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***Investigation of Rod Size Effects and Buffer
Geometry on Penetration and Interface
Defeat of Gold Rods into Silicon Carbide***

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14. ABSTRACT Reverse ballistic experiments were used to investigate rod size effects and buffer geometry on penetration and interface defeat of long, gold rods into silicon carbide (SiC-N). Rod diameters were 1.0 mm and 0.75 mm, and lengths were 70 mm and 50 mm, respectively. Within data scatter, penetration velocity was the same for bare or sleeved, pre-damaged (thermally shocked with non-contiguous cracks), and <i>in-situ</i> comminuted SiC-N. Penetration velocity was independent of rod diameter within the data scatter. It was found that the penetration resistance of SiC-N is very high during the first few microseconds after impact, after which, the penetration velocity achieves the steady-state value observed in the other experiments. Investigation of the effects of a copper buffer on the surface of the ceramic showed that the dwell-penetration transition velocity depends upon the non-dimensional ratio of buffer thickness to projectile diameter (h/D_p), with $h/D_p = 2$ being more effective than 4. Additionally, the data show that the transition velocity for the smaller diameter rod increased by 65 m/s at the same h/D_p ratio.					
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1.0 Introduction

Orphal and Franzen [1] conducted an experimental study concerning the penetration behavior of silicon carbide (SiC) using a tungsten rod at impact velocities between 1.5 to 4.6 km/s. The experiments were conducted in the reverse ballistic mode where the SiC target was launched at the penetrator, which was suspended in the flight path. More recently, another experimental study was conducted, similar to that of Ref. [1], but the velocity range was 2.0 to 6.2 km/s, and a gold (Au) rod was used for the penetrator [2]. Another difference between the two sets of experiments was that the SiC was confined within a titanium sleeve in Ref. [1], whereas the ceramic specimen was bare in Ref. [2]. The objective of these latter experiments was to investigate whether or not a failure wave or failure front exists that could be detected by a change in penetration resistance. No effect of a failure front was detected within the penetration-time results.

It has been very difficult to obtain independent laboratory measurements of the constitutive parameters for failed ceramics because they are so strong (e.g., loading platens fail before the confined specimen; confining sleeves yield and limit confining pressures, etc.). It was decided that a series of experiments to measure the penetration performance of a ceramic material with *initially* different strengths [3-4] would be of value for the study and development of computational ceramic constitutive models. Therefore, to assist in the determination of the strength of failed ceramic, ballistic experiments were performed on cylindrical SiC targets with three different grades or degrees of pre-impact damage, described in Section 3.1. These variously damaged ceramics, contained in an Al-sleeve, were launched in the reverse ballistic mode against stationary gold rods. Impact velocities ranged from 1 to 3 km/s.

Additional experiments were conducted to extend the experimental database for one of the types of pre-damaged ceramic to lower impact velocities [5-6]. Some of the impact velocities overlapped with the previous data so that direct comparisons could be made between the new and older data. Additionally, experiments were conducted with intact ceramic inserted into the aluminum sleeve. A major conclusion resulting from analysis of the combined data sets of Refs. [3-6] was that, within data scatter, *there is no difference in the penetration rate of intact (sleeved) ceramic versus pre-damaged (sleeved) SiC ceramic.*

The penetration rate of the intact bare SiC specimens reported in Ref. [2] are considerably lower than for the intact sleeved SiC targets reported in Refs. [5-6]. Besides the absence or presence of an aluminum sleeve (with a cover plate), the diameters of the Au rods were different. In Ref. [2], the rod diameter was 0.75 mm (50-mm long). In the subsequent work [3-6], the rod diameter was increased by 33% to 1.0 mm (70-mm long) to facilitate handling of the Au rod.

It was decided to investigate if a scaling effect of the rod diameter could be the reason for differences in the penetration rates of the two intact SiC data sets. A test series using the two different rod diameters against bare (not sleeved) SiC was conducted. The test set-up was similar to the earlier experiments. All specimens were launched in the reverse ballistic mode against stationary Au rods. Penetration of the gold rod was monitored with five flash X-ray tubes. Impact velocities ranged from 2 km/s to 3 km/s. Results of these eleven experiments are presented in this report.

The ability of a ceramic to defeat a projectile at the surface of the ceramic—interface defeat—is of considerable interest. A study was conducted to investigate the transition velocities for bare SiC targets and targets with a copper buffer [7-8]. Stable dwell, using the 1.0-mm

diameter Au rod, was possible for impact velocities up to approximately 825 m/s on bare SiC ceramic. With a small copper buffer on top of the ceramic, the transition velocity increased to approximately 1540 m/s. However, in an early study [9], dwell was observed at a somewhat higher impact velocity (~1620 m/s); this earlier study used the 0.75-mm diameter Au rod. Further, there was interest in determining the influence of different buffer geometries on the transition velocity. Eighteen experiments, with impact velocities between 1.4 km/s and 1.6 km/s, were conducted for this investigation, and the results are reported.

Lastly, analysis of the dwell experiments [8,10] indicated that, even at high impact velocities (~2.0 km/s), there might be a very short period of dwell before transitioning to penetration. To investigate potential dwell at very early times, four experiments were conducted in which flash X-rays obtained data within the first few microseconds of impact.

In summary, experiments at impact velocities from 1.5 to 3 km/s were conducted with bare, intact SiC to address:

- 1) a potential size effect of the rod;
- 2) the penetration behavior of intact ceramic compared to previous data for pre-damaged ceramic; and
- 3) the early-time dwell/penetration behavior of intact SiC.
- 4) Additionally, the transition velocity from interface defeat (dwell) to penetration and the influence of different buffer geometries on this transition velocity were determined in the velocity range of 1.4 to 1.6 km/s.

2.0 Experimental Set-Up

2.1 SiC-N Targets

The ceramic samples were SiC-N cylinders from BAE Systems Advanced Ceramics Division (formerly Cercom), with a 20-mm diameter and a length of 35 mm. The measured properties of the SiC-N are: density = 3.21 g/cm³; longitudinal velocity = 12.27 km/s; shear wave velocity = 7.74 km/s; Poisson's ratio = 0.17; Young's modulus = 450 GPa; and shear modulus = 192 GPa. These properties were measured/provided by BAE Systems, and agree within measurement accuracy the properties of other lots of SiC-N that have been produced by BAE Systems used in previous studies [2-9].

2.2 Projectiles

The pure gold rods had a diameter of either 0.75 mm or 1.0 mm, and a length of either 50 mm or 70 mm. Properties of the Au rod are: density, $\rho_p = 19.3$ g/cm³; hardness = 65 HV5; UTS = 220 MPa with an elongation of 30%. The 0.75-mm diameter rods were from the original 2004, Ref. [2], tests. The 1.0-mm rods were from the 2006/7, Ref. [3-8], tests. Au was used for the rod material to reduce the effect of rod strength while maintaining a high density. Figure 1 shows the rod and target dimensions at the same scale.

