

## COVER PAGE

Title: Interface Defeat for Unconfined SiC Ceramics

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## Report Documentation Page

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Experiments were performed to determine the dwell-penetration transition velocity for an unconfined SiC target impacting a long gold rod. Some of the targets used a small copper buffer to attenuate the initial impact shock which increased the transition velocity significantly (by a factor of  $\approx 2$ ). Transition velocity for bare SiC is approximately 800 m/s whereas the buffered targets had a transition velocity of approximately 1550 m/s. Once penetration is initiated, X-ray images show significant damage in the target. A possible scaling effect of the rod dimensions could be responsible for the slightly lower transition velocity compared to earlier experiments.

## **INTRODUCTION**

Ceramic dwell and interface defeat are of much interest for the design of efficient passive armor systems. Most of the studies on this topic use complicated target arrangements in which the ceramic is prestressed with heavy confinement and have multilayer cover plates of different materials [1-3]. These geometric and material target design parameters influence the dwell effect and complicate evaluation of the dwell potential of a ceramic.

This paper presents the experimental design and results for unconfined silicon carbide (SiC) cylinders which were launched in the reverse ballistic mode against stationary gold rods at impact velocities between 750 and 1700 m/s. The ceramic front face was either bare or had a Cu-buffer attached to attenuate the impact shock and provide gradual loading to the ceramic.

## **EXPERIMENTAL SET-UP**

The ceramic samples were SiC-N cylinders from BAE Systems, Advanced Ceramics Division (formerly Cercom) with diameter of 20 mm and a length of 35 mm. The pure gold rods had a diameter of 1.0 mm and a length of 70 mm (density  $\rho_P = 19.3 \text{ g/cm}^3$ ; hardness 65 HV5; UTS 220 MPa and elongation 30%). Three

different target configurations were examined: 1) a completely bare ceramic, 2) a ceramic with a small Cu-buffer (E-Cu 57, diameter  $d = 5$  mm, height  $h = 4$  mm), and 3) a ceramic with a full diameter Cu-buffer plate ( $d = 20$  mm,  $h = 2$  mm). Both buffer types were glued to the front face with an epoxy resin. The bonding thickness was below measuring accuracy ( $< 10 \mu\text{m}$  or  $\frac{1}{2}$  mil). The tests were performed with a powder gun in the reverse ballistic mode using a separating sabot for the ceramic cylinders. Dwell and penetration was observed with five 180-kV flash X-rays. For some experiments a high-speed video camera was available to monitor the impact process optically. That camera took a video sequence with an interframe time of  $2 \mu\text{s}$  and an exposure time per frame of  $0.5 \mu\text{s}$ . The test set up is shown in Fig 1.

As the time measurements for the flash X-ray pictures are very accurate (to better than  $\pm 5$  ns), the error for the velocities determined from the X-ray pictures rest in the accuracy of the position measurement, which is in the order of  $\pm 0.1$  to  $0.15$  mm. The X-ray images in this paper are digitally enhanced to emphasize the relevant information contained.

## RESULTS AND DISCUSSION

All valid experiments are listed by target group in Table 1. Test results are sorted by increasing impact velocity  $v_p$  for each group. For tests where dwell did not occur, or was very short, penetration velocity  $u$  and consumption velocity  $v_c$  of the rod was calculated by a linear regression of rod position and length inside the SiC over the trigger times of the X-ray images. Four experiments missed the attached buffer and thus were considered bare impacts. These are not listed in the table as they are in the no-dwell velocity regime.

Target resistance  $R_T$  was calculated from the well known Tate equation with the  $u$  and  $v_c$  values and with a penetrator strength  $Y_p = 0$ . Dwell time  $t_D$  was calculated from the regression equation obtained to determine  $u$ .

