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Study of the Penetration of Water
by an Explosively Formed Projectile

C. Lam and D. McQueen

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Weapons Systems Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

The report describes a numerical modelling and experimental study into the use of explosively formed projectile (EFP) for water penetration as a potential method for neutralising seamines. Dyna2D was used to model a large number of EFP designs and a short list of candidates were selected for water penetration modelling. Experimental validation of the code prediction was undertaken using multiple flash radiography to define EFP shape, velocity and break up in water. In all, the numerical predictions show good correlation with experimental results, both above and beneath the water. Two nominated candidates were fabricated for water penetration study. They were both densely compacted EFPs, one with a velocity of 2.0 km/s, and the other, a slower projectile with a velocity of 1.5 km/s to avoid classic mass erosion as it enters the water. However, the EFPs failed to perform after bridging more than 2 to 3 charge diameters of water, after which the remaining projectile mass is insignificant or is too slow for seamine neutralisation operations.

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Executive Summary

Explosively Formed Projectile (EFP) warheads, have a relatively long service history for defence applications, mainly due to their stand-off distance performance and the flexibility of tailoring the projectile characteristics to meet various applications. In this regard EFPs may offer advantages for the stand-off neutralisation of sea-mines. Although directional, a system based on an EFP could be multi shot. However, there is little information on the penetration/erosion of high velocity projectiles such as EFPs in water.

This report describes a numerical modelling and experimental study into the use of EFPs for water penetration as a potential method for neutralising sea-mines. Dyna2D was used to model a large number of EFP designs and a short list of candidates were selected for water penetration modelling. Experimental validation of the code prediction was undertaken using multiple flash radiography to define the EFP shape, velocity and break-up in water. In all, the numerical predictions show good correlation with experimental results, both above and below the water. Two nominated candidates were fabricated for a water penetration study. They were both densely compacted EFPs, one with a velocity of 2.0 km/s, and the other, a slower projectile with a velocity of 1.5 km/s to avoid classic mass erosion as it enters the water. However, the EFPs failed to perform after bridging more than 2 to 3 charge diameters of water, after which the remaining projectile mass is insignificant or is too slow for sea-mine neutralisation operations.

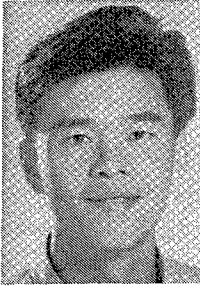
Another approach would be to study high density EFPs eg tantalum, which would be expected to exhibit markedly less deceleration in water compared to copper.

These results suggest that the large blast charges currently in the Australian sea-mine countermeasures inventory remain a favoured technology for the neutralisation of sea-mines filled with conventional explosives. However recent trials at Port Wakefield in South Australia using a range of conventional and IM filled charges have demonstrated that there is a requirement for a new technological solution for the neutralisation of sea-mines filled with insensitive explosives.

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Chanphu Lam graduated from Victoria University of Technology, Melbourne, Australia, in 1990 with a B.Sc. degree in Applied Physics and Computing. He joined Weapons Systems Division of Aeronautical and Maritime Research Laboratory in 1991. Since then he has worked on hydrodynamic computer modelling, and customised scientific software development in support of explosives research tasks. Currently, he is working on the computer modelling of Explosively Formed Projectiles for hard target demolition, explosive ordnance disposal and mine neutralisation.

Darren McQueen

Weapons Systems Division



Darren McQueen completed the Certificates of Technology in Applied Mechanics and Mechanical Design Drafting in 1987, following his time as a Fitter and Machinist. He joined AMRL in 1987 and has worked on investigations into the effectiveness of explosive filled ordnance and explosively formed projectiles for low order disposal techniques.

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1. Introduction

Explosively-Formed Projectile (EFP) warheads, have a relatively long service history for defence applications, mainly due to their stand-off distance performance and the flexibility of tailoring the projectile characteristics to meet various applications. The formation of an EFP from a liner requires the enormous amount of heat and pressure produced by the detonation of a high explosive (HE). This causes the liner to collapse and invert to form an EFP. A typical EFP charge is shown in Figure 1. It consists of an explosive filled cylindrical tube confined at one end by a hemispherical liner. A perspex back-locator is placed at the back face of the charge to centre a small detonator.