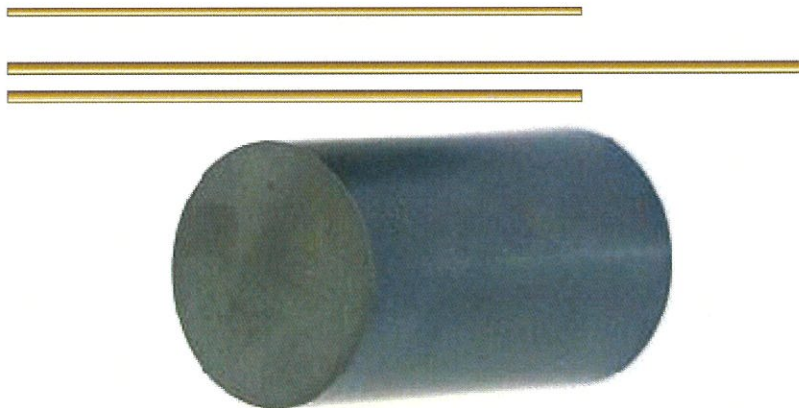


Figure 1. Dimensions of rod and target to scale.

2.3 Buffer Configurations

One of the test series had a copper buffer attached to the surface of the ceramic cylinder. The front buffers were made from E-Cu-57, and were glued to the front face with an epoxy resin. The bonding gap was below measuring accuracy (<10 μ m). For the first buffer experiments, the buffers covered either the full front of the ceramic (cover plate CP) or were cylinders with a diameter of 7 mm (small buffer B). During the test series, a third buffer geometry was introduced to overcome shortcomings of the design of the small buffer, which tended to separate from the ceramic during launch and prior to impact. The new design—which replaced the small buffer—is the cruciform shape pictured in Fig. 2 (buffer C). While maintaining a relatively large open space at the outer section of the ceramic front surface, the inner portion fully covered an area with a diameter of approximately 8 mm (about the same size as the small buffer B). The

extra surface area of the cruciform shape provided sufficient contact for the glue bond to maintain integrity during launch. The surface ratio of the three buffer types is 1 to 3 to 8.5 for B to C to CP. The heights of the buffers were varied from 2 mm to 4 mm.

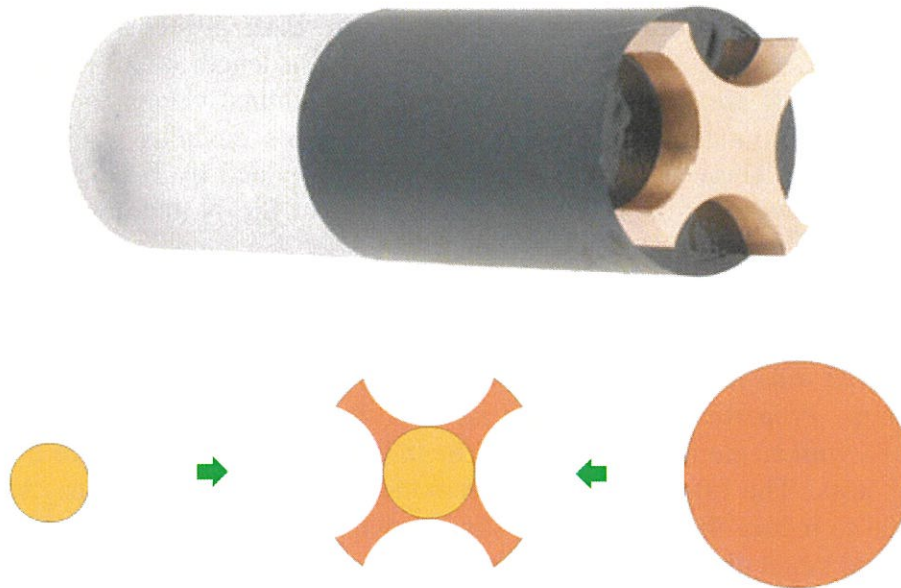


Figure 2. Above: SiC with polycarbonate backing to increase L/D ratio for a stable flight. Below: Three different buffer configurations; from left to right: buffer (B), cruciform (C) and cover plate (CP).

2.4 Reverse Ballistic Test Methodology

The reverse ballistic method was used in conducting the experiments; the test set-up was similar to the experiments done in Refs. [2-8]. The arrangement for the impact tank is shown in Fig. 3. Depending upon the impact velocity, the SiC targets were launched either from a powder gun or two-stage light-gas gun. Most of the experiments used a single piece sabot, but a separating sabot was adopted during the buffer experiments to decrease yaw.

The Au rod was aligned in the trajectory by laser light reflection from the blunt nose of the rod with yaw angles $< \pm 0.1^\circ$. The rear of the rod was inserted in a Styrofoam holder which allowed adjustment in three dimensions. The rod was positioned about 2 m from the gun muzzle to keep the yaw angle of the target specimen as small as possible, but still permit sabot separation for the experiments using a separating sabot.

Dwell and penetration were observed with five 180-kV flash X-rays. For some experiments, a high-speed video camera (Shimadzu HPV-1) was used to monitor the impact process optically. That camera took a video sequence with an interframe time of 2 μ s and an exposure time per frame of 0.5 μ s.

The X-ray film was placed 200 mm from the trajectory inside the tank and had the shape of a circular segment. The time measurements for the flash X-ray pictures are very accurate (better than ± 5 ns). Thus, the error for the velocities determined from the X-ray pictures rest in the accuracy of the position measurement, which is on the order of ± 0.1 to 0.15 mm. Some of the X-

ray images in this report are digitally enhanced to emphasize the relevant information contained in the images.