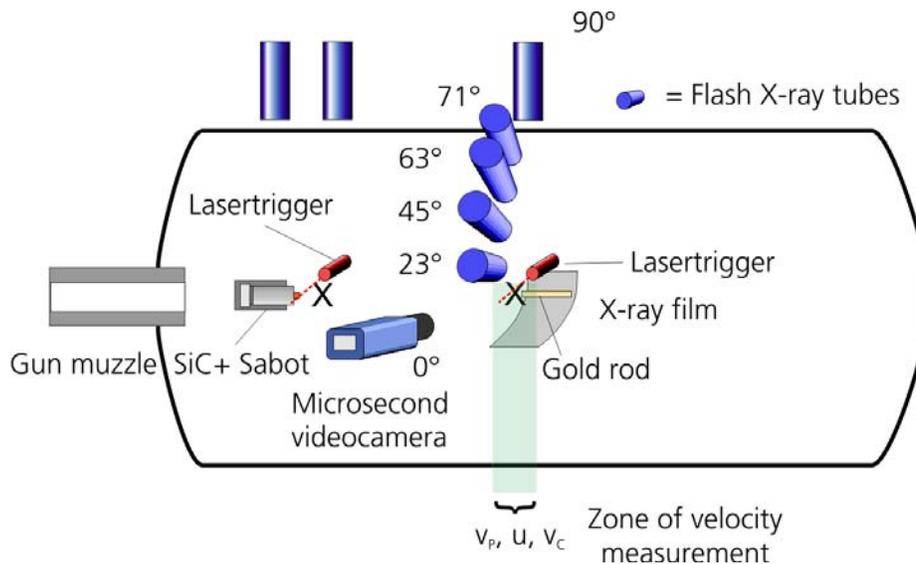


Figure 1. Test-set-up, video camera slightly slanted vs. X-ray plane

Table 1. Experimental results

Exp. No.	Yaw [°]	oc [mm]	$v_p$ [m/s]	$u$ [m/s]	$v_c$ [m/s]	$R_T$ [Gpa]	Type	Dwell time $t_D$ [ $\mu$ s]
11353	0.5	2.1	776±2	0	= $v_p$	5.81	bare	sust. dwell
11354	2.9	1.7	958±4	233±22	683±27	4.44	bare	> 6
11355	1.2	1.7	1212±6	482±40	717±51	4.69	bare	< 6
11358	0.4	1.7	1381±7	598±43	775±48	5.37	bare	no dwell
11377	1.1	0.8	1416±7	560±55	842±59	6.48	buff	≈ 16
11393	1.0	1.1	1484±5	0	= $v_p$	21.25	buff	sust. dwell
11395	1.6	1.1	1526±9	0	= $v_p$	22.48	buff	sust. dwell
11390	1.7	1.1	1550±8	715±20	808±27	5.70	buff	≈ 10
11375	1.1	1.1	1686±10	824±75	846±87	6.10	buff	≈ 8
11360	1.4	2.7	1382±7	0	= $v_p$	18.42	plate	sust. dwell
11389	1.5	1.7	1571±5	652±48	923±40	7.73	plate	≈ 11
11362	4.9	2.1	1612±6	671±49	933±55	7.88	plate	≈ 6

Yaw: combined horizontal and vertical yaw

oc: off-centre impact

### Bare SiC Experiments

Experiments with a bare target show that dwell is possible for velocities near 800 m/s. With higher impact velocities the rod dwells only for a short period, if at all, before it penetrates the ceramic (Fig. 2).

