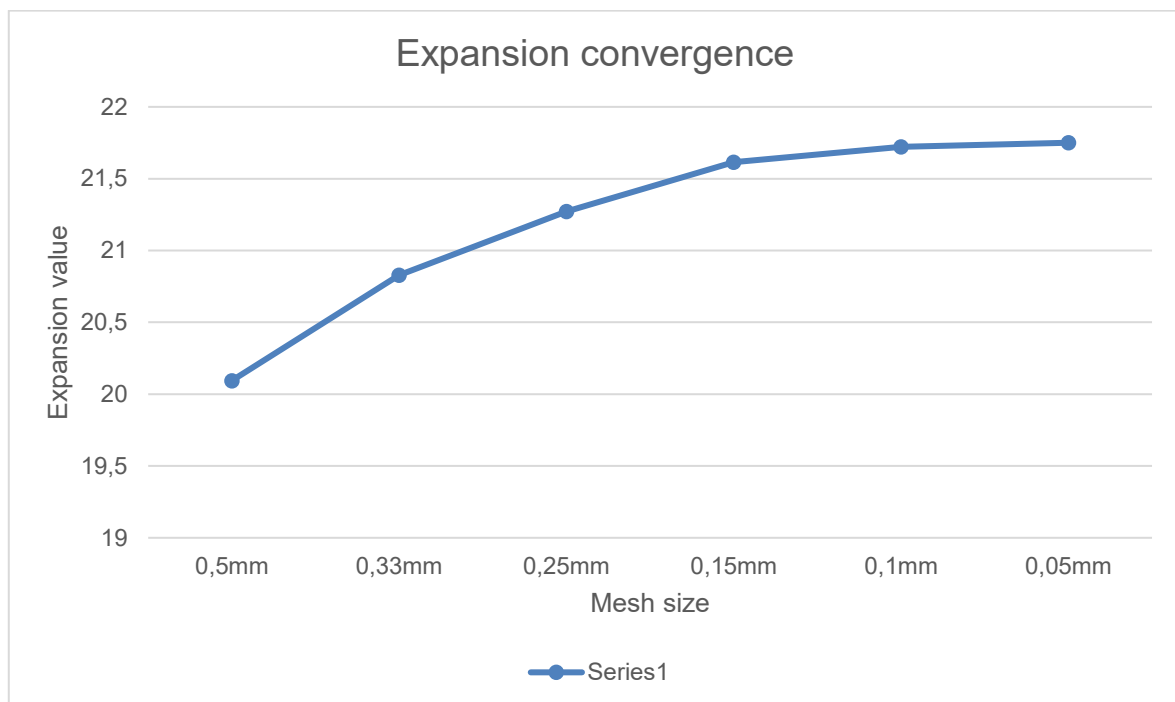


Figure 35: Expansion value convergence

```

lsrun.out - Notepad
File Edit Format View Help
which may be too small (< 0.1) to permit a stable calculation.

*** Warning 21129 (STR+1129)
shell element, ID 130833 violates heuristic shape criterion
area/(longest diagonal)/(longest diagonal) equals: 1.0495E-04
which may be too small (< 0.1) to permit a stable calculation.

*** Warning 21129 (STR+1129)
shell element, ID 130834 violates heuristic shape criterion
area/(longest diagonal)/(longest diagonal) equals: 1.0505E-04
which may be too small (< 0.1) to permit a stable calculation.

*** Warning 21129 (STR+1129)
shell element, ID 130835 violates heuristic shape criterion
area/(longest diagonal)/(longest diagonal) equals: 1.0495E-04
which may be too small (< 0.1) to permit a stable calculation.

*** Warning 21129 (STR+1129)
shell element, ID 130836 violates heuristic shape criterion
area/(longest diagonal)/(longest diagonal) equals: 1.0485E-04
which may be too small (< 0.1) to permit a stable calculation.

*** Warning 21129 (STR+1129)
shell element, ID 130837 violates heuristic shape criterion
area/(longest diagonal)/(longest diagonal) equals: 1.0485E-04
which may be too small (< 0.1) to permit a stable calculation.

*** Warning 21129 (STR+1129)
shell element, ID 130838 violates heuristic shape criterion
area/(longest diagonal)/(longest diagonal) equals: 1.0485E-04
which may be too small (< 0.1) to permit a stable calculation.

*** Warning 21129 (STR+1129)
shell element, ID 130839 violates heuristic shape criterion
area/(longest diagonal)/(longest diagonal) equals: 1.0485E-04
which may be too small (< 0.1) to permit a stable calculation.

```

Figure 36: Error about stable calculation

```

lsrun.out - Notepad
File Edit Format View Help
355000 t 3.6230E-02 dt 1.01E-07 flush i/o buffers 08/12/25 20:02:38
360000 t 3.6736E-02 dt 1.00E-07 flush i/o buffers 08/12/25 20:11:50
362624 t 3.7000E-02 dt 1.03E-07 write d3plot file 08/12/25 20:16:42
365000 t 3.7238E-02 dt 1.01E-07 flush i/o buffers 08/12/25 20:21:06
370000 t 3.7738E-02 dt 9.84E-08 flush i/o buffers 08/12/25 20:30:19
372623 t 3.8000E-02 dt 9.82E-08 write d3plot file 08/12/25 20:35:11
375000 t 3.8237E-02 dt 9.90E-08 flush i/o buffers 08/12/25 20:39:34
380000 t 3.8735E-02 dt 9.89E-08 flush i/o buffers 08/12/25 20:48:48
382653 t 3.9000E-02 dt 9.67E-08 write d3plot file 08/12/25 20:53:42
385000 t 3.9235E-02 dt 9.91E-08 flush i/o buffers 08/12/25 20:58:02
390000 t 3.9740E-02 dt 1.03E-07 flush i/o buffers 08/12/25 21:07:17

*** Error 40509 (SOL+509)
negative volume in solid element # 142990 cycle 391613 time 3.9905E-02
391613 t 3.9905E-02 dt 5.53E-08 write d3plot file 08/12/25 21:10:15

*** Error 40502 (SOL+502)
node # 141129 has out-of-range velocities
x-velocity= NaN
y-velocity= NaN

*** Error 40502 (SOL+502)
node # 141130 has out-of-range velocities
x-velocity= NaN
y-velocity= NaN

*** Error 40502 (SOL+502)
node # 141131 has out-of-range velocities
x-velocity= NaN
y-velocity= NaN

*** Error 40502 (SOL+502)
node # 141132 has out-of-range velocities
x-velocity= NaN
y-velocity= NaN

*** Error 40502 (SOL+502)

```

Figure 37: Error message about negative volume and velocities

3.6 CHAPTER SUMMARY

This chapter discussed the JWL EOS development methodology as developed at the CSIR and the way in which the author adjusted it to achieve his aims and objectives. The test setup was explained in detail, with the adjustments made by the author to update on the designs where possible. The adjusted test layout was discussed as well as a detailed explanation of the firing sequence and the reasoning behind the process and why certain decisions were made.

A brief explanation was given on how the images from the Nova cameras were processed as well as the complete step-by-step process for determining the JWL parameters from these extracted expansion data sets. A short description of every step of the process to calculate the unknown parameters was discussed.

The author also gave a description of how the LS-Dyna model was set up along with the boundaries and conditions for a successful model. The process of data extraction was discussed along with problems with the model that had to be resolved to achieve accurate simulation results.

CHAPTER 4 – JWL EOS PARAMETER RESULTS (VERIFICATION AND VALIDATION)

4.1 VERIFICATION

Verification of the CSIR method, as translated into an Excel spreadsheet, was done by determining the JWL EOS parameters of an already parameterised explosive (Composition B) used during a previous test and comparing the P-V curve obtained from the CSIR method to the P-V curve obtained from literature of said parameterised explosive.

Verification of the CSIR LS-Dyna model was done by comparing the expansion results extracted from the CSIR LS-Dyna simulation, of the same parameterised explosive (Composition B), to the expansion results obtained through image recordings from the previous test with said same parameterised explosive.

4.1.1 EXPANSION DATA FROM PREVIOUS TEST

Expansion data was retrieved from a test done prior to verify the method. [26] The data retrieved for Composition B can be seen in Table 6. Point 1 represents the first horizontal line on which the radial expansion of the cylinder is measured and Point 2 represents the second horizontal line further down the cylinder on which the radial expansion is measured. These points are arbitrary and are selected according to the operator's discretion. There are more data points that got extracted due to the use of the Cordin Ultra High-Speed camera to record the tests and captures images up to speeds of 2 million FPS at 1000x1000 pixel resolution. This results in better resolution and more points to measure the expansion of the copper cylinder for more accurate results, but the camera was unavailable for use during the tests done for this dissertation.

Table 6: Extracted data from previous Composition B test

Time (ms)	Point 1 (mm)	Point 2 (mm)
0,003	0,000	0,000
0,004	0,500	0,000
0,005	1,700	1,000
0,006	2,500	1,500
0,007	3,400	2,700
0,008	4,100	3,300
0,009	4,900	4,100
0,010	6,400	5,300
0,011	6,500	5,300
0,012	6,600	5,900
0,013	8,200	7,400
0,014	9,100	8,400
0,015	10,600	9,600
0,016	11,500	10,500
0,016	12,500	11,800
0,017	13,900	12,700
0,018	14,400	13,600

4.1.2 DATA PROCESSING AND JWL PARAMETERISATION

The JWL parameters for the two points as listed in Table 6 were determined using the online tool MyCurveFit. The values for A, B, R_1 and R_2 are used in computer modelling and are used to plot the JWL P-V curve as determined by the two data extraction sets and plotted against the JWL curve as given for Composition B. The comparison plot can be seen in Figure 38 where the JWL curves produced by the CSIR method closely matches the JWL curve as given for Composition B. The parameters for Composition B are given as follows:

A – 540 GPa

B – 7 GPa

R_1 – 4.2

R_2 – 1.1

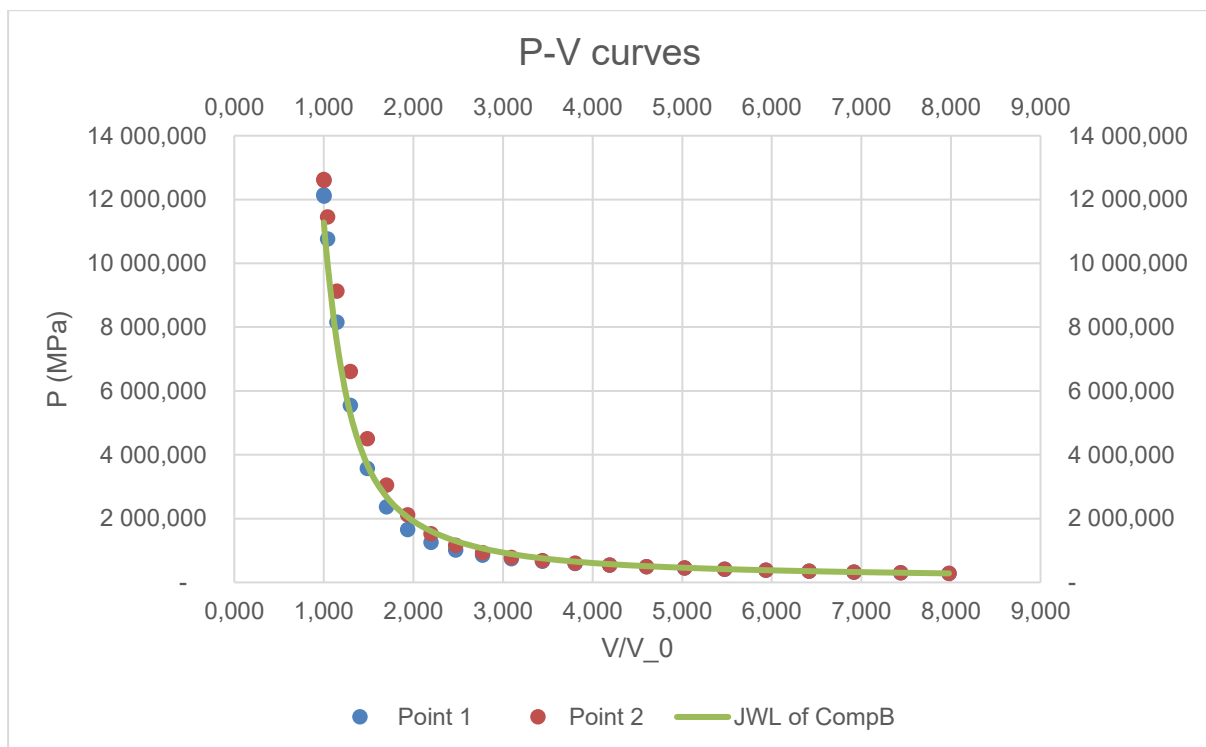


Figure 38: JWL curve of Point 1 and 2 compared to JWL of Composition B

4.1.3 LS-DYNA MODEL RESULTS

As can be seen in Table 7 for the previous test results, the peak pressure for the LS-Dyna extracted data is 12107,211MPa, which is close to the value of 11832,763MPa (or 1% error) gained from the literature JWL for Composition B.

Table 7: LS-Dyna extracted data

V (specific volume)	P (MPa)
1,057	12107,211
1,197	5444,604
1,408	2165,066
1,677	1689,925
1,979	1475,564
2,320	826,169
2,691	509,619
3,098	337,962
3,540	226,197
4,018	161,629
4,529	120,373
5,074	95,709
5,651	79,870

V (specific volume)	P (MPa)
6,260	68,139
6,901	58,783
7,573	51,339
8,277	45,356
9,012	40,409
9,779	36,177
10,577	32,540
11,405	29,437

Figure 39 shows the expansion data extracted from the previous test with Composition B compared to the expansion data gained from the LS-Dyna computer model using the JWL values for Composition B. The data overlaps but is not completely accurate, this can be due to the rough nature of the data extraction process used or an unstable detonation wave. This is why the data is extracted from the bottom two thirds of the copper cylinder to give the detonation wave time to stabilize and minimize uncertainties. It could also be human error since the data is extracted by counting the pixels in the image, with a darker pixel representing the copper cylinder and a lighter pixel the background. If the pixel is grey then the researcher must make an estimated guess as to where inside the pixel the wall could be, this can lead to small errors.

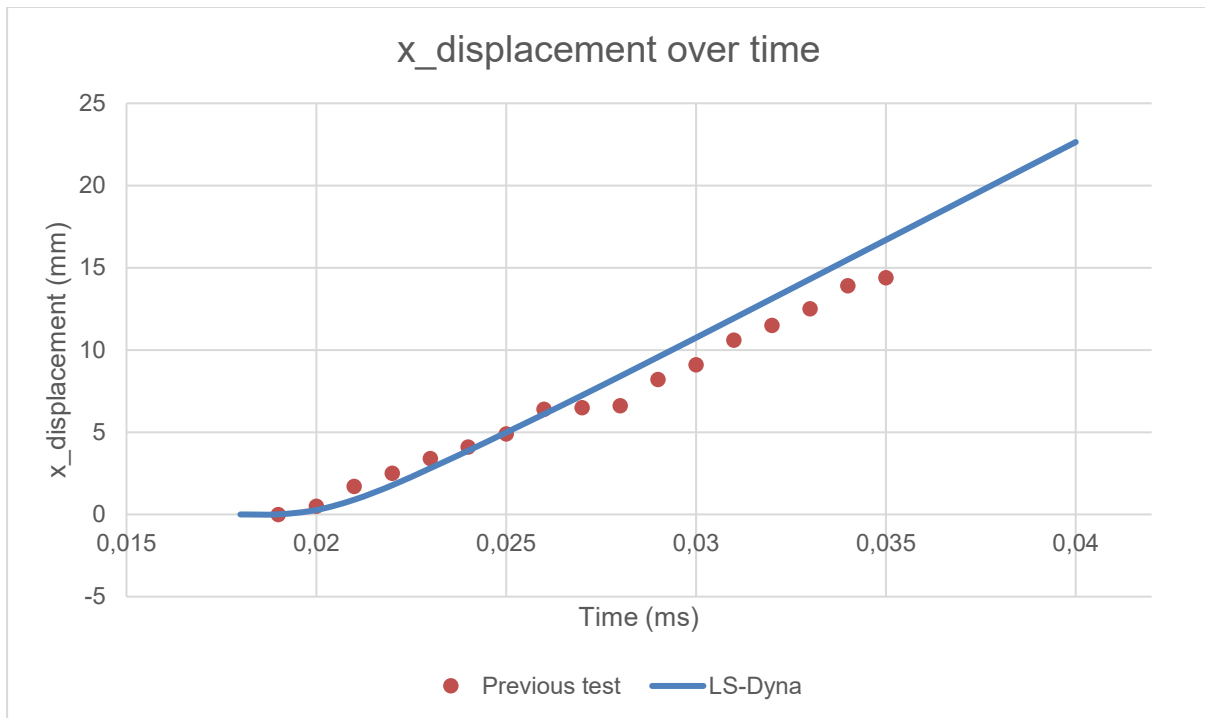


Figure 39: LS-Dyna expansion vs previous test expansion

The collected data could not be examined in more detail, due to only the results being available in the previous reports from which the data was collected. The potential effects of temperature at which the tests were conducted, as well as density of explosive was not mentioned in the previous reports and is something that can be investigated in future tests.

4.2 VALIDATION

Validation of the expansion results, as obtained in the tests by way of camera recording, was done by reproducing the results using the CSIR LS-Dyna simulation model. The first test failed to result in any workable data since the image was overexposed by the blinding light coming from the Argon bomb resulting in a white-only video. This was remedied by closing the apertures on both cameras to their fullest. Both cameras were set up next to each other for

each test to ensure capturing of data even if one failed to record. A total of four sets of data was obtained with the final two tests as a result at both 125 000 FPS and 300 000 FPS for each camera respectively.

4.2.1 EXTRACTING EXPANSION DATA FROM THE IMAGES

The software that was used is called Google SketchUp and the individual images were imported into the software with approximate lines drawn over the outer wall of the cylinder along with lines approximating the positions of the reference teeth at each time step as shown in Figure 40. The software can identify parallel lines which makes it easier to plot the positions due to the direct perpendicular view. Each of the following images imported then had the previous plot overlayed onto it and the new position of the outer wall plotted as can be seen in Figure 41.