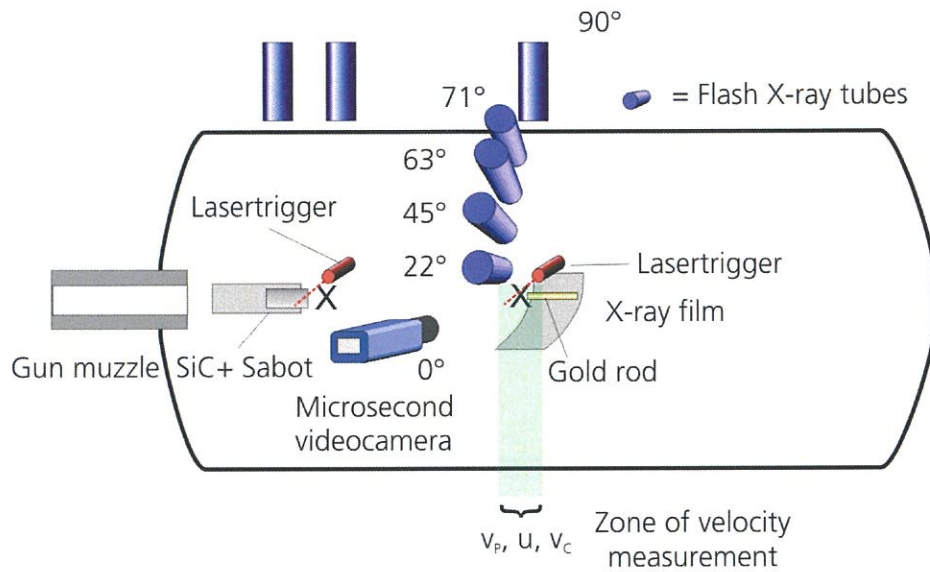


Figure 3. Test set-up.

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3.0 Investigation of Rod Size Effect on Penetration Velocity

3.1 Previous Work

Pre-damaged SiC-N specimens—with a diameter of 18 mm and a length of 35 mm—were placed inside (slip fit) a 7075-T6 aluminum sleeve of 31.5-mm outer diameter and 45-mm length (Fig. 4). The 7075-T6 base plate was machined with a 45-deg bevel, and then welded to the cylindrical sleeve. After the specimen was inserted into the Al sleeve, a 7075-T6 cover plate was press-fit into place using superglue. Three specimen types were prepared. 1) Thermally shocked (TS): pre-damage, in the form of non-contiguous cracks, was induced by 3 cycles of heating the specimen for one hour at 750°C with a subsequent ice water quench; thereafter, placing in the Al-sleeve. Although cracked, the specimens had integrity and strength. 2) Thermally shocked/cyclic loaded (TS/CL or *in-situ* comminuted): specimens were thermally shocked as above and then subjected to six MTS machine loading/unloading cycles to 1.7 GPa while in the aluminum sleeve. After the cyclic loading, the loading anvils were removed and the cover and base plates were applied. The specimen, if removed from the aluminum sleeve, had interlocked comminuted pieces, and crumbled easily under a very small—“finger-pressure”—applied load. 3) Compacted powder (CP): SiC-N powder was placed into the Al-sleeve through a series of incremental pours and compaction using an MTS machine, achieving 72-73% of the theoretical density of SiC-N ($\rho_{\text{comp. powder}} \approx 2.35 \text{ g/cm}^3$). (Compacted powder is not a pre-damaged ceramic; it is the raw material from which the intact SiC is fabricated. But for purposes of this report, we will use the word “damage” to describe all three specimen types.)

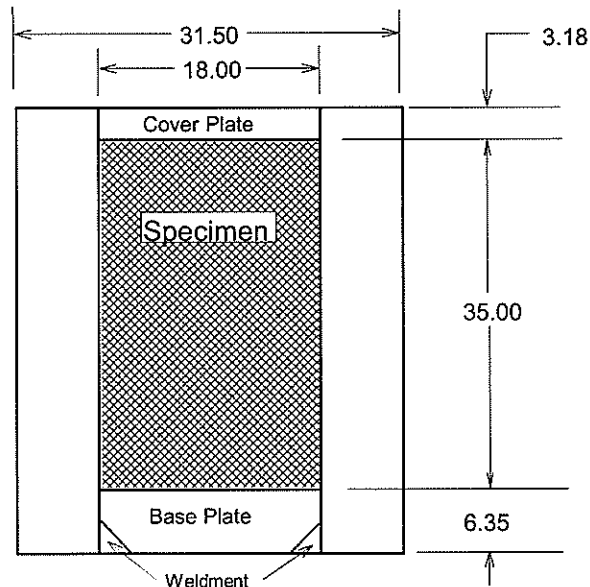


Figure 4. Test specimen with aluminum sleeve and cover plates (dimensions in mm).

The experiments were conducted in the reverse ballistics mode, with the test specimen launched at a suspended gold rod with a diameter of 1.0 mm and length of 70 mm. Additional details on the experiments can be found in Ref. [3-4]. The thermally shocked targets were launched at high velocities ($> 2.2 \text{ km/s}$); all of these had steady-state penetration. Steady-state penetration was observed for impact velocities above 1.8 km/s for the *in-situ* comminuted (TS/CL) ceramic, and above 1.5 km/s for the compacted powder specimens. The slope of the

penetration-time (P - t) regression gives the penetration velocity, u . The penetration velocities versus impact velocities for these experiments, Refs. [3-4], are shown in Fig. 5.

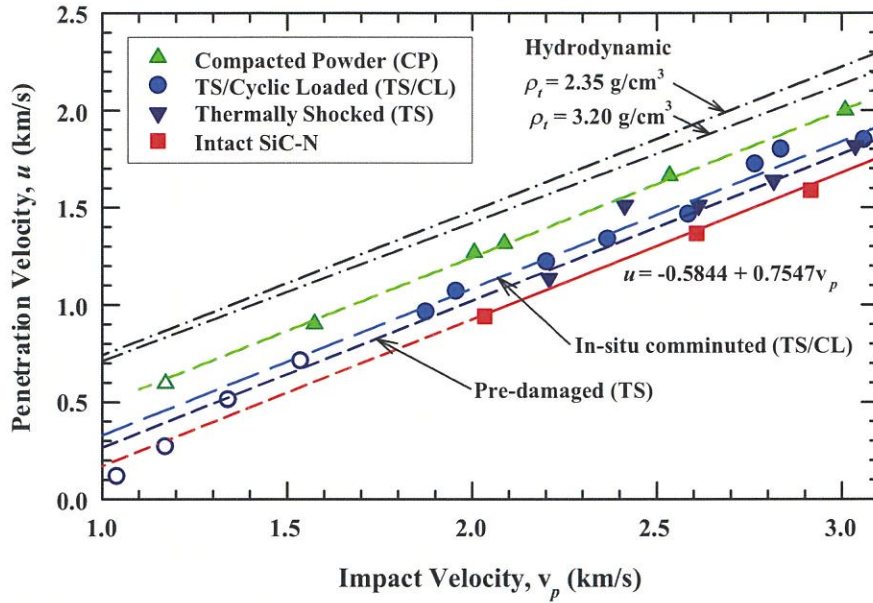


Figure 5. u vs. v_p for different types of SiC-N specimens, from Ref. [4].

Open symbols denote results where the P - t response was nonlinear over some or most of the penetration event. The penetration velocities of only the early or linear portion of penetration are plotted for these open symbols. Also included in the figure are the data for intact (bare) SiC-N specimens from Ref. [2]. The data for the intact SiC extends to impact velocities of ~ 6 km/s; only the three lowest velocity data points are shown here.