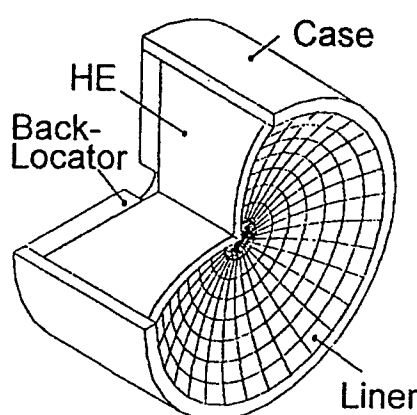


Figure 1. A typical EFP charge configuration.

EFP design has in the past depended on an experimental trial-and-error methodology and the lack of a reliable finite element code has undoubtedly made the exercise expensive and time consuming. The Dyna2D [1] hydrocode is one of many codes developed to make the exercise more efficient and cost effective.

DSTO/AMRL is investigating the potential use of an EFP as a stand-off sea mine neutralisation device. The device should neutralise munitions submerged in shallow water without detonating them. The standard AMRL EFP charge produces a relatively thin projectile [4] which is rapidly eroded and is unsuitable for the task. An ideal EFP should possess sufficient mass to reduce the effect of erosion, a large enough diameter to create a hole on the mine case for high pressure gas venting, and a relatively low velocity to prevent excessive shock transmitted to the mine on impact.

This report describes the application of the Dyna2D finite element code to numerically model the formation and penetration of the projectile, and the experimental verification of the model with flash radiography.

2. NUMERICAL MODELLING

The numerical analysis involved two phases; the first phase was the formation of a suitable projectile and the second phase was the assessment of its capability to penetrate water. Both phases were investigated using the Hi-Dyna2D Lagrangian finite element hydrocode to assess the relative performance of the projectiles. Various EFP designs were modelled including variable liner thickness, solid and elongated nose with tubular bodies, and high density elongated projectiles.

The Hi-Dyna2D code is a PC implementation, based on the public domain version of Dyna2D. It is an explicit Lagrangian two dimensional finite element code suitable for the analysis of complex material deformations, shock wave propagation and detonation events in axisymmetric or plain strain mode. A diverse range of material models and Equations of State are available to represent different material behaviour. Features such as the automatic erosion algorithm are useful in the modelling of material failure and penetration. The code comes in three parts, Maze [1] is the interactive mesh generator, Dyna2D is the hydrodynamic, finite element code and Orion [3] is the graphics processor. It is capable of handling 12000 elements for 4 Mbytes of RAM. All the simulations were performed on an IBM compatible 486 DX2 66 MHz processor with 16 Mbytes of RAM. A simulation of this type generally requires less than an hour of computation time, depending on the mesh of the model.

2.1 Explosively-Formed Projectile.

The EFP characteristics are governed by a range of parameters such as the geometry of the liner, side confinement and shape of the detonation front. A number of EFP designs were modelled and the suitable EFPs were chosen for the water penetration modelling. Illustrated in Figure 2 are the two designs chosen for the penetration modelling and experimental verification. The design on the left has a steel case and a liner whose thickness is constant. On the right is a contoured liner, where the thickness of the liner is reduced at the periphery, with a perspex case.

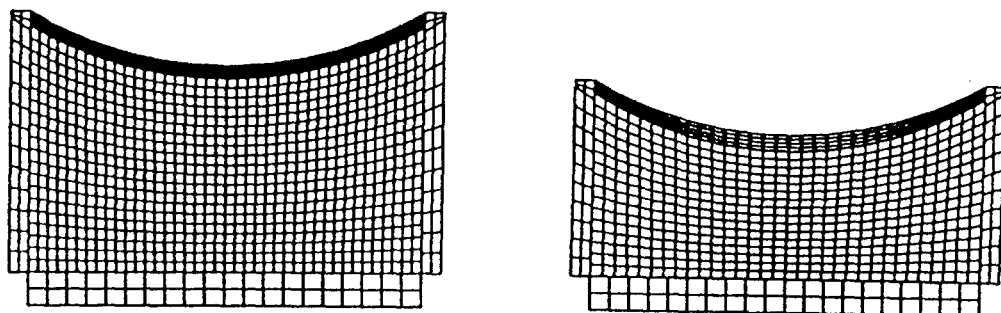


Figure 2. Computer model of the two EFP charges.