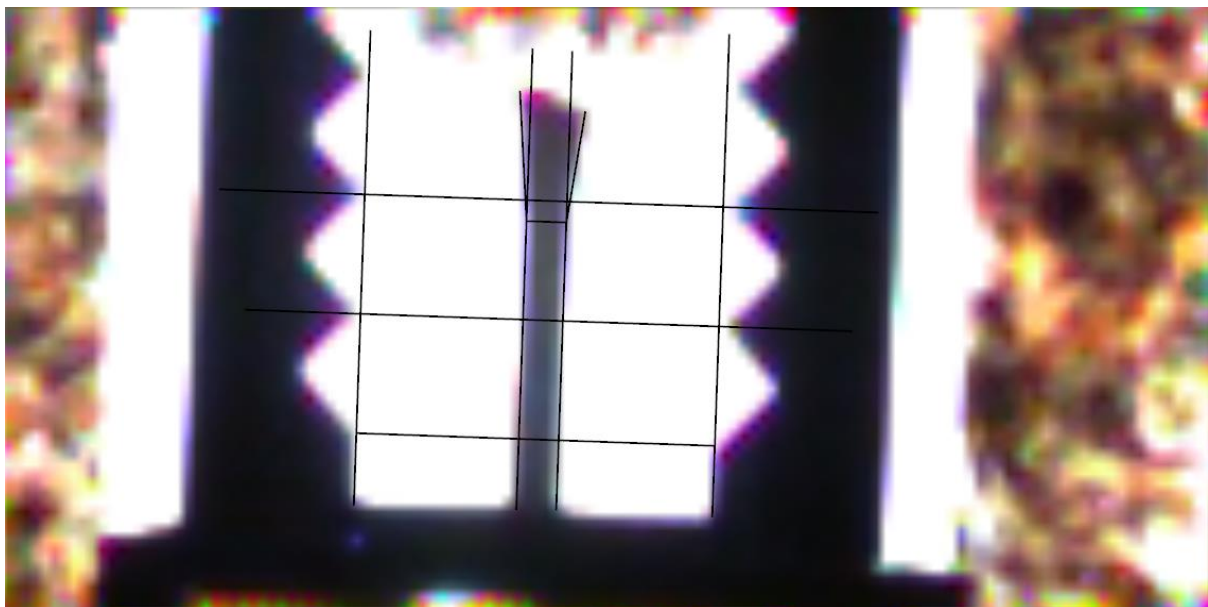


Figure 40: Expansion plotting

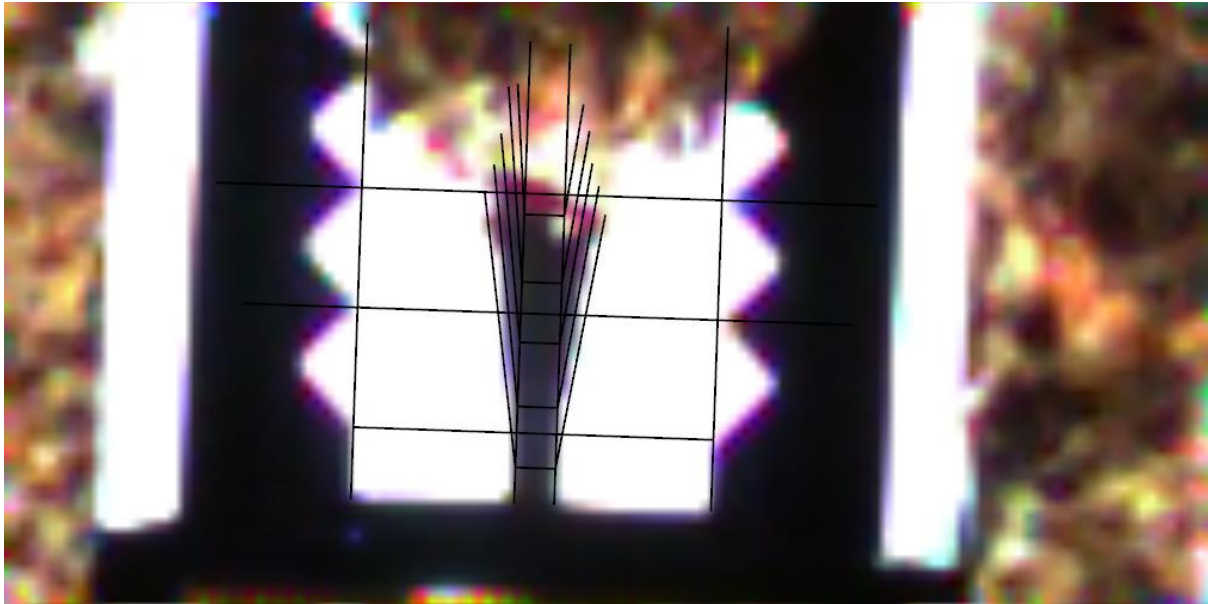


Figure 41: Expansion plotting at later time

This process was continued until all the images of the image sequence, as shown in Figure 42 with workable data, had been plotted and the final plot was then extracted as can be seen in Figure 43. The three horizontal lines are considered the three points on the cylinder in the downward direction on which the outward expansion is measured.

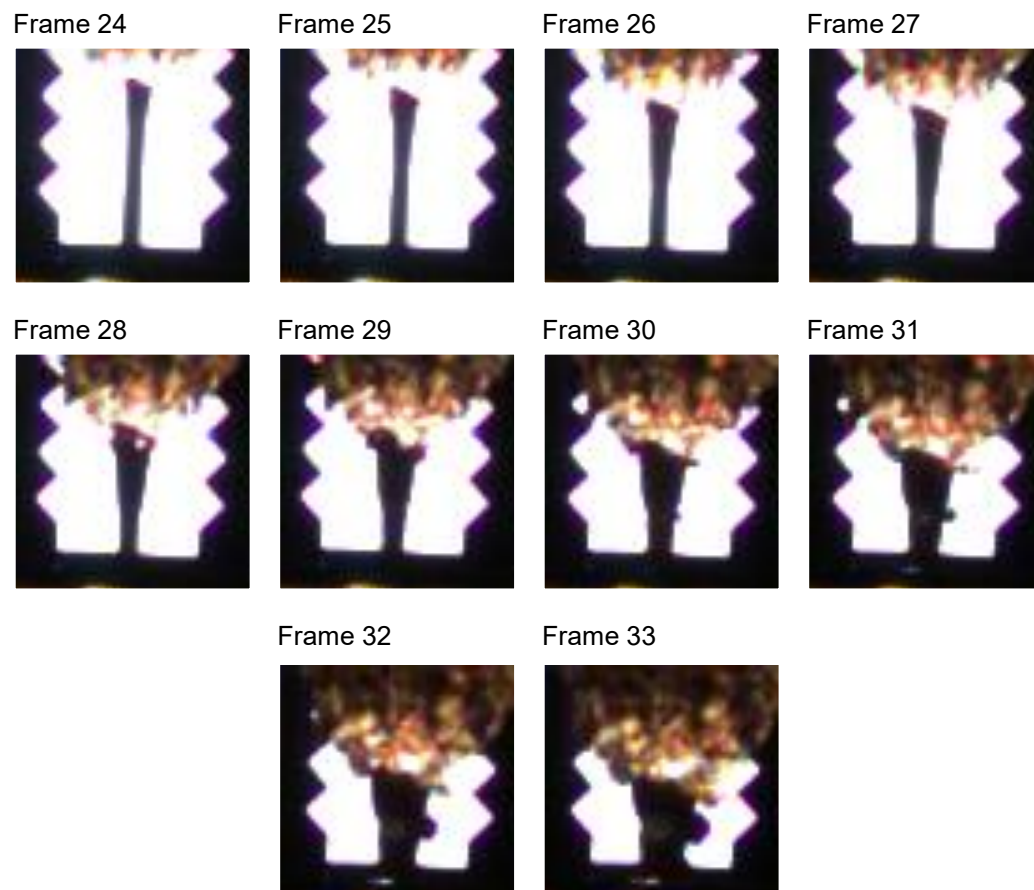


Figure 42: Video image sequence of copper cylinder captured by Nova S6 camera

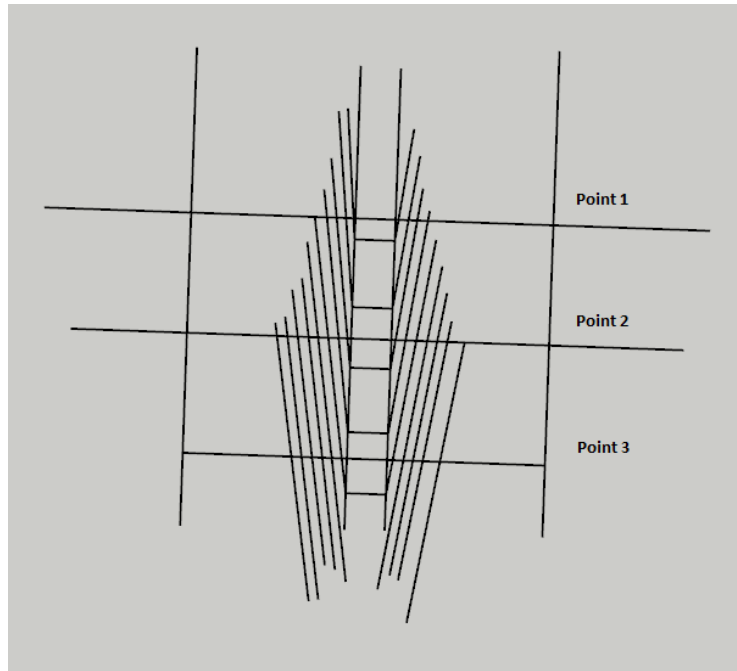


Figure 43: Final plot of copper cylinder expansion extracted from video image sequence

This was done for each of the 4 sets of data, and the software was then used to measure the distance between vertical points. This was also used to measure the distance from the original cylinder to the expansion point on the horizontal reference line and noted in an Excel spreadsheet for each one of the image timeline positions. Due to low image resolution the data extraction was expected to be less accurate because lower image resolution created a more blurred image which, when combined with the fireball of the explosion, made it difficult to pinpoint the exact position of the cylinder wall.

4.2.2 EXCEL CONVERSIONS AND CALCULATIONS

The software uses its own scale, so the distances had to be adjusted accordingly, and this is where the reference “teeth” come in. The distance between each “tooth” is 50 mm, by knowing this and the measured distance of the points in the software, the ratio could be determined

and used to calculate the true expansion distance for each point. This was all done in the Excel spreadsheet created since the author is very confident in using Excel, but other software like MATLAB could also be used. In Table 8 and Table 9 the converted expansion data is shown as extracted from the images for two successful tests. The time is in microseconds, and the radii are in millimetres with the average VOD calculated for the four sets of data equalling 7661,171m/s. Only the data for the camera set at 300k FPS is shown because the camera set to 125k FPS captured too little data for any further processing.

Table 8: Test 2 expansion data

Left		Right	
Time (µs)	Radius (mm)	Time (µs)	Radius (mm)
Point 1			
33,33	12,70	33,33	12,70
36,67	13,46	36,67	13,88
40,00	16,54	40,00	18,07
43,33	20,46	43,33	21,72
46,67	24,50	46,67	26,13
50,00	29,56	50,00	31,12
Point 2			
40,00	12,70	40,00	12,70
43,33	14,22	43,33	14,45
46,67	17,88	46,67	18,60

Left		Right	
Time (μ s)	Radius (mm)	Time (μ s)	Radius (mm)
50,00	22,18	50,00	23,05
53,33	26,44	53,33	27,62
56,67	30,36	56,67	31,76
60,00	34,85	60,00	35,99
63,33	39,15	63,33	39,57
66,67	43,52	66,67	43,14
Point 3			
46,67	12,70	46,67	12,70
50,00	14,83	50,00	15,02
53,33	18,98	53,33	19,44
56,67	22,94	56,67	23,39
60,00	27,16	60,00	27,46
63,33	31,54	63,33	31,04
66,67	35,76	66,67	34,62

Table 9: Test 3 expansion data

Left		Right	
Time (μs)	Radius (mm)	Time (μs)	Radius (mm)
Point 1			
36,67	12,70	36,67	12,70
40,00	16,33	40,00	16,33
43,33	20,52	43,33	21,22
46,67	24,85	46,67	25,97
Point 2			
40,00	12,70	40,00	12,70
43,33	13,68	43,33	13,82
46,67	18,15	46,67	18,57
50,00	22,62	50,00	23,32
53,33	27,50	53,33	28,20
56,67	30,72	56,67	31,56
60,00	33,93	60,00	35,19
Point 3			
46,67	12,70	46,67	12,70
50,00	15,63	50,00	15,91

Left		Right	
Time (μ s)	Radius (mm)	Time (μ s)	Radius (mm)
53,33	19,96	53,33	20,66
56,67	23,18	56,67	24,15
60,00	26,25	60,00	27,64

4.2.3 CSIR METHOD TO DETERMINE JWL

The Excel spreadsheet created follows the CSIR methodology as explained in Procedure of determining the JWL parameters and the only input from the user is to input the expansion at each point in time, curve fitting the first equation parameters a and b, and then curve fitting the final JWL parameters on the P-V curve generated by the points at the end of the method.