The test series with intact SiC-N in [2] provided a linear relationship between penetration velocity u of the gold rod in the ceramic and impact velocity v_p :

$$\text{Ref. [2]} \quad u = -0.5844 + 0.7547v_p. \quad (1)$$

For Eqn. (1), the velocities have units of km/s. The velocity range for the regression analysis was $2.0 < v_p < 6.3$ km/s.

This regression line for intact SiC has been extrapolated in Fig. 5 to lower impact velocities, as indicated by the dashed line. We know that the u versus v_p response of intact SiC-N cannot be linearly extrapolated to the very low impact velocities shown in Fig. 5, because at some impact velocity the projectile begins to dwell at the target interface (for example, see [7-8]), but the linear extrapolation serves as a “trend” line.

The hydrodynamic lines are calculated from

$$u_{hydro} = \frac{v_p}{1 + \sqrt{\rho_t / \rho_p}} \quad (2)$$

where ρ_t and ρ_p are the target (SiC) and projectile (Au) densities, respectively. The density for intact SiC-N is 3.20 g/cm^3 , whereas the density for the compacted powder is 2.35 g/cm^3 . The density of the Au rod is 19.3 g/cm^3 .

Linear regression analyses were performed on the experimental data shown in Fig. 5, and it

was found that the slopes for TS, TS/CL, and CP were very similar to that for the intact SiC. Therefore, linear regression analyses were conducted to determine the intercepts for the TS, TS/CL, and CP data, *with the slope constrained to be 0.7547*, the value determined for the intact SiC data. These are the parallel regression lines shown in Fig. 5. For the regression to the TS data, the data point at $v_p = 2.4$ km/s was omitted since it deviates more than 6.5 standard deviations from a regression fitted without the point. Examining Fig. 5, it was concluded that:

$$u_{\text{intact}} < u_{\text{pre-damaged}} < u_{\text{in-situ comminuted}} < u_{\text{powder}} < u_{\text{hydrodynamic}} \quad (3)$$

corresponding to reductions in strength or resistance to penetration in the reverse order; i.e., u_{intact} has the highest penetration resistance, etc.

Additional experiments were conducted approximately one year later [5-6] to verify that the TS datum at 2.4 km/s was really an outlier, and to extend the TS data to lower impact velocities. Additionally, it was decided to compare the penetration response of intact SiC-N encased in the aluminum sleeve to the response of the bare SiC-N. Two target sets were constructed:

- Six thermally shocked (TS) SiC-N specimens, denoted as TS-2, were prepared by heating for one hour at 750°C with a subsequent ice water quench (3 cycles), thereafter placing them in an Al-sleeve (Fig. 4);
- Six intact SiC-N specimens, 18-mm diameter and 35-mm long, and inserted into an Al sleeve (Fig. 4).

Results for these two sets of experiments are displayed in Fig. 6 as the inverted open inverted triangles (TS-2) and the solid hexagons (sleeved intact).¹

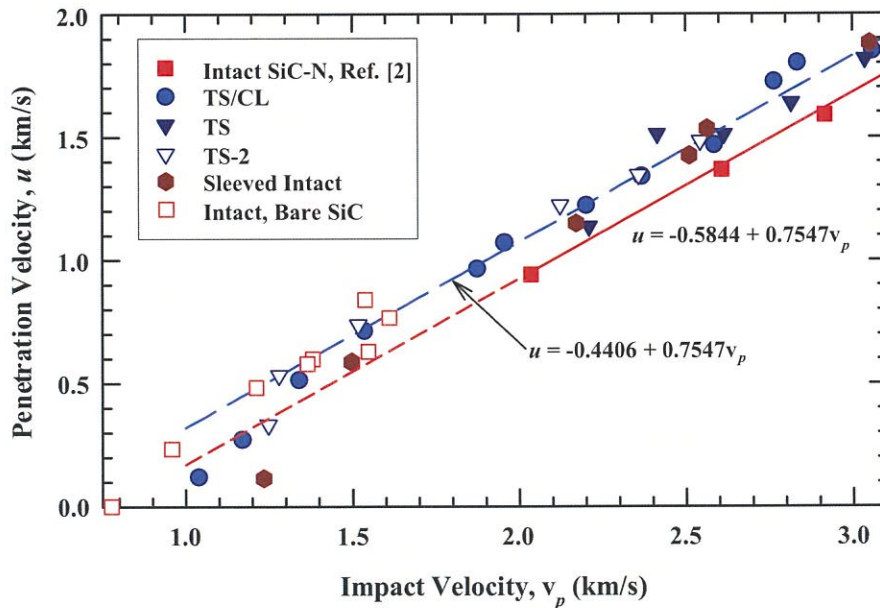


Figure 6. Comparison of results of additional experiments to original data set: u vs. v_p .

No longer do the TS data (TS combined with the TS-2 data) consistently lie below the *in-situ* comminuted (TS/CL) results (the solid circles) for impact velocities above 1.5 km/s. At impact velocities less than ~1.5 km/s, some portion of the penetration of the TS-2 experiments is nonlinear in time; only the nominally linear P - t data were used to estimate the penetration velocity, similar to what was done previously for the low velocity TS/CL data (open circles in

¹ The compacted powder results and the hydrodynamic lines are deleted from Fig. 6 for clarity.

Fig. 5, but now shown as solid circles in Fig. 6). At these lower impact velocities, the new TS-2 data are also indistinguishable, within data scatter, from the TS/CL results.

The results for the intact SiC-N specimens encased in the Al sleeve are shown as the solid hexagons in Fig. 6. It was expected that the presence of the cover plate would affect the lowest velocity experiment by allowing dwell [7-8], and the lowest impact velocity of 1.234 km/s showed dwell-like behavior and very little penetration. However, the results at the higher impact velocities were clearly surprising. *Within data scatter, the penetration response of these intact (but confined within the aluminum cylinder) SiC-N cylinders cannot be distinguished from the penetration response of the two pre-damaged SiC-N specimens (circles and inverted triangles).*

There are also data from an additional eight experiments that were performed earlier that can be considered. These experiments were designed to investigate interface defeat and the transition from dwell to penetration [7-8]. In these 8 experiments, the targets were bare, 20-mm diameter SiC-N cylinders (no aluminum sleeve was used for these experiments). The Au rods were all 1.00-mm in diameter. Because the interest was in dwell and interface defeat, the impact velocities were relatively low, all below ~1.6 km/s. The open squares in Fig. 6 denote the penetration velocity as a function of impact velocity for these 8 experiments. Interface defeat on a bare ceramic was seen at an impact velocity of 0.776 km/s. Otherwise, the penetration response is similar to the other 1.00-mm diameter Au rod data. As these experiments did not have the aluminum sleeve or cover plate, and since there is no difference in the penetration response of the intact and pre-damaged targets, it is unlikely that the disagreement between the original intact data [2] and these newer data can be explained by differences in confinement.