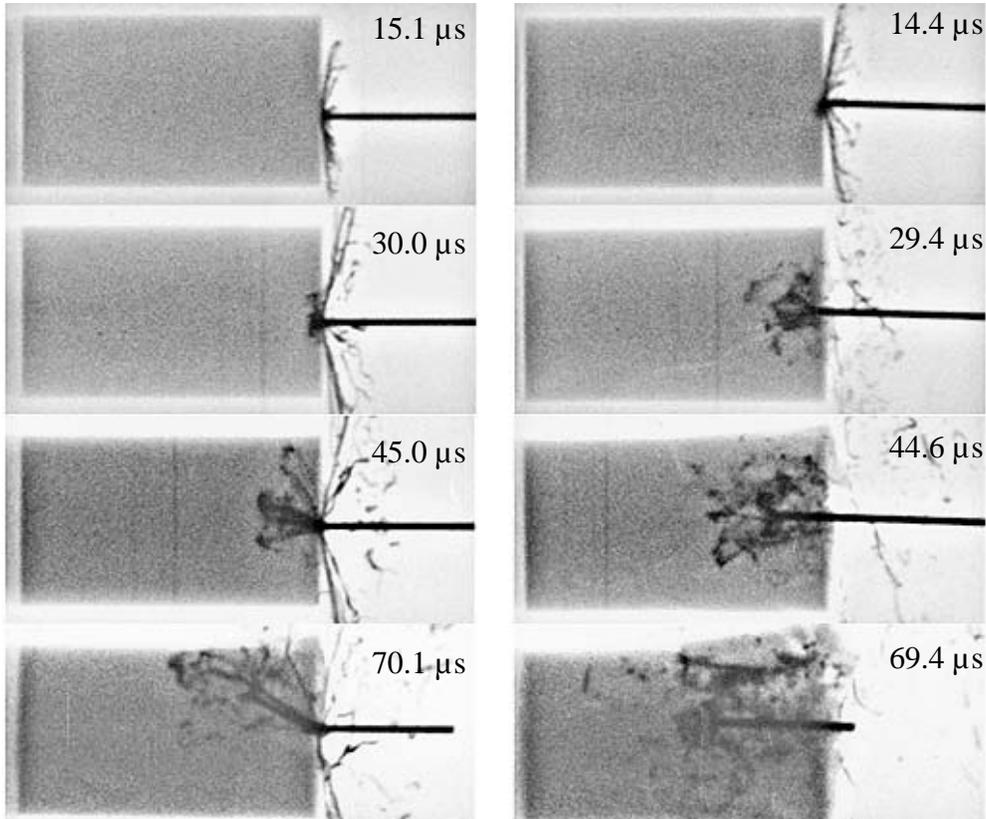


Figure 2. X-ray images for Exp.11353 ( $v_p = 776$  m/s, left) and 11354 ( $v_p = 956$  m/s, right).

In the left-hand set of pictures in Fig. 2, the rod does not penetrate the SiC but is diverted at the front surface, presumably due to a chipped or cracked edge. The right-hand pictures show that the ceramic cracks heavily during penetration.

### Buffered SiC Experiments

The dwell velocity for buffered experiments is substantially higher than for the unbuffered target. Sustained dwell is possible up to impact velocities of 1530 m/s. Impact velocities above 1550 m/s produce a short dwell period before transitioning to penetration. Targets where the front was fully covered by a plate show a similar behavior, although the plate was only half the thickness of the buffers.

The buffer separated from the target before impact in two of the experiments. Exp.11377 (Fig 3 left) shows, for the relatively low impact velocity of 1416 m/s, a short dwell phase of about 16  $\mu\text{s}$  before penetration of the rod starts. With a correctly attached buffer, sustained dwell can be expected at a higher  $v_p$  (right sequence of images). In the last frame, a conical crack develops at the target surface (similar to findings in [4]), but dwell persists.