As can be seen in Figure 44, the y values of the equation in step 4 of the method had been fit to the curve of the x displacement values, r_c is just for reference on the radius of the cylinder expansion which is the original cylinder radius plus the expansion. The curve fitting tool used is an online one that is free, MyCurveFit, and was further refined in Excel itself for more accurate results. This was done for each one of the four data sets on each side of the copper cylinder with the above figure showing the curve fitting for test number 2, point 1, on the left side of the cylinder.

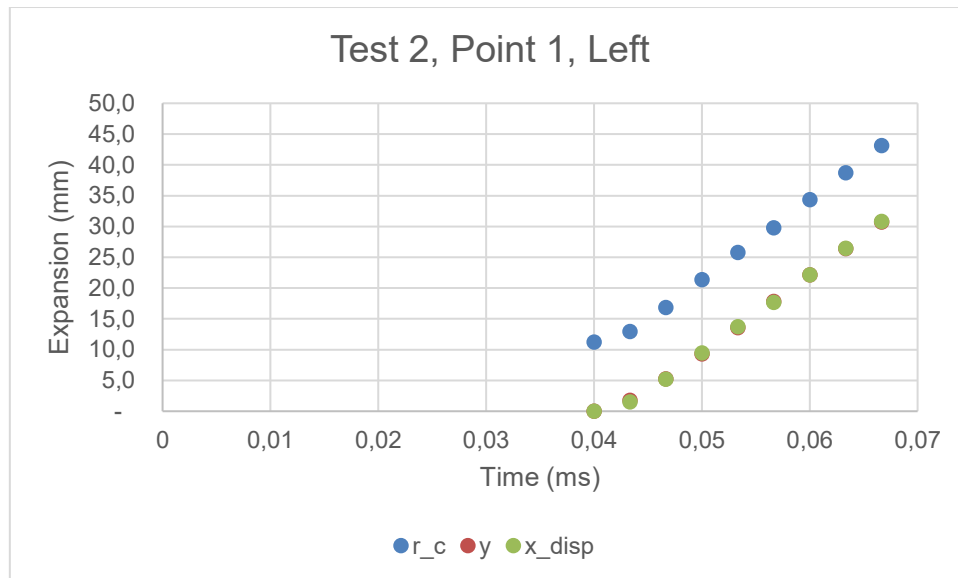


Figure 44: Curve fitting y on x displacement

With these determined a and b values for each point, the next steps were automatically updated in the Excel spreadsheet and generated the final P and V values. Not all data sets could be used due to the lack of data points for each vertical point. At least four points are needed to curve fit the final data values with a curve that has four unknown parameters. This resulted in only eight P-V data sets that could be curve fitted to find the JWL parameters. The next step was to compare the results of each set to the JWL curve of C4 in a combined graph.

In Figure 45 the plotted JWL curves for the eight processed data sets can be seen compared to the JWL curve of C4. It is expected for the PE9 JWL curves to be like the JWL curve of C4 due to the reported similarity between the two and as shown in the table and graph above, this does seem to be the case. The peak pressure of C4 is 11283,320 MPa which compares very closely with that of the average peak pressure for PE9 which is the South African equivalent to C4, 11239,496 MPa, calculated using the CSIR method. (C4 contains 91% RDX compared to PE9 which contains 90% RDX).

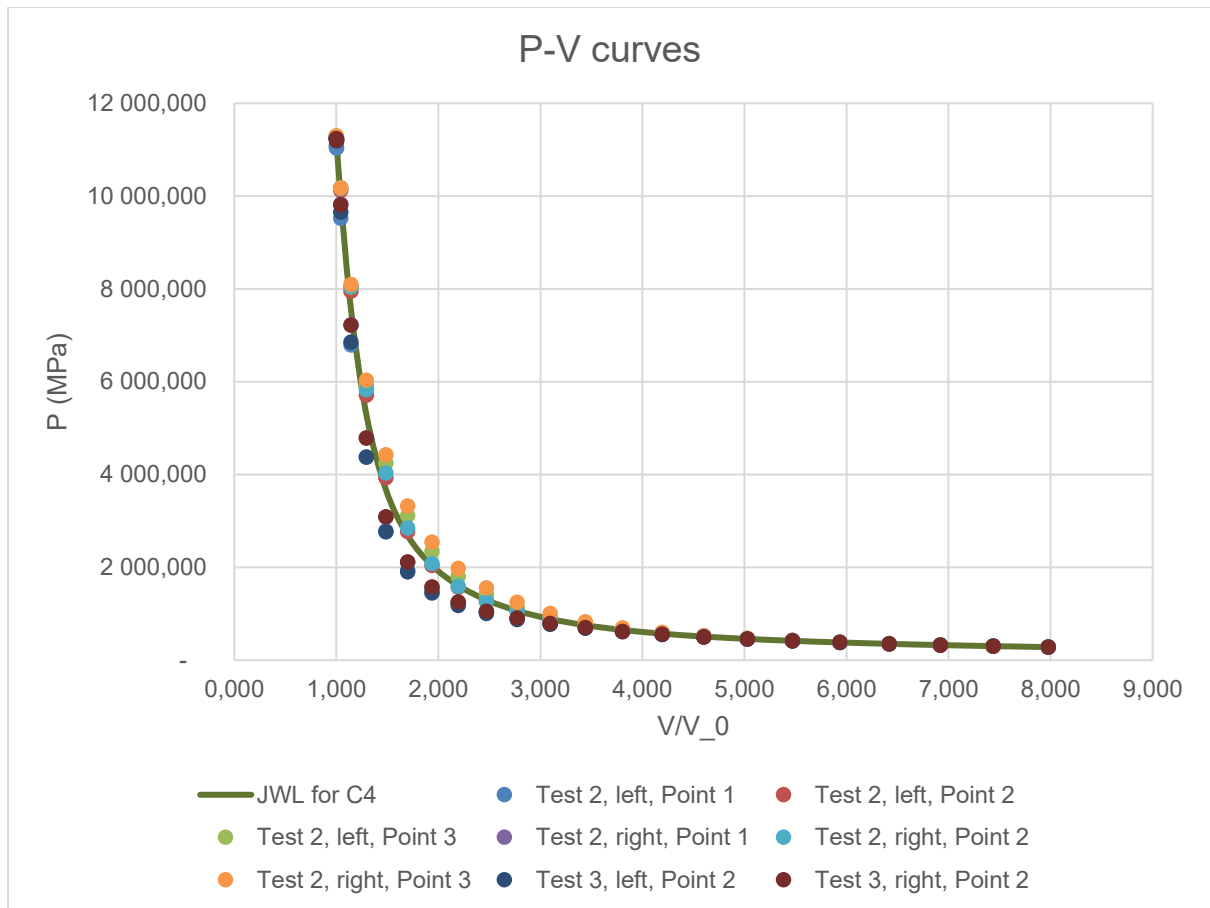


Figure 45: JWL curves of processed data points compared to JWL curve of C4

As can be seen in Figure 46, the average P-V curve for the eight data sets aligns with the P-V curve for C4, with a deviation of less than 1%. This is the reason for choosing multiple points to generate multiple sets, to get the average to compensate for any deviations in data extraction that may arise from inaccurate measuring due to rough image capturing.

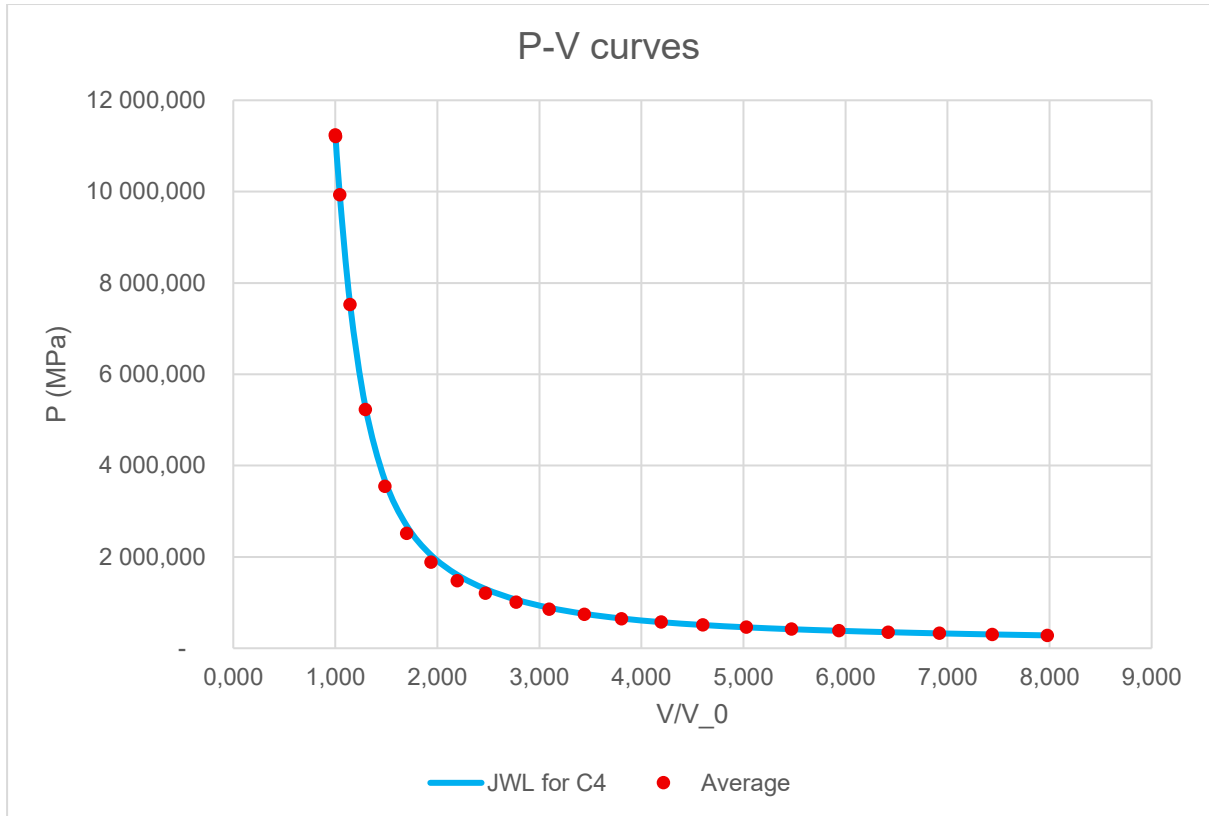


Figure 46: Average of JWL curve for calculated data sets compared to the JWL curve of C4

4.2.4 LS-DYNA MODEL RESULTS

In Figure 47 the simulated copper cylinder radial expansion data in the form of x-displacement results for each of the individual JWL sets can be seen compared to the experimental average as extracted with image processing from the recorded videos.