Within data scatter, there is no difference in the penetration velocity as a function of impact velocity for the new bare intact, sleeved intact, thermally shocked predamaged (TS and TS-2), and thermally shocked with cyclic loading predamaged (TS/CL) silicon carbide. A linear regression analysis was conducted on all the TS/CL, TS, TS-2, sleeved intact, and the intact bare data with a penetration velocity greater than 0.40 km/s. Deleting the data with a penetration velocity less than 0.40 km/s eliminated the obvious nonlinear penetration response data. This removed 6 of the data points, leaving a total of 31 data points in the regression set. The slope was fixed at 0.7547 as was done previously (the slope on the original intact SiC-N data was determined over a velocity range of 2.0 – 6.0 km/s). The regression analysis, with this constrained slope, of the 31 data points gives:

$$\text{Ref. [6]} \quad u = -0.4406 + 0.7547v_p \quad (4)$$

with an r^2 value of 0.985. The standard deviation for the fit on penetration velocity is 56.9 m/s. Conducting a two-parameter regression analysis (to determine the slope as well as the intercept) only changes the slope by 1.7%, with essentially no improvement in the regression statistics.

Equation (4) is plotted as the long dashed line in Fig. 6. As was done in Fig. 5, the solid line is extrapolated to lower impact velocities, denoted by the short dashed line. It is observed that all “new” data (all data except the original Ref. [2] data) lie above the solid and extrapolated lines for the original SiC data (solid squares in Fig. 6), although there are a couple of new data points at ~1.5 km/s that are near the extrapolated line (as well as one TS datum at ~2.2 km/s).

3.2 New Experiments on Bare, Intact SiC-N

The results displayed in Fig. 6 raised the question: Why is there a discrepancy between the penetration velocities of the initial experiments of Ref. [2] and the newer intact SiC experiments

shown in Fig. 6? One difference was that the intact experiments of Ref. [2] used a 0.75-mm diameter Au rod, whereas all the other experiments in Fig. 6 had a diameter of 1.0 mm. Recently, Andersson, *et al.* [11], suggested a projectile size effect for the dwell transition velocity, but made no predictions concerning the penetration velocity. Therefore, to provide insight into the surprising results of Fig. 6, additional experiments were conducted using 20-mm diameter SiC-N cylinders (from the same production lot). No aluminum confinement was used, i.e., these were bare, intact ceramic specimens. The cylinders were launched at suspended Au rods 0.75 mm and 1.0 mm in diameter, over a velocity range of 2.1 to 3.0 km/s.

3.2.1 Experimental Data

A total of 11 experiments were performed. The flash X-rays are provided in Appendix A, along with the depths of penetration and rod lengths as measured from the X-ray shadowgraphs. Time zero is impact onto the surface of the ceramic. The penetration-time ($P-t$) data are plotted, as are the rod length-time (L_R-t) data, for each of the experiments immediately after the respective flash X-ray images. The solid lines, which are the regression fits, denote the range of data used for the regression analyses. The slopes of the linear regressions provide the penetration velocity, u , and the consumption velocity, v_c , which are summarized in Table 1. For each test, the yaw angle of the projectile and the off-center distance of the impact point (oc) were also measured and are listed in Table 1. Test results are sorted by increasing impact velocity v_p in Table 1.

Table 1. Experimental Results for Investigation of Rod Size Effects

Exp.	Rod [mm]	Yaw [°]	oc [mm]	v_p [km/s]	u [km/s]	v_c [km/s]
11547	0.75 x 50	3.7	5.0	2.082±0.014	1.191±0.021	0.851±0.018
11546	1.00 x 70	2.6	2.8	2.086±0.015	1.162±0.023	0.913±0.041
11550	0.75 x 50	2.6	1.1	2.334±0.012	1.345±0.025	0.991±0.015
11549	1.00 x 70	1.2	0.5	2.360±0.019	1.282±0.028	1.053±0.016
11558	0.75 x 50	1.8	3.1	2.510±0.021	1.572±0.044	0.918±0.008
11551	1.00 x 70	1.5	3.1	2.576±0.017	1.457±0.014	1.091±0.040
11552	1.00 x 50	0.9	2.3	2.594±0.025	1.517±0.008	1.064±0.042
11555	1.00 x 50	0.7	0.8	2.800±0.019	1.482±0.022	1.288±0.023
11554	0.75 x 50	0.9	2.3	2.815±0.018	1.656±0.013	1.153±0.018
11557	1.00 x 50	0.8	5.0	3.003±0.020	1.869±0.011	1.112±0.019
11556	0.75 x 50	0.5	1.7	3.020±0.014	1.888±0.005	1.141±0.008

Shaded row: ceramic sample with 15 mm diameter and 40 mm length (original Ref. [2] specimen)

3.2.2 Comparison with Sleeved Experiments

The data for the two different rod diameters (open and solid diamond symbols) are shown in Fig. 7. For the new test series, there are no differences, within data scatter, in penetration velocity u as a function of impact velocity v_p when compared to the sleeved intact, pre-damaged, and *in-situ* damaged ceramic. Occasionally, there is an outlier (e.g., a solid diamond located at 2.8 km/s), which seem to appear randomly. For these new tests, there is no rod scaling effect detectable with the data scatter.

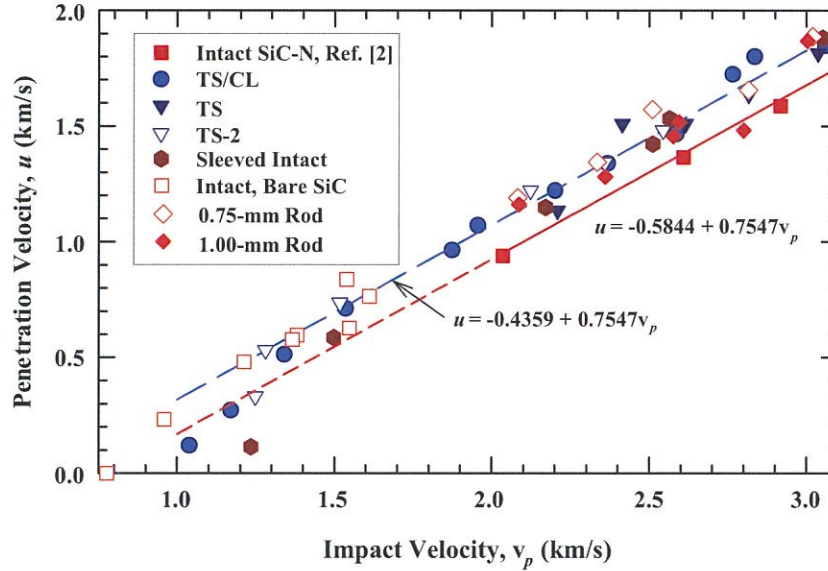


Figure 7. Penetration velocity vs. impact velocity for sleeved and bare SiC-N.