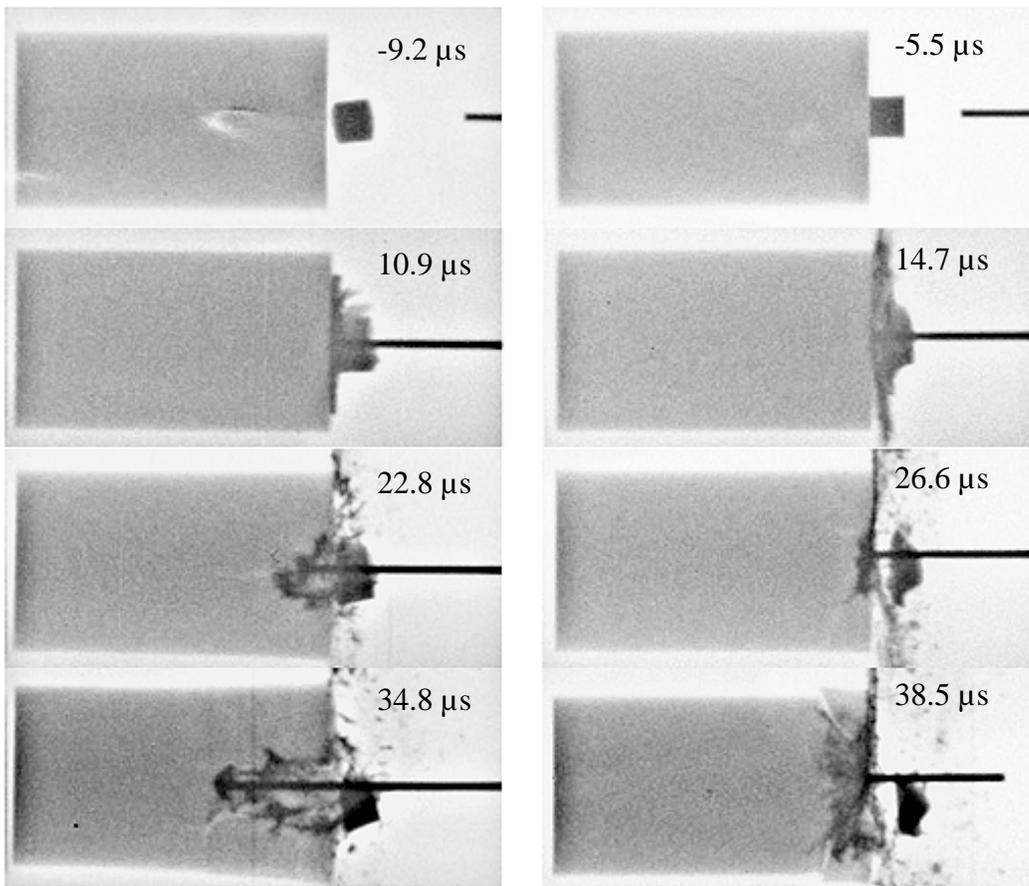


Figure 3. X-ray images for Exp.11377 ( $v_p = 1416$  m/s, left) and 11393 ( $v_p = 1484$  m/s, right).

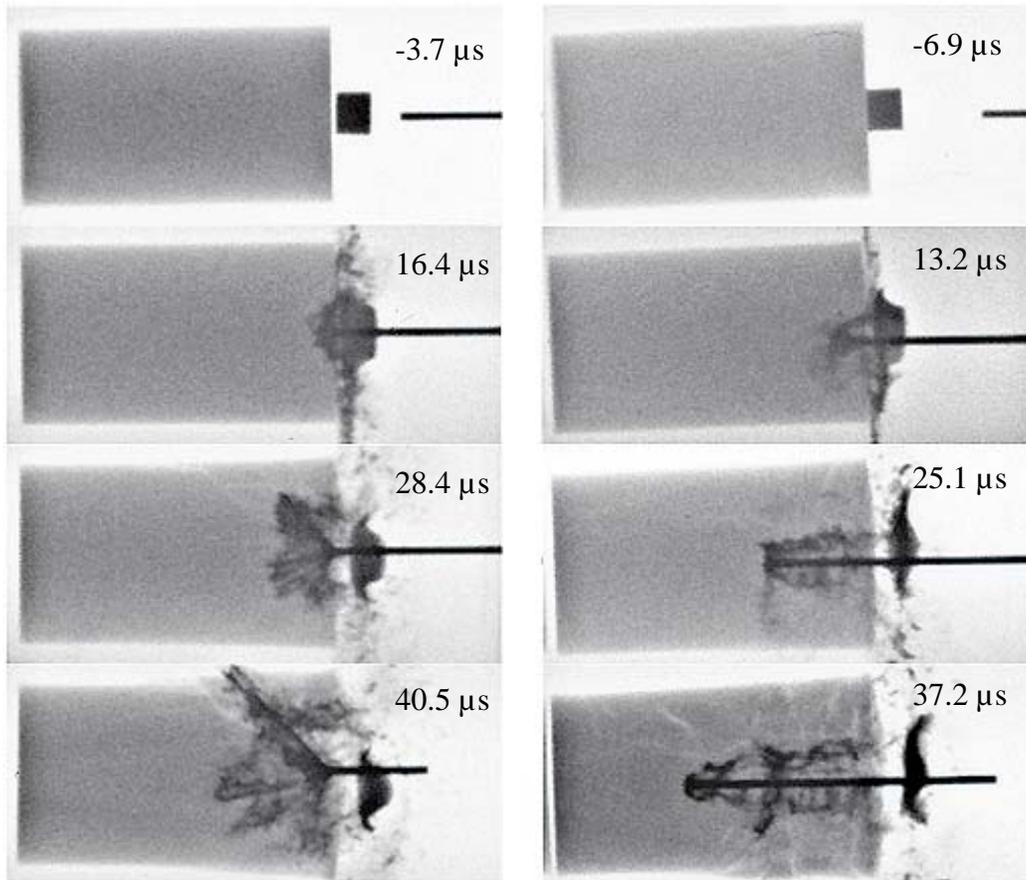


Figure 4. X-ray images for Exp.11395 ( $v_p = 1526$  m/s, left) and 11390 ( $v_p = 1550$  m/s, right).