Modelling of the liners was done using closely meshed 4×20 elements, as this provides better final EFP profile definition. The explosive filling has 20×20 elements to correspond with the nodes on the liner for improved interaction and enhanced coupling of the shock wave through the explosive mesh. Coarser grids were used for less significant parts such as the back-locator to shorten the computation time. The EFP charges were single node initiated at the center of the charge along the explosive and back-locator interface. A minor mesh adjustment was necessary at the front corner of the casing to simulate a more realistic model where the high pressure gases are permitted to leak as they expand radially, this occurred around $20 \mu\text{s}$ after detonation. At this point the casing, back-locator and high explosive were deleted from the model as they no longer influenced the EFP formation process. This was done by using the rezoning facility in which the model can be redefined. Also deleted were elements near the perimeter of the liner where the cells became so severely distorted that they could cause an unexpected termination of the code or could dramatically increase the computation time.

The EFP charge modelled consists of a copper liner, C-4 explosive (RDX-binder 91:9) filling, aluminium or steel casing and a perspex back-locator. Table 1 defines the material models and Equation of State (EOS) used for the modelling of the charge initiation and the EFP formation process. The C-4 composition was the closest material available on the database that could substitute for the PE4 composition (RDX-binder 88:12) used in the experiments.

Table 1. Material model used in the EFP simulations

Component	Material Model	EOS	Input Failure Strain*
Copper Liner	Johnson-Cook	Grüneisen	4.0
C-4 Explosive	Linear Burn	JWL	
Perspex Back-Locator	Steinberg-Guinan	Grüneisen	
Aluminium Case	Steinberg-Guinan	Grüneisen	
Steel Case	Johnson-Cook	Grüneisen	
Water Column*	Elastic-Plastic	Grüneisen	2.0

* - used in the water penetration model

For this application, our preliminary study had indicated that the Johnson-Cook[5] material model used to represent the copper liner had good correlation with experimental results without the need to alter the default material data. Therefore the same material model was maintained for all subsequent simulation.

2.2 Water Penetration

The two simulation models described above were extended to include a water column placed at two charge diameters in front of the charge. The water column was modelled

as an elastic-plastic hydrodynamic material, with a low yield stress and elastic modulus, the erosion algorithm was included to simulate the penetration process. Appropriate material parameters for water were used in the model [4]. The input failure strain, f_s , is used by the automatic erosion algorithm as a limiting value which eliminates elements with a plastic strain exceeding f_s , hence simulating the penetration process and erosion of the projectile as it interacts with the water. The *TSTOP* and *VSTOP* flag could also be activated to eliminate elements with an extremely low time-step or a negative volume that would cause the program to abort.

The water column had 23 by 36 elements meshed in such a way that the cells are smaller around the EFP impact region. In doing so, a higher crater definition can be achieved with the same number of elements. The running of the computation was started with the detonation of the charge, then the charge components were removed, and ended with the near final resting place of the projectile in the water column. The simulation was allowed to run to 400 μ s at which point the projectile has either eroded or has a terminal velocity that is too low to have any significant effect on the mine case.

To assess the penetration capability of a higher density material in the model, the copper EFP was replaced by tungsten at a point in time just, before impact with the water; this is of course experimentally impossible. In order to compare the performance of the copper and tungsten projectiles, the EFP shapes, sizes and velocities must be the same. Rather than designing a completely new charge for the tungsten liner to produce identical projectile characteristics, Dyna2D allows the replacement of material properties. Therefore, the charge shown in Figure 2 was modelled until the formation process ceased (or just before impact), then the copper material was replaced with tungsten alloy (Johnson-Cook and Grüneisen EOS) and the computation was allowed to continue.

3. EXPERIMENTS

The experiments conducted were based on the design of the two EFP configurations as shown in Figure 2. The first of these is 60 mm in diameter with an outside radius of 60 mm, 2 mm uniform thickness and made of commercially available high conductivity copper. The case confinement is 3 mm thick mild steel and allows for an explosive head height of 1/2 the charge diameter above the apex. The second design is also of high conductivity copper with a contoured liner thickness, 60 mm diameter with a 57 mm outside radius and a 60 mm inside radius. Its case is 3 mm thick aluminium and allows for an explosive head height of 1/3 the charge diameter.