The linear regression fit was recalculated to include 10 of the 11 data points (the datum at 2.8 km/s was deleted since it was a substantial outlier), again holding the slope at 0.7547 since that slope was determined between 2.0 and 6.2 km/s. There are now 41 data points out of a possible 48 (six data points were deleted with $u < 0.40$ km/s, and the point at 2.8 km/s was deleted), giving:

$$\text{New Fit} \quad u = -0.4359 + 0.7547v_p. \quad (5)$$

with a $r^2 = 0.984$. The standard deviation for the penetration velocity is 56.1 m/s. The intercept changed by only 1% with the addition of the 10 new points. This fit is shown as the long dashed line in Fig. 7.

Clearly, the penetration data do not match the data from the Ref. [2] test series. This is somewhat surprising as test set-up and materials used are practically the same, and the possibility of rod scaling was eliminated. This resulted in an examination of the data analysis procedures used in the different test series, which is described in the following section.

3.3 Review of Data Processing

A thorough examination of procedures for analyzing the P - t data from the X-ray images for the various different experimental series was conducted. As will be shown, certain assumptions can affect results.

3.3.1 Changes in Length Measurements

The original test series of bare (not sleeved) SiC-N was designed to investigate the presence of the then called failure wave [2]. Analysis suggested that a failure wave—if present—would induce only subtle changes in the penetration velocity of the rod; therefore, new and sophisticated measurement techniques were introduced to minimize overall error. X-ray times were measured with an oscilloscope at very high resolution and gave the exact time of exposure for each X-ray image. Errors for target and rod position measurement, as stated earlier, were in the order of ± 0.1 to 0.15 mm. The position measurements were done according to Fig. 8 where the back of the rod acted as a fiducial mark for the distances S_1 , S_2 and S_3 .

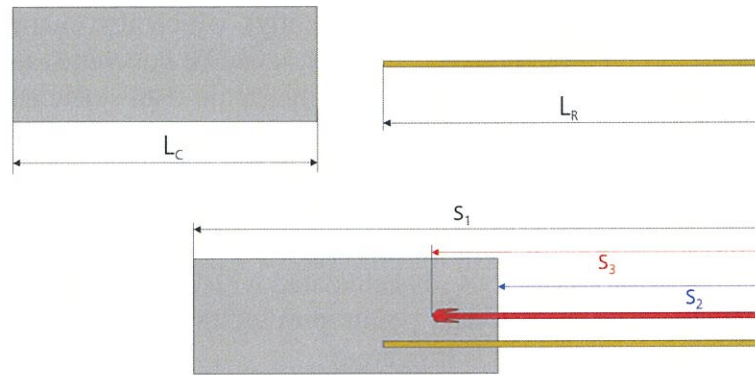


Figure 8. Definition of distances for position measurements – 2004 series, Ref. [2].

In 2005 [12], experiments with glass specimens were initiated and impact with the front surface of the glass resulted in a substantial dust cloud. Subsequently, the fiducial mark for measurement of S_2 was changed to the back of target (Fig. 9). This measuring method was maintained for all following test series, both glass and ceramic.

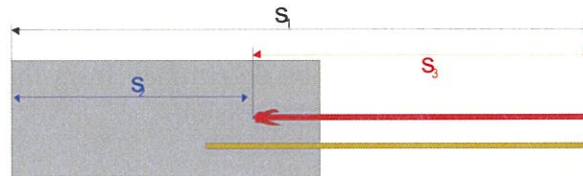


Figure 9. Definition of distances for position measurements – 2005 to current.

This brings up the question if these changes are responsible for the fact that the penetration data of this report do not match the data of Ref. [2]. Therefore, three experiments from Ref. [2] were re-measured and re-calculated in the same manner as the current test series. Results are shown in Fig. 10. It can be clearly seen that although there are some differences, the revised data still “cluster” about the solid line. Differences in impact velocity are due to a different

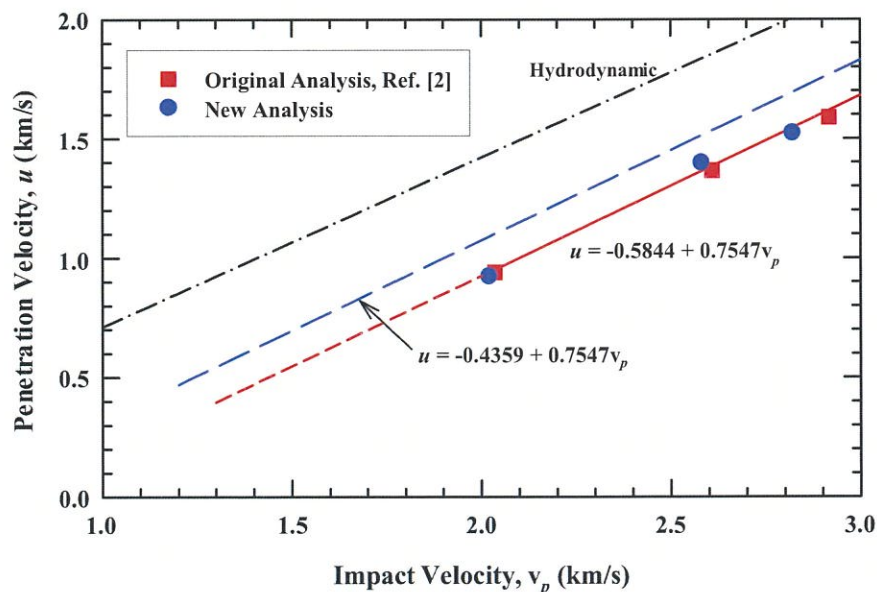


Figure 10. Penetration velocity vs. impact velocity for three of the Ref. [2] experiments.

calculation of target travel (as S_2 is measured differently), which also changes the calculated time of impact and thus the penetration velocity. Overall, it can be concluded that changes in position measurement do not influence the results of the penetration data sufficiently to account for the differences in the Ref. [2] data and the new results.