For Exp. 11395 in Fig. 4, the buffer also separates but only very slightly. Here, at  $v_p = 1526$  m/s, the target shows sustained dwell, although the target surface is clearly more damaged than for e.g. Exp. 11393. This is an indication that the buffer separation influences damage and dwell potential. These phenomena are investigated in detail in [5].

At impact velocities around 1550 m/s penetration starts after a short dwell phase (Fig. 4 right). During penetration the X-ray images show that the ceramic is heavily damaged around much of the circumference

As mentioned previously, a high-speed video camera was available for some of the experiments. Comparing selected frames of the video with the X-ray image reveal some interesting details. Figure 5 (Exp. 11390) shows early dwell with later penetration both in the X-rays and still images from the video camera. The early video still shows clearly the disc which is formed by the diverted rod material on the target surface. Also, it can be seen that during penetration, (presumably) rod material emerges through cracks in the ceramic to the side surface (arrow), which corresponds to a cloud sideways to the rod ceramic interface in the X-ray image (also denoted by an arrow).

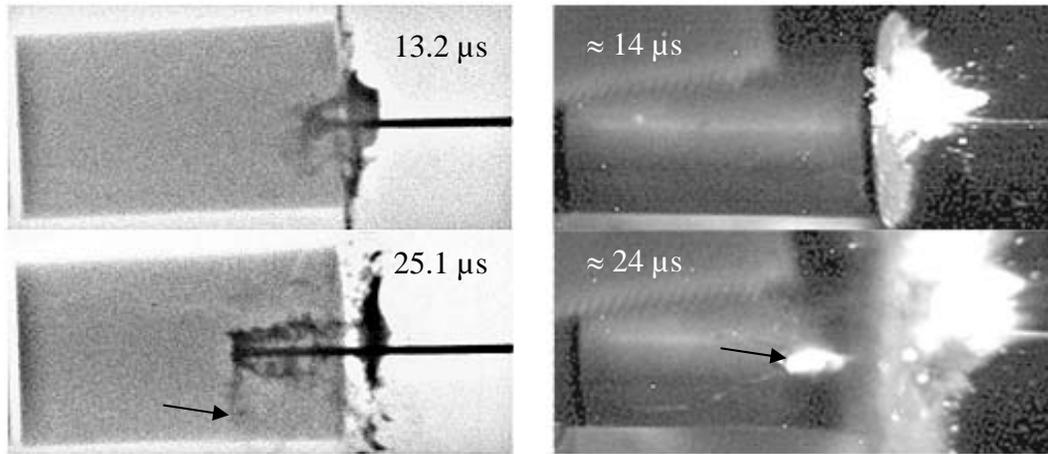


Figure 5. X-ray images (left) and video stills (right) for Exp. 11390 ( $v_p = 1550$  m/s) at nearly the same time after impact.

### Transition from Dwell to Penetration

The transition from dwell to penetration can be determined quite well by examining the penetration velocity  $u$  versus  $v_p$ , as shown in Fig. 6. Therefore it is helpful to look at the dwell times of Table 1. They are calculated from the linear regression equation of the penetration depth  $p$  vs. time  $t$ :

$$p = at + b \quad (1)$$

Slope  $a$  of Eq. (1) gives the penetration velocity  $u$ . Dwell time  $t_D$  for  $p = 0$  is then calculated from the axis intercept  $b$  as:

$$t_D = -b/a \quad (2)$$

When the rod erodes completely on the ceramic surface there is sustained dwell and  $u$  is of course zero. For the experiments where penetration occurs, the calculated dwell time decreases with increasing  $v_p$ . A reasonable estimation for bare SiC puts the transition velocity in the region of 800 m/s since the dwell time for the higher  $v_p$  is already quite low. The transition velocity increases to 1530-1550 m/s for the buffered targets. The SiC targets that had a cover-plate seem to perform about the same as the buffered targets.