These charges are mounted along the central axis of the a 150 mm diameter thin walled PVC cylinder filled with water, at a standoff length of 120 mm or 2 charge diameters to allow free air space for the formation of the EFP. A reference point is also included in the set up for the measurement of projectile position.

Projectile penetration and velocities in water were measured using multiple flash radiography techniques (FXR). These experiments were carried out with a four channel FXR system. Two orthogonal 300 kV and two orthogonal 600 kV pulsers were arranged around the common central axis-of-flight of the EFPs.

The FXR pulsers were triggered from the Exploding Bridgewire (EBW) detonator. A delay was set into the system to trigger the pulsers at varying times based on the modelling prediction, hence the estimated position of the projectile at various distances into the water column can be captured.

Four flash radiographs were taken in each experiment over the range of the projectile positions from 30 μs to 290 μs . Images were recorded by a film and the florescent intensifying screen combination placed in a protective cassettes and positioned near the charge. EFP penetration velocities were calculated from the radiographic images and recorded times.

4. RESULTS AND DISCUSSION

The simulation of the two EFPs was confirmed with experimental results using the flash X-ray facility at the AMRL firing chamber. The Dyna2D predictions, were used to determine the time settings of the X-ray trigger pulses, needed to confidently capture the projectile images. The charge with a steel case, shown in Figure 2, had strong confinement, a higher explosive quantity and consequently produced a compact and high velocity projectile as presented in Figure 3. The design with an aluminium case had a weaker retaining wall, less explosive filling and more copper in the liner which generated a lower velocity 'dumpling' projectile as depicted in Figure 4.

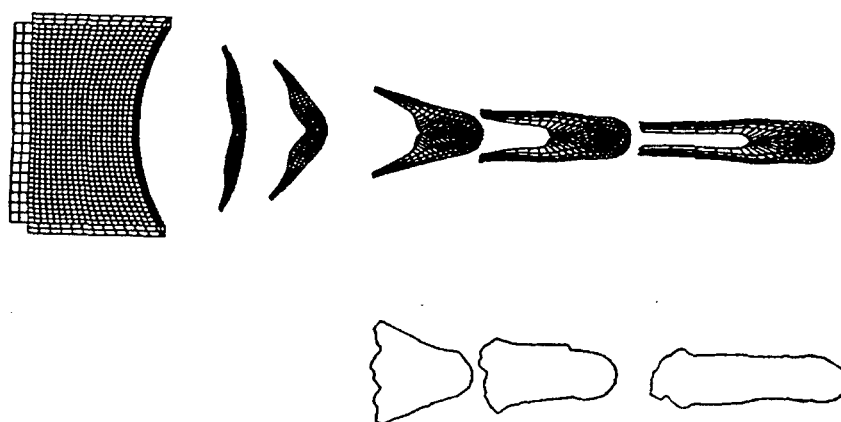


Figure 3. The elongated EFP formation sequence at time 0, 20, 30, 50, 70 and 100 μs

In Figures 3 and 4 comparisons of the modelled (top) and traced X-ray image (bottom) of the EFPs are depicted, during flight through air. It was somewhat difficult to compare the interior shapes of the projectiles as they were not fully visible on the flash x-ray. However the predicted shape and size of the two EFPs at different time sequences agree reasonably well with the adjacent X-ray tracings. Likewise, a good correlation with experiment of the EFP impact velocity was achieved. The hydrocode predicted that the instantaneous velocity for the two EFPs was 1.94 and 1.51 km/s and the respective X-ray calculated average velocity was 2.0 and 1.44 km/s. The complete EFP formation process according to the numerical simulation requires around 80 to 100 μ s after initiation with subsequent projectile velocity stabilisation. A minor discrepancy observed in Figures 3 and 4 is that the predicted EFPs, to some extent, appear to have collapsed sooner than the experimental projectile. This may be due to a delay in the detonator functioning time that results in a temporal displacement in the comparison.