3.3.2 Changes in Regression Analysis of P - t Data

All velocities derived from the experiments are calculated by a linear regression analysis of the P - t data. First, the impact velocity v_p is calculated with the data retrieved from the available X-ray images. Usually, four to five data points provide the distance d travelled by the target versus time t after the X-ray sequence is triggered:

$$d = a + bt \quad (6)$$

A linear regression is conducted on these four or five data points to determine the slope b in Eqn. (6), which gives the impact velocity v_p . As the trigger event is always before impact (approximately 10 mm to 15 mm in front of the stationary rod), the time of impact t_0 is then calculated from the axis intercept b as:

$$t_0 = -a/b \quad (7)$$

With that calculated t_0 , penetration velocity u can be determined from the penetration depth P versus penetration time $t_P = t - t_0$, again using linear regression:

$$P = c + ut_P \quad (8)$$

In the ideal case, axis intercept c would be zero as penetration starts at the time of impact and would be steady state, i.e., linear with time.

For the Ref. [2] original test series completed in 2004, this “ideal-case thinking” influenced the procedure for determining the penetration velocity u . Apart from the maximum four data points after impact, the origin 0/0 was taken as a fifth data point with a forced regression through 0/0; that is, the x-axis intercept was by definition zero, i.e., $c = 0$ in Eqn. (8).

Starting with experiments with glass specimens [12], with the introduction of the modified procedure for measuring distances (Fig. 9), the regression calculation was changed from a forced fit at 0/0 to one where 0/0 was an additional data point, but with a possible non-zero axis intercept. Later, there were the pre-damaged ceramic experiments with the aluminum sleeve and aluminum cover [3-6]; also, experiments were conducted with a copper buffer [7-8]. For these experiments, only the penetration data within the ceramic was used for the regression calculations since the penetration rate through the cover/buffer material is different than that in the ceramic, which prevents the use of 0/0 as an additional point.

These different procedures for calculating u are visualized in Fig. 11 for Exp. 2654 of the 2004 series ($v_p = 2.608$ km/s). Four points of penetration depth were measured with 0/0 as a possible fifth point. Calculated penetration velocity ranges from 1.366 km/s for the forced 0/0 calculation up to 1.456 km/s for regression without 0/0 included, an increase of nearly 6.2%.

Generally, it can be stated that u for an individual experiment is the highest for a regression analysis without 0/0, and the lowest for a regression analysis with forced 0/0. A regression with 0/0 as an additional point is in-between but closer to the forced 0/0 value. As will be shown in Section 5, penetration is slower for the first several microseconds after impact, after which it

achieves steady state. The above discussion is also applicable to the calculation of the consumption velocity v_c but with the opposite result (v_c increases with a forced 0/0 regression).

Analysis of the 2004 data shows the influence of the different regression methods on the overall penetration curve u vs. v_p (Fig. 12). A change from forced 0/0 regression to regression with 0/0 as an additional point has little effect. The small difference of the resulting regression fit is within a very small error. This is an important finding as it shows that penetration, in general, is very close to a steady-state condition over this velocity range.

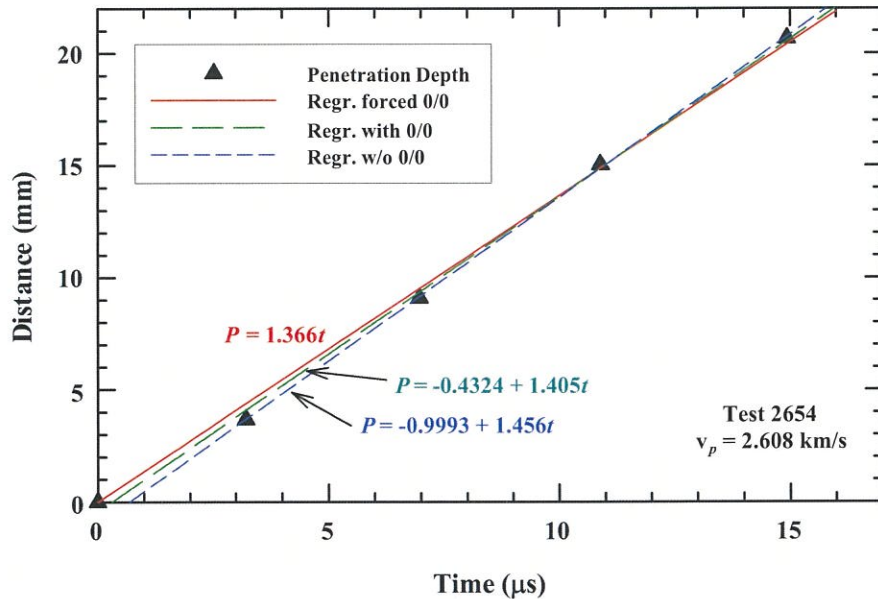


Figure 11. Penetration depth vs. time after impact for Exp. 2654 of the 2004 experiments [2] – different regression calculations for u .

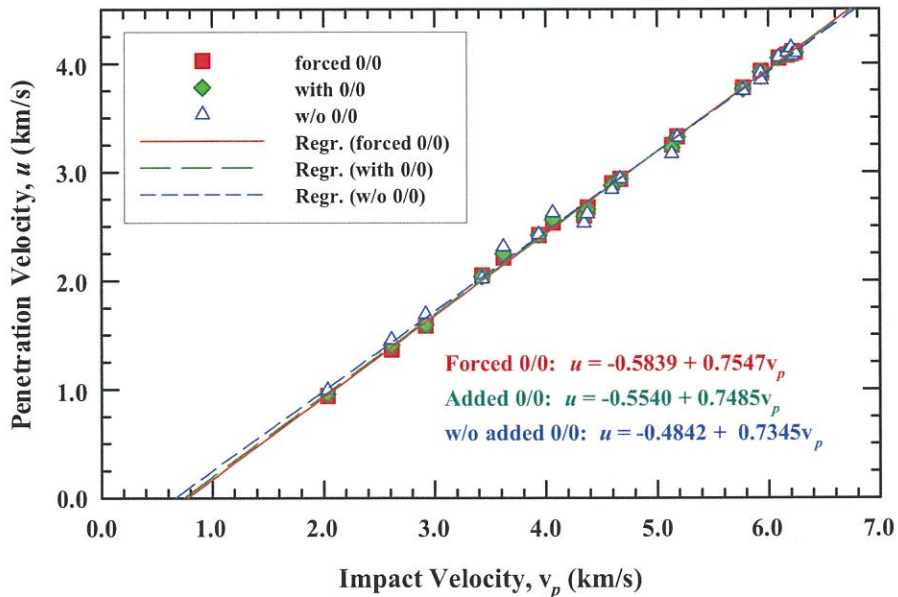


Figure 12. Penetration velocity vs. impact velocity for the 2004 [2] experiments – different regression calculations for u .