Interestingly, all the  $u$  values of this experimental campaign lie in the region of the experiments done with pre-damaged ceramics in [6-7]. Although the SiC here is undamaged prior to impact,  $u$  is within the scatter of the pre-damaged samples. This behavior is discussed in more detail in [7].

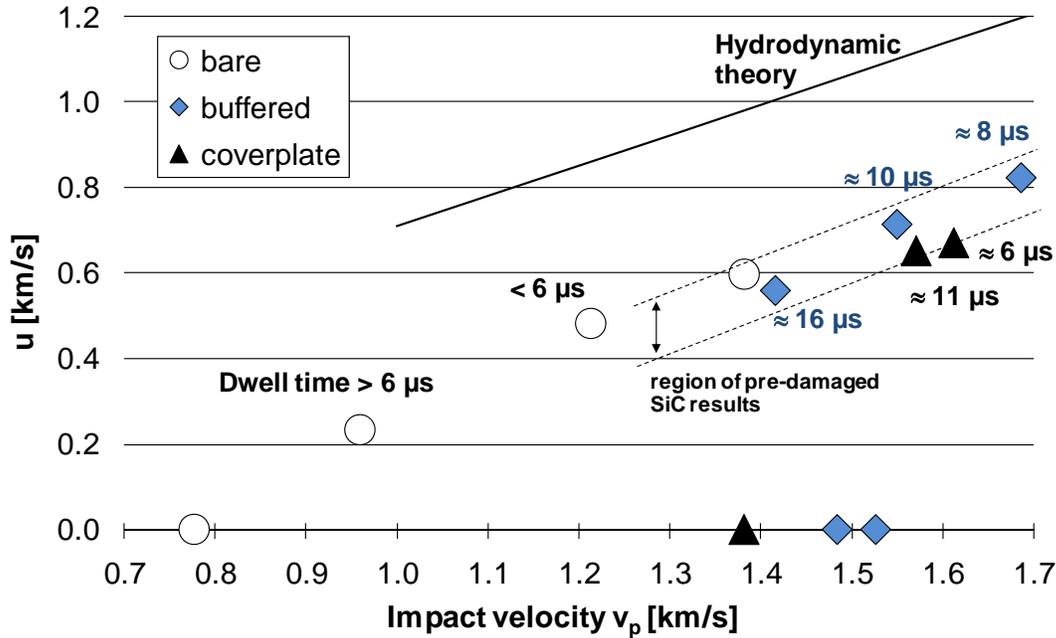


Figure 6.  $u$  vs.  $v_p$  for bare, buffered and cover plated SiC-N experiments.

The transition velocity of  $\approx 1550$  m/s for the buffered targets is approximately 50 to 100 m/s lower than what was determined computationally in 2005 in a similar test set-up [8], where sustained dwell up to  $v_p = 1620$  m/s was seen in experiments. A possible substantial difference to the current experiments is the dimension of the rod, which was then 0.75 mm in diameter and is now 1.0 mm – a 33% increase. The buffer in both cases had a height of 4 rod diameters and the target had a diameter of 20 rod diameters. Further experiments are planned to investigate the influence of the rod diameter on the transition velocity.

## SUMMARY AND CONCLUSIONS

Reverse impact experiments have been conducted to determine dwell and transition velocities for unconfined SiC ceramic against long gold rods. The targets were either completely bare or had a small copper buffer on the front. Results show that for a bare ceramic, stable dwell is possible for impact velocities up to approximately 800 m/s. With a small Cu-buffer on the top, the transition velocity is increased to around 1550 m/s. X-ray images and high-speed videos reveal that once penetration is initiated, the ceramic is damaged around much of the circumference. It is noted that the penetration velocities correspond well with experiments done with pre-damaged ceramic [6-7].

The transition velocities determined for the buffered experiments conducted here are 50 to 100 m/s lower than determined in a similar test arrangement where the rod diameter was considerably smaller than now [8]. There appears to be a scaling or size effect involving with the rod diameter. Additional experiments are currently being performed to investigate this possible scaling effect.

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