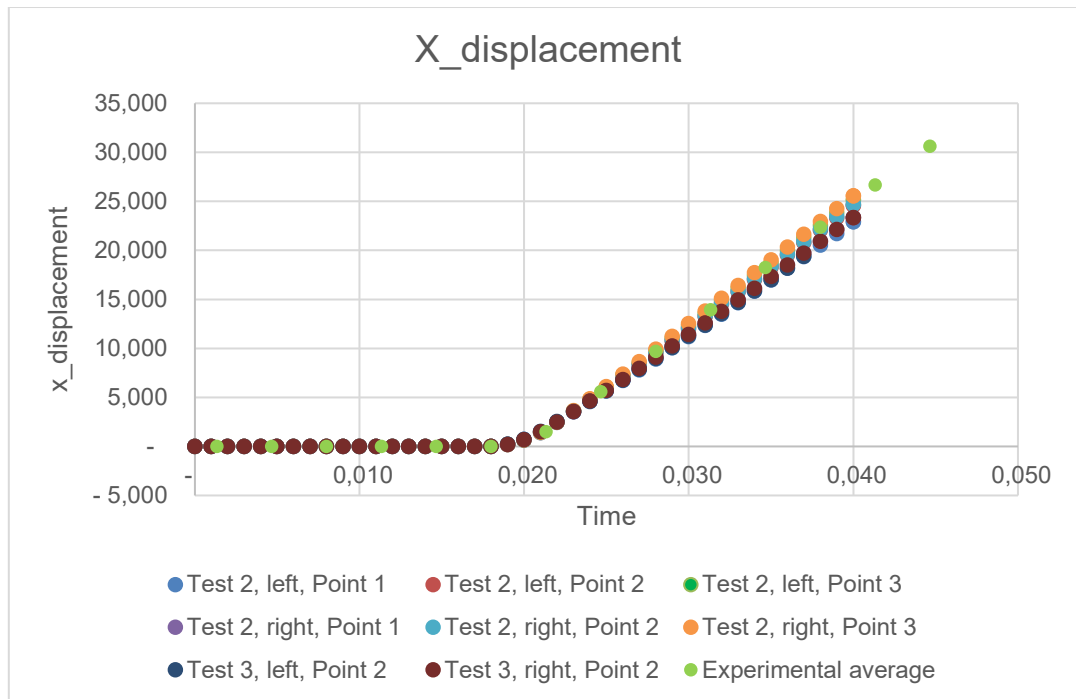


Figure 47: Individual simulation results compared to experimental average

In Figure 48 the averaged LS-Dyna copper cylinder radial expansion data in the form of x-displacement, can be seen compared to the experimental average as calculated. The LS-Dyna average collates the eight different expansion data sets as extracted from the LS-Dyna software into a single graph to compare with the experimental data. All the results had a deviation of less than 8.2% (at the furthest expansion point) and averages at 2.88% deviation from the experimental average.

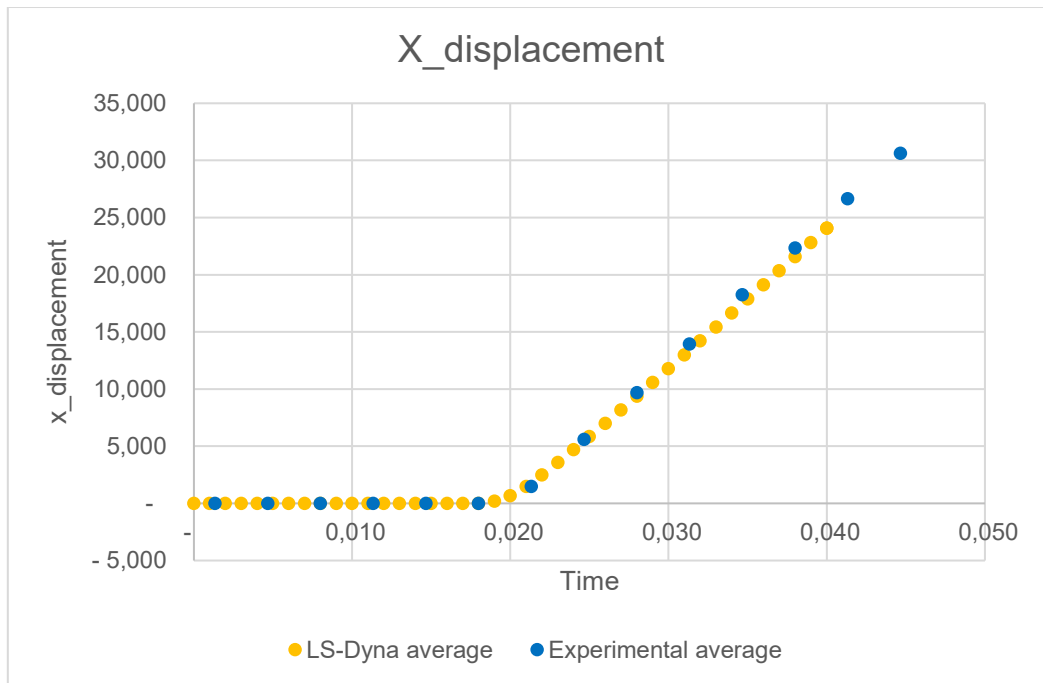


Figure 48: LS-Dyna average expansion data compared to experimental average expansion data

Figure 49 shows the individual video capture image and simulation image that were overlapped and Figure 50 shows the LS-Dyna simulation timesteps overlapped with the video image sequence at similar timestamps.

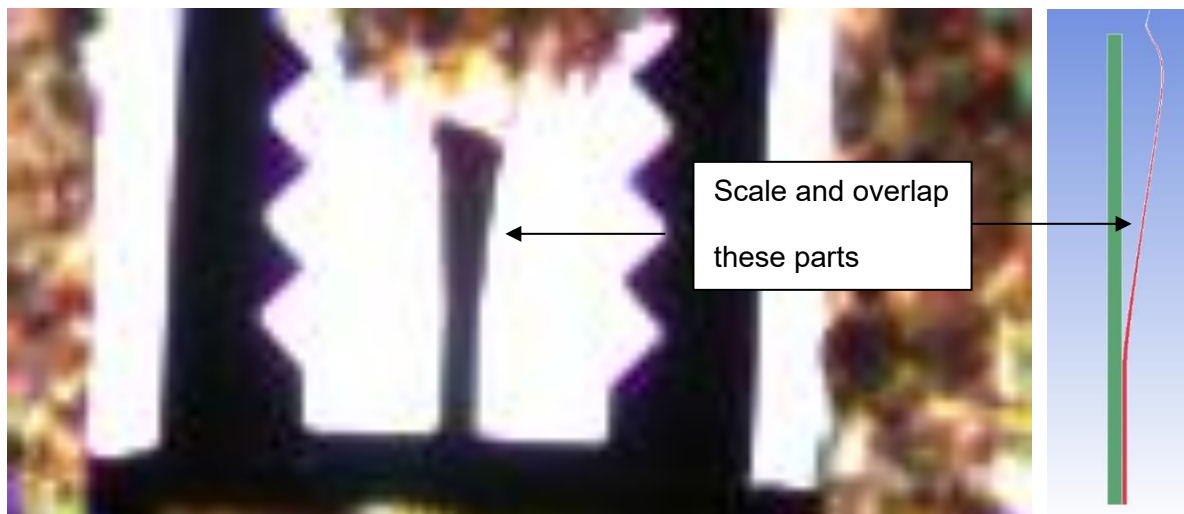


Figure 49: Video image (left) and simulation image (right) to be overlapped

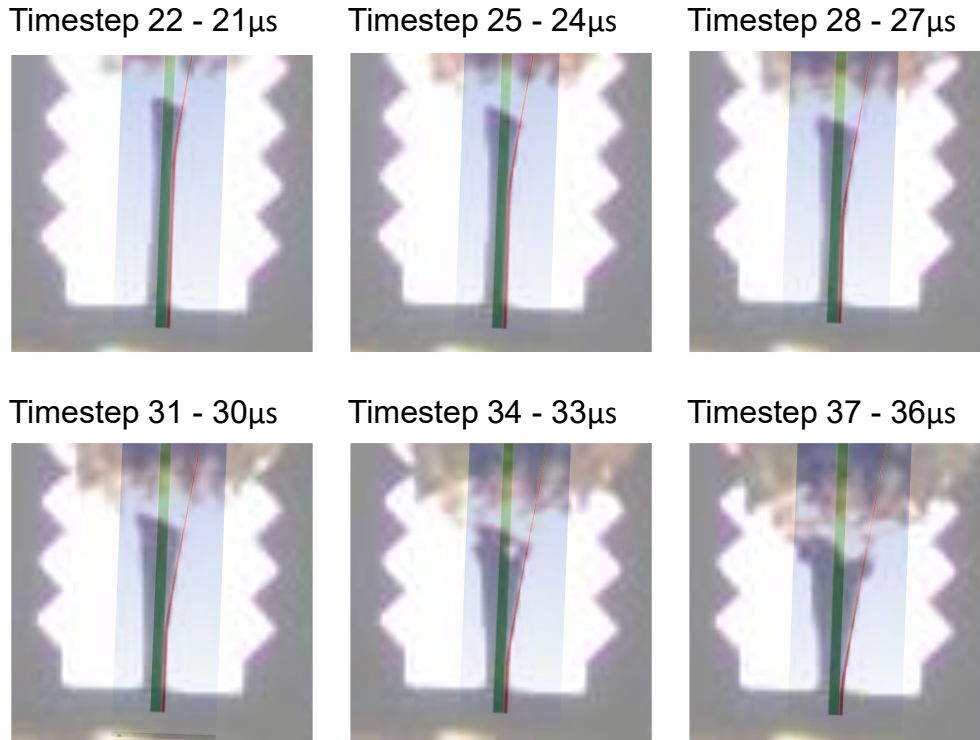


Figure 50: Timestep sequence overlap

4.3 JWL EOS PARAMETER RESULTS FOR PE9

In Table 10 the material model values and JWL EOS parameters calculated for PE9, for each one of the eight points by curve fitting, can be seen. The value of the parameters vary as was expected since there are multiple solutions that will fit the curve, it is up to the researcher to decide on the values that best fit the curve.