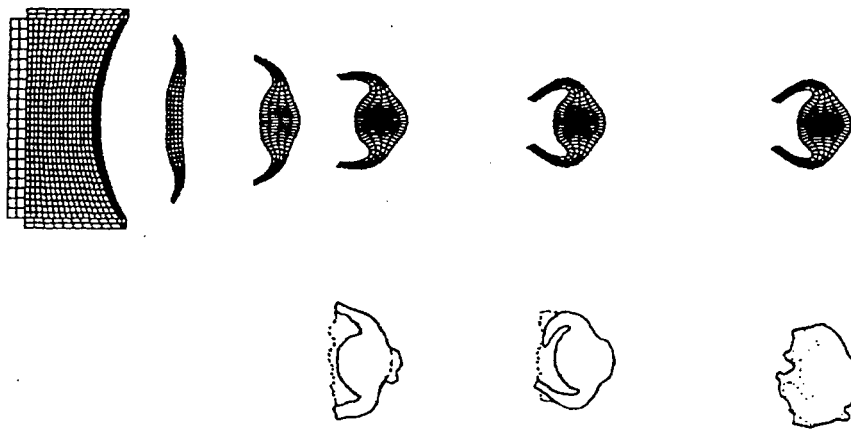


Figure 4. The 'dumpling' EFP formation sequence at time 0, 20, 40, 60, 100 and 150 μ s

A comparison between the numerical (left) and the experimental (right) projectile in flight through water is illustrated in Figures 5 and 6. The intended high velocity and streamlined EFP of Figure 5 was required to squeeze its way through the water barrier, however it underwent rapid erosion and velocity retardation during the penetration process. The effective depth was about 2 to 3 charge diameters.

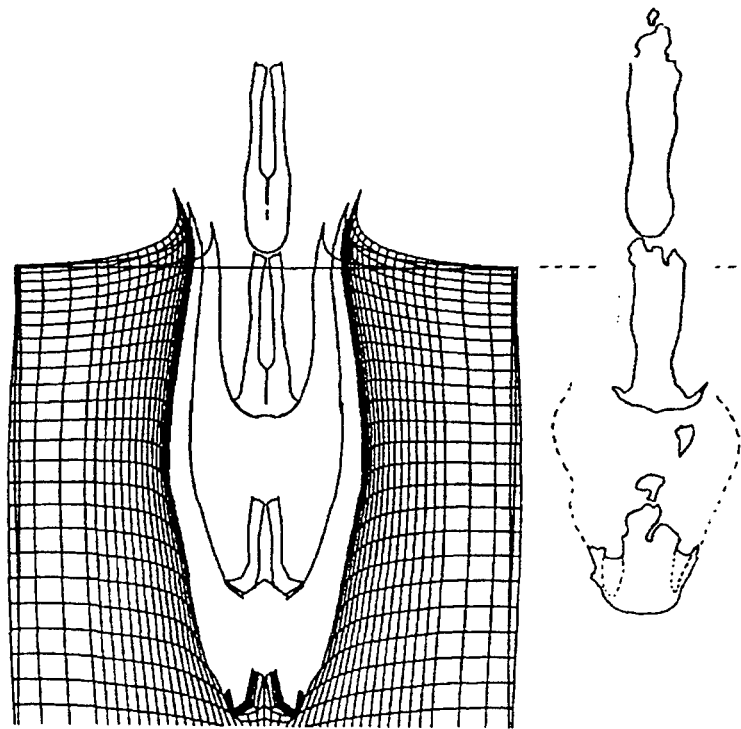


Figure 5. The elongated EFP in water column at time 120, 150, 190 and 230 μ s after initiation.

Thereafter, the main body of the projectile is completely consumed, leaving a relatively slow (~ 1.3 km/s @15 cm) and insignificant residue, incapable of performing the required task beyond the depth of half a meter. Similarly, the low velocity and dense 'dumpling' projectile as in Figure 6 is tailored to counter mass erosion, it penetrated the water column with little mass loss, but the swift deceleration restricted the range of effective penetration to about 2 charge diameters. From this point, the dramatic decrease in velocity, ~ 0.7 km/s @13.5 cm depth, virtually eliminated the effectiveness of the EFP beyond half a meter.