Table 10: PE9 parameters as calculated for each one of the eight tests

	*MAT_HIGH_EXPLOSIVE_BURN							
	mid	ro	d	pcj	beta	k	g	sigy
	1	0,00175	8193	28000	0	0	0	0

Test	*EOS_JWL							
	eosid	a	b	r1	r2	omeg	e0	vo
1	1	748812	1446,8	4,43	1,00	0,25	9000	1
2	1	215917	3732,8	3,22	1,00	0,25	9000	1
3	1	335718	20000	4,10	1,47	0,25	9000	1
4	1	470296	1441,2	3,94	1,00	0,25	9000	1
5	1	192640	3676,3	3,10	1,00	0,25	9000	1
6	1	413391	20000	4,39	1,36	0,25	9000	1
7	1	755934	1120,2	4,41	1,00	0,25	9000	1
8	1	476628	1564,2	3,95	1,00	0,25	9000	1

4.4 CHAPTER SUMMARY

In this chapter the author gave the results to the image processing and the results of the calculations using these image results. The Excel spreadsheet that the author created to do these calculations and process the image data was also discussed in detail along with the results produced by this spreadsheet. The graphs generated were also given for both the verification process as well as the validation process.

The successful verification of the CSIR methodology and the accuracy of the LS-Dyna computer model was described in detail. The validation of the results was confirmed with LS-Dyna computer model results.

CHAPTER 5 - DISCUSSIONS

5.1 IMAGE ANALYSIS

Analysing the images was not as easy as originally thought, the main concern from the start had always been the FPS and the resolution associated with it. The tests, according to the methodology developed at the CSIR, were originally planned to use the Cording Ultra High-Speed (UHSP) camera and can record up to speeds of 2 million frames per second while all images are at a fixed resolution of 1000x1000 pixels. Even though it can only record 32 images in total, this is sufficient for image analysis to extract expansion data for JWL parameterisation.

With careful planning the timing can be done to get the maximum amount of images that produce results. At such a high pixel resolution the expansion calculation can be very accurate but during the timeline of this dissertation the camera could not be used due to technical difficulties. The camera had not been in use for several years and all the skilled or experienced staff (experienced in the use of this specific camera and doing these types of tests) had left the employment of the CSIR.

There were attempts to fix the camera for use, but this was very time consuming, and no further delays to the tests could be permitted. The components for the camera needed to be imported from the United States of America and since this camera is under strict supervision, local and internationally, the import and export of said components had to go through many checks and took many months to complete. Even after one component was replaced, it came to attention that there was another component that needed to be replaced. This resulted in a combined loss of nearly 9 months. (One component was dependent on another and did not reveal its dysfunction until after the first one was replaced)

For this reason, and due to the lack of time left, it was decided to use another camera that the CSIR had available for use, the Photron Nova S6. Unfortunately, this camera is not as

specialised as the Cordin UHSP which meant that even though the camera records a video instead of a few images, the camera only had a maximum frame rate of 800 000 FPS. And since the camera records a video, the higher the framerate is set, the lower the resolution that it records. This limited the framerate at which one could record while still getting sufficient resolution quality for image analysis.

This is why two cameras were used for the same tests: One camera was set to record at 125 000 FPS and the other at 300 000 FPS. The first camera could record a maximum resolution of 256x128 pixels, and the second camera could record a maximum resolution of 128x96 pixels at their respective speeds.

The slower camera produced less images at a clearer image resolution while the faster camera produced more images at a less clear image resolution. Both factors influenced the following Excel calculations due to the accuracy of expansion data extraction from the image analysis process and is discussed in the following subsection.

5.2 EXCEL CONVERSIONS AND CALCULATIONS

The Excel conversions were implemented successfully when looking at the results produced while the spreadsheet also translates the CSIR method well and does everything step by step, simplifying and easing the process. The curve fitting for the 4th step was easy since it only has two variables. While plotting the curve and the extracted expansion data points on the same graph, the two variables can be adjusted until the curve fits the points sufficiently.

The online curve fitting tool, MyCurveFit worked sufficiently to achieve the goal of this dissertation. Since there are four variables it is expected to have multiple solutions for the four parameters of A, B, R_1 and R_2 that all approximate the curve well, it is then up to the user to pick the values that best fit the curve.

PE9 compared well to C4 when looking at the results as determined with the CSIR method in this dissertation, and when comparing the P-V curves of PE9 and C4 as in Figure 46.

The results would have been even more consistent and accurate had the proper camera (Cordin UHSP camera) been used for the tests. The low resolution created small variations in data points from which to work while more data points would increase the accuracy due to the averaging effect of curve fitting in the CSIR methodology.

5.3 LS-DYNA MODEL

There was an expected amount of variation in the results of the eight sets due to the eight different JWL parameter sets that were calculated and the variation is noticeable because the LS-Dyna model is more sensitive to differences in parameters.

Better and more accurate results would have been obtained had the problems with the intended camera been fixed. Regardless, the CSIR method mitigated the input errors enough to produce successful results. According to the manual mentioned in Verification and validation using simulation software these results mean that the method is verified, and the results validated using simulation software as was the aim of this dissertation.

The model had to be updated to be usable with the most recent version of LS-Dyna (v15.0.0). This was also necessary to run the simulations since the license for the older versions had run out and had to be moved over to a newer version to run the final simulations.

5.4 CHAPTER SUMMARY

This chapter discussed the accuracy and the validity of the CSIR method in determining the JWL EOS parameters for PE9. It is evident that the method is very accurate and can easily be verified. The results are valid and would have been more accurate if the appropriate equipment was used as specified in the original test instructions. The accuracy of the simulation results was also discussed.

CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

In conclusion the results were better than was initially expected after the sudden change from a specialised camera, recommended for the tests, to a camera less suited for these types of tests. Originally it was expected that the image analysis would produce unacceptable data, it might not have been as good as it could have been if the correct camera was used, but the data was adequate and workable.

The parameters calculated were accurate but vary to such a degree that an average or all-encompassing EOS cannot be determined at this time. More work with better dedicated equipment is needed for better parameterisation.

It turns out that the CSIR method is a lot more forgiving, regarding inaccurate inputs, than what was initially thought. It still was not as accurate as it could have been, but by having multiple sets, the averages could be used to try and mitigate any mistakes or variations even further. The CSIR method was successfully translated into Excel and verified using previous Composition B test data by comparing the P-V curves.

The setup for the tests was simple enough to replicate and with experience can be done very quickly. After everything was prepared in the morning by the team that assisted in completing the tests, four shots were fired in total within a time span of 1 hour and 10 minutes. This was very fast considering the setup and the safety precautions involved in the handling of explosives.

The process as explained step by step in Table 1 was difficult to copy into the Excel spreadsheet, and some of the points needed some investigation to figure out what was explained and required. But after some work to understand the process and what was done, the method became easy to interpret with results that speak for themselves.

The LS-Dyna computer model had its fair share of problems, but with the assistance of experienced operators and a lot of investigation, the model was fixed and produced successful results. The computer model was successfully verified using previous Composition B test data by comparing the expansion results. The computer model was then used to successfully validate the results achieved with the physical PE9 tests by comparing the expansion results from the tests and the computer model.

6.2 RECOMMENDATIONS

It is highly recommended to fix and use the Cordin UHSP camera for any future tests, seeing as the CSIR method was developed with its use in mind. This is because higher speeds can be obtained resulting in more data points extracted through image analysis and at a much higher resolution which in turn will lead to more accurate points and thus more accurate results. This will result in parameters that are more accurate and concise and can be published and used for future modelling.

The Cordin UHSP camera has also been purposely installed in a dedicated facility where all the dangers, concerns and problems that were encountered during the current tests are mitigated almost entirely. There are no open cables that can be damaged, and the facility has thick armour plating and protection against shrapnel. The only remaining concern is the open armoured glass in front of the camera that can still be damaged during tests.

It is also recommended to get a second FS43 firing unit as originally planned, since the changes to the setup that were made to accommodate the use of only one, made operating the Cordin UHSP camera more difficult. Luckily for these tests the Nova S6 was used, and it could accommodate the change better due to the much longer recording time while not needing the precise timing that the Cordin camera requires due to the limited amount of images that it captures.

It is also suggested to investigate whether normal copper could work, which will remove the need to import high purity copper from abroad that then also needs to be machined into tubes before they can be used, all at great expense.

There were many attempts at simplification and improvement of the test method, but few succeeded with the current test method being the simplest and most accurate. Many improvements can be made in the future if new ideas are brought to the table, and time can be made to test these ideas.

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APPENDIX A

During the tests there were a few concerns regarding the safety and integrity of the test equipment because the shrapnel from the copper cylinder created by the detonation has a large damaging effect. The use of copper in Explosively Formed Projectiles is specifically used to penetrate the armour of tanks.

During the first pre-test conducted, the shrapnel severed the BNC cable that triggers the cameras, it severed the power cable that powers the cameras and damaged the viewport protective glass of the cubicle directly in front of one of the cameras. Had the protective glass not been there, one of the cameras would have been completely lost. These damages can be seen in Figure 51, Figure 52, and Figure 53.



Figure 51: Damaged power cable



Figure 52: Damaged BNC cable



Figure 53: Damaged protective glass

After the first test both cables going to the cameras were covered more securely and the camera adjusted to view past the damaged area of the protective glass. The camera cubicle

was also moved further back, from the initial 7m to 15m. This was to put more distance between the explosion and the cameras, which reduced shrapnel hit chance significantly due to the explosion happening radially and thus the further away, the more spread out the shrapnel.

After making these adjustments, the damage observed to the cubicle and the surrounding area was significantly reduced and no further damages or other problems during the remaining tests were encountered.

There was significant damage done to the stand of the light detector, which was expected due to its proximity to the explosion (only 3m) and can be seen in Figure 54. That is why it is best to use cheap disposable stands for these tests.



Figure 54: Damage to light detector stand

The rest of the test setup worked as intended, the Argon bomb became easier to fill and seal after gaining some experience, the wooden stands were easy to adjust to the correct height using the height adjustable metal feet, and the light detector detected the Argon bomb lighting as it was designed to do. The cubicle and the bunker provided sufficient protection from the blast for both operators and equipment, the new design for holding the copper cylinder upright worked well and kept the cylinder vertically in place, whereas in the previous tests it skewed slightly. The designed booster holder fit snugly on the copper cylinder and the PE4 cup was easy to attach to the Argon bomb as can be seen in Figure 55 and Figure 56.



Figure 55: PE4 attached to Argon bomb



Figure 56: Copper cylinder vertical in stand

APPENDIX B

*ALE_MULTI-MATERIAL_GROUP (2)	
1	SID ☐ IDTYPE 1 1

*BOUNDARY_NON_REFLECTING_2D (1)		
1	NSID ☐ AD AS 1	

*BOUNDARY_SPC_SYMMETRY_PLANE (1)								
1	IDSP	PID ☐	X	Y	Z	VX	VY	VZ
	1	2	0.0	0.0	0.0	1.0000000	0.0	0.0
2	TOL							
	0.0200000							

*CONSTRAINED_LAGRANGE_IN_SOLID (1)								
☒ Option Card1 ☐ Option Card2								
1	COUPID	TITLE						
	1	Coupling between Explosive and Tube						
2	LSTRSID ☐	ALESID ☐	LSTRSTYP	ALESTYP	NQUAD	CTYPE	DIREC	MCOUPL ☐
	2	1	1	0	2	4	3	-1
3	START	END	PFAC ☐	FRIC	FRCMIN	NORM	NORMTYP	DAMP
	0.0	1.000e+10	0.1	0.0	0.5000000	0	0	0.0
4	K	HMIN	HMAX	ILEAK	PLEAK	LCIDPOR ☐	NVENT	BLOCKAGE
	0.0	0.0	0.0	2	0.1000000	0	0	0
5	IBOXID	IPENCHK	INTFORC	IALESOF	LAGMUL	PFACMM	THKE	
	0	0	0	0	0.0	2	0.0	

*CONTROL_TERMINATION (1)						
1	ENDTIM	ENDCYC	DTMIN	ENDENG	ENDMAS ☐	NOSOL
	0.0400000	0	0.0	0.0	1.000e+08	0

*DATABASE_OPTION (2)

☒ GLSTAT	0.0	0	0	1
	DT	BINARY	LCUR ☒	IOOPT
☐ GLSTAT_MASS_PROPERTIES	0.001	0	0	1
	DT	BINARY	LCUR ☒	IOOPT
☐ ICVOUT	0.0	0	0	1
	DT	BINARY	LCUR ☒	IOOPT
☐ JNTFORC	0.0	0	0	1
	DT	BINARY	LCUR ☒	IOOPT
☒ MATSUM	0.001	0	0	1
	DT	BINARY	LCUR ☒	IOOPT

*DATABASE_BINARY_D3DUMP (1)

1	CYCL	LCDT ☒	BEAM	NPLTC	PSETID ☒
	0.0	0	0	0	0

Active optional cards
☒ None ☐ Opt1

*DATABASE_BINARY_D3PLOT (1)

1	DT	LCDT ☒	BEAM	NPLTC	PSETID ☒
	0.0010000	0	0	0	0

Active optional cards
☐ None ☒ Opt1

2	IOOPT	RATE	CUTOFF	WINDOW	TYPE	PSET ☒
	0	0.0	0.0	0.0	0	0

*DATABASE_BINARY_D3THDT (1)

1	DT	LCDT ☒	BEAM	NPLTC	PSETID ☒
	1.000e-04	0	0	0	0

*DATABASE_EXTENT_BINARY (1)

1	NEIPH 6	NEIPS 6	MAXINT 3	STRFLG 0	SIGFLG 1	EPSFLG 1	RLTFLG 1	ENGFLG 1
2	CMPFLG 0	IEVERP 0	BEAMIP 0	DCOMP 1	SHGE 1	STSSZ 1	N3THDT 2	IALEMAT 1
3	NINTSLD 0	PKP_SEN 0	SCLP 1.0000000	HYDRO 0	MSSCL 0	THERM 0	INTOUT	NODOUT
4	DTDT 0	RESPLT 0	NEIPB 0	QUADSLD 0	CUBSLD 0	DELERES 0		

Keyword Input Form

RefBy Add Accept Delete Default Done 3 Air

☐ Use *Parameter ☐ Comment (Subsys: 1 JWL-PE9-jets.k) Setting

*EOS_LINEAR_POLYNOMIAL(TITLE) (1)

TITLE
Air

1	EOSID	C0	C1	C2	C3	C4	C5	C6
	3	0.0	0.0	0.0	0.0	0.4000000	0.4000000	0.0
2	E0	V0						
	0.2525000	1.0000000						

COMMENT:

Total Card: 1 Smallest ID: 3 Largest ID: 3 Total deleted card: 0

Keyword Manager

Keyword Edit: Keyword Search

Edit: EOS_LINEAR_POLYNOMIAL

☒ Model ☐ All

Name

- [-] ALE
- [-] BOUNDARY
- [-] CONSTRAINED
- [-] CONTROL
- [-] DATABASE
- [-] ELEMENT
- [-] EOS
 - [-] GRUNEISEN
 - [-] JWL
 - [-] LINEAR_POLYNOMIAL
- [-] HOURGLASS
- [-] INITIAL
- [-] KEYWORD

Material arrange

GroupBy Sort

Model Type

Load From MatDB

Keyword Input Form

RefBy Pick Add Accept Delete Default Done 2 OFHC Copper

☐ Use *Parameter ☐ Comment (Subsys: 1 JWL-PE9-jets.k) Setting

*EOS_GRUNEISEN(TITLE) (1)

TITLE
OFHC Copper

1	EOSID	C	S1	S2	S3	GAMMA0	A	E0
	2	3940.0000	1.4900000	0.0	0.0	2.0200000	0.0	0.0
2	V0	UNUSED	LCID					
	1.0000000		0					

COMMENT:

Total Card: 1 Smallest ID: 2 Largest ID: 2 Total deleted card: 0

Keyword Manager

Keyword Edit: Keyword Search

Edit: EOS_GRUNEISEN

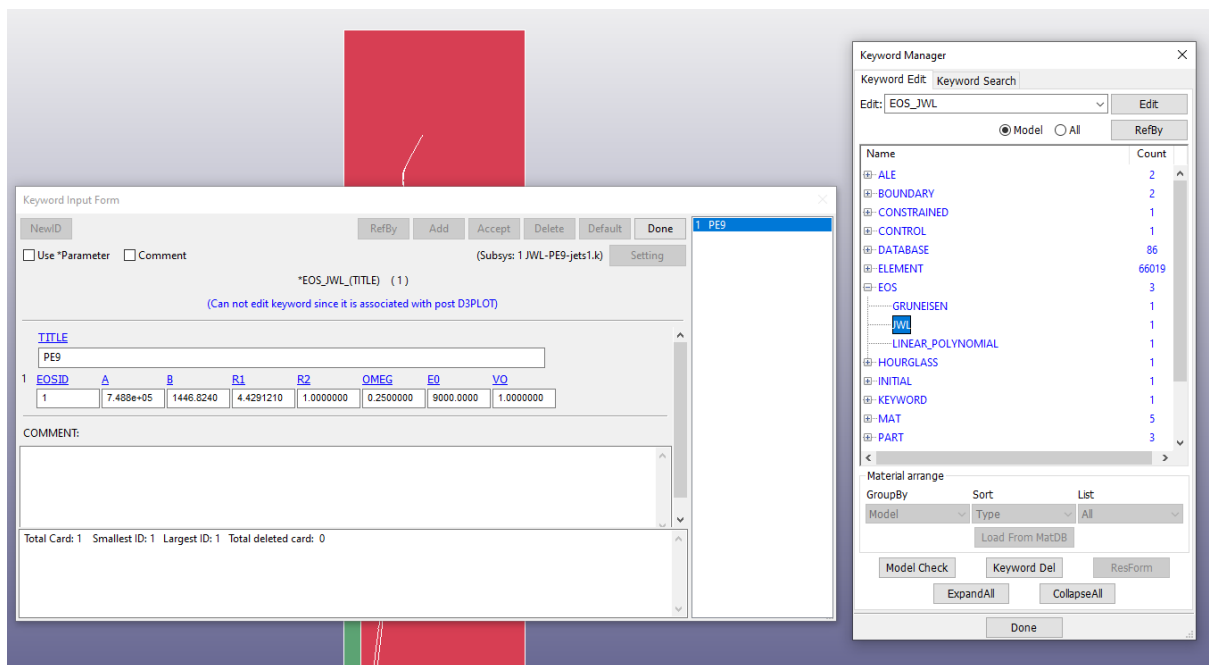
☒ Model ☐ All

Name

- [-] ALE
- [-] BOUNDARY
- [-] CONSTRAINED
- [-] CONTROL
- [-] DATABASE
- [-] ELEMENT
- [-] EOS
 - [-] GRUNEISEN
 - [-] JWL
 - [-] LINEAR_POLYNOMIAL
- [-] HOURGLASS
- [-] INITIAL
- [-] KEYWORD

Material arrange

GroupBy Sort List



*HOURLGLASS_(TITLE) (1)

TITLE
Lagrange hourglass

HGID	IHQ	QM	IBQ	Q1	Q2	QB/VDC	QW
1	4	0.1000000	0	1.5000000	0.0600000	0.1000000	0.1000000

*INITIAL_DETONATION (1)

PID	X	Y	Z	LT	=	MMGSET
0	0.0	305.00000	0.0	0.0		0

Keyword Manager

Keyword Edit

Keyword Search

Edit:

Edit

☒ Model ☐ All

RefBy

Name	Count
☐ ALE	2
☐ BOUNDARY	2
☐ CONSTRAINED	1
☐ CONTROL	1
☐ DATABASE	86
☐ ELEMENT	66019
☐ EOS	3
☐ HOURGLASS	1
☐ INITIAL	1
☐ KEYWORD	1
☐ MAT	5
☐ PART	3
☐ SECTION	2
☐ SET	2
☐ TITLE	1