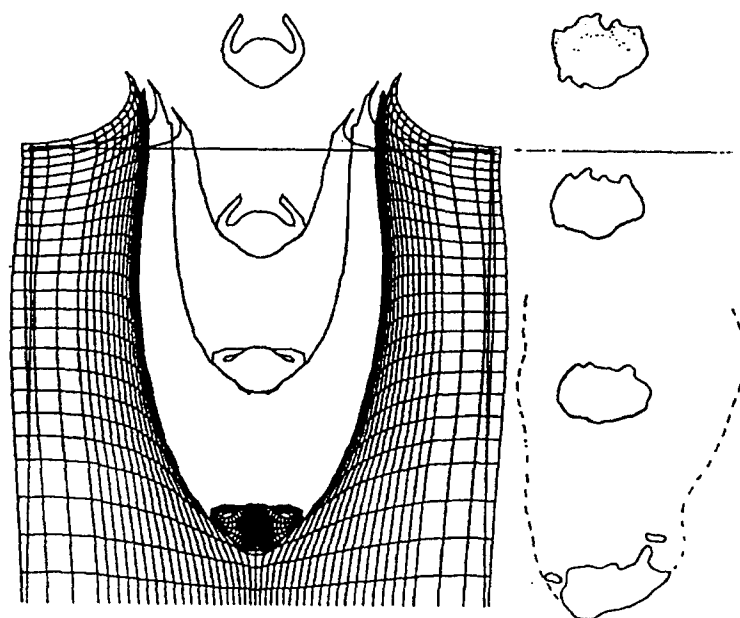


Figure 6. The 'dumpling' EFP in water columns at time 150, 190, 230 and 290 μ s after initiation.

The tungsten elongated projectile as modelled earlier, having identical velocity and shape as the copper penetrator, eroded at a slower rate and experienced gradual velocity retardation. The computation indicated an improvement, with a doubling of the effective penetration depth. Penetration profiles of all three EFPs are compared in Figure 7.

AMRL R60 EFP Water Penetration

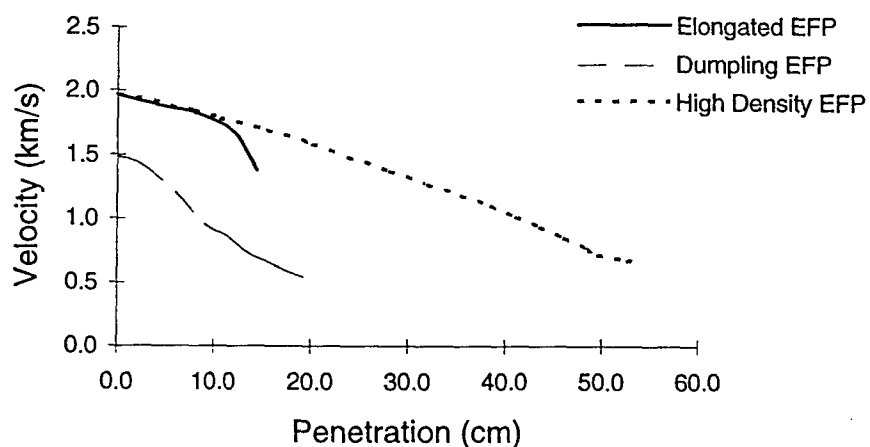


Figure 7. Water penetration profile of three EFPs.

5. CONCLUSION

The application of a hydrocode to the numerical investigation of the formation and penetration of an EFP has been presented. Both phases of the simulations, through air and water, show good correlation between the modelling and the experimental results. The Hi-Dyna2D Lagrangian finite element analysis code has been demonstrated to be capable of solving large material deformations as in the case of EFP formation and the automatic erosion algorithm has been successfully applied to model material erosion.

The flash radiography techniques for capturing experimental EFP images are briefly described here and these images have played a crucial part in the validation of numerical predictions.

The simulations and experiments suggest that the intended projectiles have a limited penetration capability through water. This is due to the projectiles either suffering rapid mass erosion as they enter the water and/or encountering swift deceleration during the time of flight through water, which defeated the purpose of the projectile.

6. ACKNOWLEDGMENTS

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