Material arrange

GroupBy

Model

Sort

Type

List

All

Load From MatDB

Model Check

Keyword Del

ResForm

ExpandAll

CollapseAll

Done

*KEYWORD (1)

1 MEMORY MEMORY2 NCPU

25000000		4
----------	--	---

Keyword Input Form

NewID

MatDB

RefBy

Pick

Add

Accept

Delete

Default

Done

☐ Use *Parameter
 ☐ Comment

(Subsys: 1 JWL-PE9-jets.k)

Setting

*MAT_NULL_(TITLE) (009) (1)

TITLE

Air

1

MID	RO	PC	MU	TEROD	CEROD	YM	PR
h	1.290e-06	-0.1010000	0.0	0.0	0.0	0.0	0.0

COMMENT:

Total Card: 1 Smallest ID: 4 Largest ID: 4 Total deleted card: 0

4 Air

Keyword Manager

Keyword Edit

Keyword Search

Edit:

MAT_NULL

☒ Model
 ☐ All

Name

HOURGLASS

INITIAL

KEYWORD

MAT

003-PLASTIC_KINEMATIC

008-HIGH_EXPLOSIVE_BURN

009-NULL

010-ELASTIC_PLASTIC_HYDRO

013-ISOTROPIC_ELASTIC_FAILURE

015-JOHNSON_COOK

098-SIMPLIFIED_JOHNSON_COOK

140-VACUUM

NODE

Material arrange

GroupBy

Sort

List

Model

Type

All

Keyword Input Form

NewID

MatDB

RefBy

Pick

Add

Accept

Delete

Default

Done

☐ Use *Parameter
 ☐ Comment

(Subsys: 1 JWL-PE9-jets.k)

Setting

*MAT_ELASTIC_PLASTIC_HYDRO_(TITLE) (010) (1)

TITLE

OFHC for jets

1

MID	RO	G	SIGY	EH	PC	FS	CHARL
7	0.0089300	4.600e+04	90.000000	0.5000000	0.0	0.0	0.0

2

EPS1	EPS2	EPS3	EPS4	EPS5	EPS6	EPS7	EPS8
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

3

EPS9	EPS10	EPS11	EPS12	EPS13	EPS14	EPS15	EPS16
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

4

ES1	ES2	ES3	ES4	ES5	ES6	ES7	ES8
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

5

ES9	ES10	ES11	ES12	ES13	ES14	ES15	ES16
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Plot

Raise

New

Padd

Total Card: 1 Smallest ID: 7 Largest ID: 7 Total deleted card: 0

7 OFHC for jets

Keyword Manager

Keyword Edit

Keyword Search

Edit:

MAT_ELASTIC_PLASTIC_HYDRO

☒ Model
 ☐ All

Name

HOURGLASS

INITIAL

KEYWORD

MAT

003-PLASTIC_KINEMATIC

008-HIGH_EXPLOSIVE_BURN

009-NULL

010-ELASTIC_PLASTIC_HYDRO

013-ISOTROPIC_ELASTIC_FAILURE

015-JOHNSON_COOK

098-SIMPLIFIED_JOHNSON_COOK

140-VACUUM

NODE

Material arrange

GroupBy

Sort

List

Model

Type

All

Load From MatDB

Keyword Input Form

☐ Use *Parameter
 ☐ Comment

(Subsys: 1 JWL-PE9-jets1.k)

*MAT_HIGH_EXPLOSIVE_BURN,(TITLE) (008) (1)
 (Can not edit keyword since it is associated with post D3PLOT)

TITLE
 PE9

1	MID	RO	D	PCJ	BETA	K	G	SIGY
1		0.0017500	8193.0000	2.800e+04	0.0	0.0	0.0	0.0

COMMENT:

Total Card: 1 Smallest ID: 1 Largest ID: 1 Total deleted card: 0

Keyword Manager

Keyword Edit:

Edit: MAT_HIGH_EXPLOSIVE_BURN
 ☐ Model
 ☐ All

Name	Count
EOS	3
GRUNEISEN	1
JWL	1
LINEAR_POLYNOMIAL	1
HOURLGLASS	1
INITIAL	1
KEYWORD	1
MAT	5
008-HIGH_EXPLOSIVE_BURN	1
009-NULL	1
010-ELASTIC_PLASTIC_HYDRO	1
015-JOHNSON_COOK	1
140-VACUUM	1
PART	3
SECTION	2

Material arrange
 GroupBy: Model Sort: Type List: All

Keyword Input Form

☐ Use *Parameter
 ☐ Comment

(Subsys: 1 JWL-PE9-jets.k)

*MAT_VACUUM,(TITLE) (140) (1)

TITLE
 Vacuum

1	MID	RHO
1	β	1.000e-09

COMMENT:

Total Card: 1 Smallest ID: 3 Largest ID: 3 Total deleted card: 0

Keyword Manager

Keyword Edit:

Edit: MAT_VACUUM
 ☐ Model
 ☐ All

Name	Count
HOURLGLASS	1
INITIAL	1
KEYWORD	1
MAT	5
003-PLASTIC_KINEMATIC	1
008-HIGH_EXPLOSIVE_BURN	1
009-NULL	1
010-ELASTIC_PLASTIC_HYDRO	1
013-ISOTROPIC_ELASTIC_FAILURE	1
015-JOHNSON_COOK	1
098-SIMPLIFIED_JOHNSON_COOK	1
140-VACUUM	1
NODE	1

Material arrange
 GroupBy: Model Sort: Type List: All

Keyword Input Form

☐ Use *Parameter
 ☐ Comment

(Subsys: 1 JWL-PE9-jets.k)

*PART,(TITLE) (3)

TITLE
 Air

1	PID	SECID	MID	EOSID	HGID	GRAV	ADPOPT	TMID
1	1	1	4	3	0	0	0	0

1	Air
2	Tube
3	PE9

Keyword Input Form

☐ Use *Parameter
 ☐ Comment
 (Subsys: 1 JWL-PE9-jets.k)

*PART_(TITLE) (3)

1 TITLE

Tube

2 PID SECID MID EOSID HGID GRAV ADPOPT TMID

2 2 7 2 1 0 0 0

Keyword Input Form

☐ Use *Parameter
 ☐ Comment
 (Subsys: 1 JWL-PE9-jets.k)

*PART_(TITLE) (3)

1 TITLE

PE9

2 PID SECID MID EOSID HGID GRAV ADPOPT TMID

3 1 1 1 0 0 0 0

*SECTION_SHELL_(TITLE) (1)

TITLE

2D axial symmetry element

1 SECID ELFORM SHRF NIP PROPT QR/IRID ICOMP SETYP

2 15 1.0000000 2 1 0 0 1

2 T1 T2 T3 T4 NLOC MAREA IDOF EDGSET

0.1000000 0.1000000 0.1000000 0.1000000 0.0 0.0 0.0 0

*SECTION_ALE2D_(TITLE) (1)

TITLE

1 SECID ALEFORM AET ELFORM

1 11 0 14

APPENDIX C

C.1 Initiation of two charges in close succession

The cylinder test setup involves the sequencing of two explosive charges to detonate in close succession. Normal operational procedures at DBEL allow for this occurrence, but the risk is always heightened when more than one charge need to be armed or detonated sequentially. Attention needs to be given to safe arming procedure when two different firing units are used. Attention to possible misfire procedures must also be considered. This applies mostly to the responsible people at DBEL but other participants to the test must also take note of the complexity of the test and strive to clarify every functional aspect of the instrumentation used in the test in clear and no uncertain terms. The onus is on the responsible person in control of the safety of the test to ensure that every aspect of the instrumentation used in the test to sequence the firing is understood and within the bounds of the SOP of the firing range.

It has also to be noted that an event may happen were either one of the charges detonate and the other does not. This presents a risk for a delayed detonation or run up reaction after the firing.

C.2 Fragmentation

The use of an explosive filled copper cylinder in the tests implies that fragments will be generated. The velocity of the fragments is known (between 1200-1700m/s) but the size of the fragments cannot be estimated accurately. Normally, with a ductile material like copper, thin slivers are generated in an expanding cylinder due to the stress distribution. However, failure can be controlled by many pre-history factors in the cylinders, and the origin of the current cylinders is unknown.

By initiating the cylinder from the top and firing downward, there is an inherent downward motion for the bulk of the fragment spray. This reduces the hit probability on the vulnerable components such as the camera ports, but a real chance of a hit on the ports still exists.

Extra precaution needs to be taken to protect the camera in the form of sacrificial transparent materials. In this case, a normal glass pane of 8mm and a clear Lexan sheet of 2mm is used as a buffer in front of the normal armoured glass window of the camera. The addition of the Lexan in particular, is going to degrade the image quality substantially, but it is necessary to buffer the two glass panes from each other. In the absence of the Lexan layer the damage is likely to spread across the fragmenting glass panes.

The cylinder fragments do not pose a risk to personnel outside the danger area. The fragment lethal radius is approximately 20m and the physical trajectories of non-lethal fragments will be restricted to within 150m.

C.3 Assessment method and classification

The risk assessment is conducted by combining the probability of an identified risk occurring with the severity or effect should it occur as shown in the matrix contained in Figure 57.

Probability	Will Happen	5	B	B	A	A
	Almost Certain	4	C	B	B	A
	Could Happen	3	C	C	B	B
	Unlikely	2	C	C	C	B
	Highly Unlikely	1	C	C	C	C
Class A Risk: High			1	2	3	4
Class B Risk: Medium						
Class C Risk: Low			Minor	Moderate	Severe	Major
			Severity			

Figure 57: Risk assessment matrix

C.4 Risk assessment

The risk assessments and precautions for conducting the copper tube test are in Table 11.

Table 11: Summary of risk assessment

Serial	Risk	Probability	Severity	Classification	Precaution	Probability	Severity	Classification
01	Blast damage	5	1	C	Small amounts of explosives – far removed from anything All personnel under cover	1	1	C
02	Misfire of the charges	2	3	B	Uncouple all instrumentation. Proceed with normal procedures for misfires	1	2	C
03	Fragmentation damage	4	2	A	Protect equipment as far as possible without sacrificing data. No risk to personnel under cover. No risk outside of the danger area.	2	2	C