The results of Fig. 12 show that by using a forced 0/0 regression for the 2004 test series, the overall results and conclusions of Ref. [2] were not distorted. The major effect of not forcing the regression fit through 0/0 is for impact velocities below ~ 3.0 km/s. Although the slope changed only 2.7%, the intercept changed 20%. The importance is discussed in the next subsection. It should be noted that for all publications concerning the 2004 experiments, the forced 0/0 regression method was described correctly in the specific publication, e.g., Ref. [2]. Results of the later test series (sleeved ceramic [3-6], dwell and interface defeat [7-8], or glass [12-14]) do not mention a forced 0/0 regression method since it was not used.

3.3.3 Relevance for Current and Earlier Experimental Results

As discussed above, the tests with sleeved ceramic were evaluated by a regression analysis without the 0/0 point due to the attached cover. The original 2004 results are compared to sleeved results, plus the new data from Table 1 in Fig. 7. The current (not sleeved) experiments in this report, as well as the penetration data for the opened rectangles from dwell experiments [8,10], were calculated the same way as the sleeved ceramic experiments, i.e. without 0/0.

In Ref. [15], the authors take the results of the current experiments and recalculate the penetration velocities using the forced 0/0 regression procedure. Penetration data of the current series now match the data of the 2004 series, albeit with a degree of scatter. Of course, there were only three experiments in 2004 in the velocity region of 2 to 3 km/s, each at a different impact velocity, which tends to preclude “visible” scatter. Nominally repeat experiments at higher impact velocities—see Fig. 12—show comparable scatter in the penetration velocity as the lower impact velocity experiments.

Here, we take a different approach than in Ref. [15]. The three $u < 3$ -km/s data points from the 2004 test series were re-analyzed without the 0/0 point, and are replotted in Fig. 13 as the open circles. The open circles fall within the scatter of all the other data. Therefore, it can be concluded that the 2004 data and all the newer data are consistent with the observation that the penetration velocity—within data scatter—is independent of whether the ceramic is intact, pre-damaged (TS and TS-2) or *in-situ* comminuted (TS/CL), or sleeved or not sleeved, for impact velocities greater than ~ 1.3 km/s. Also, there does not appear to be any effect of rod diameter on the penetration velocity. The apparent differences in the penetration velocities shown in Fig. 7 were the result of insufficient experimental data to quantify data scatter, and differences in the analysis techniques for determining the penetration velocities.

The scatter is likely due the failure dynamics of a brittle material during penetration, i.e., it is inherent to the material;² for example, see the compilation of data by Orphal for three different ceramics [16]. It is noted that the failure front in glass can be quite irregular, particularly at lower impact velocities [12,17]. It is conjectured that the dynamics of the transition from intact to cracked and then highly comminuted ceramic can be quite variable, particularly if the penetration stresses are comparable to the strength of the confined ceramic. X-rays often show a penetration channel with small disturbances and side-channels—particularly at the lower impact velocities—which can have a strong influence on the measured penetration depths. It has also been demonstrated, using numerical simulations, that the penetration velocity through comminuted ceramic surrounded by intact (elastic) ceramic is influenced by the radial extent of the comminuted material [18]. Thus, it seems reasonable to conclude that the variability

² The accuracy and precision of the data are too good for the scatter to be primarily the result of errors or uncertainties in the measurements.

observed in the penetration velocity of SiC-N as a function of impact velocity is the result of variability in the failure dynamics as the ceramic transitions from intact to failed material.

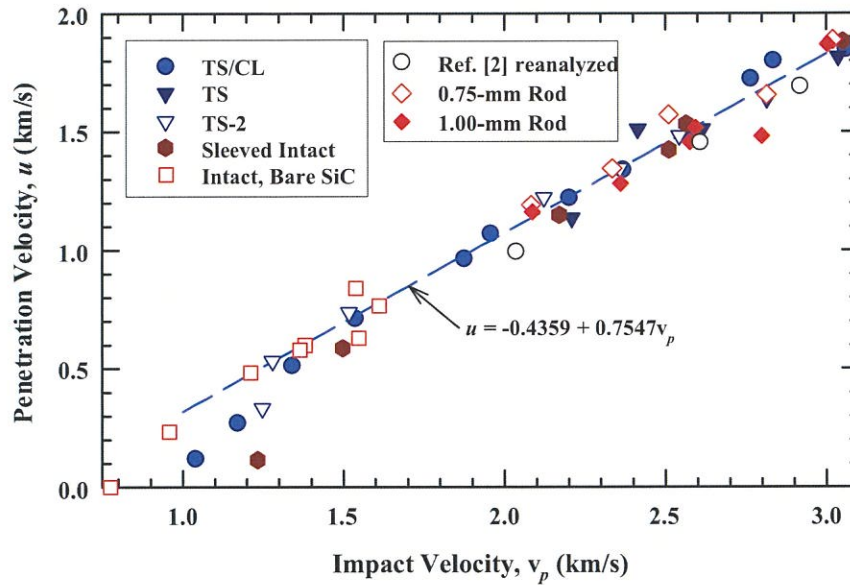


Figure 13. Penetration velocity vs. impact velocity for the original (2004) SiC-N experiments w/o forced 0/0 regression (open circles).

3.4 Re-Evaluation of u vs. v_p Regression Analysis

It was decided to re-do the regression analysis for u versus v_p for SiC-N, using all the experimental data over the entire velocity range.³ All penetration data were analyzed without a 0/0 data point. No data with a penetration velocity less than 400 m/s were included in the linear regression fit. A total of 63 data points, ranging in impact velocity from 1.21 km/s to 6.24 km/s, were used for the linear regression of u versus v_p . An initial regression was conducted, and points greater than 2σ (a total of 3 points) were eliminated and the regression was recalculated, giving:

$$u = -0.3662 + 0.7165v_p \quad (9)$$

The linear regression has an r^2 value of 0.996, with a standard deviation (σ) of 65.1 m/s. The resulting regression line is plotted in Fig. 14, showing all the experimental data. Figure 14 is reproduced as Fig. 15, except with expanded u and v_p axes.

A conclusion of the observation that there is no difference, within data scatter, in the penetration velocity of intact and the various predamaged SiC-N specimens is that the projectile is penetrating damaged (highly comminuted) material. It has been observed in glass [12-14] that a damage front propagates faster than the penetration front; and therefore, the projectile penetrates damaged material. This idea was first proposed in computational modeling of tungsten alloy long rods into glass [19], prior to any experimental evidence. This concept—assuming that the projectile penetrates failed ceramic—was carried further by Walker when he

³ There were three SiC-B data points included in the original regression analysis of Ref. [2]. These 3 data points had impact velocities at approximately 3.5 km/s. The SiC-B data were not included in the revised analysis reported here.

showed good agreement between an analytic model and penetration of thick ceramic by long rods [20-21].

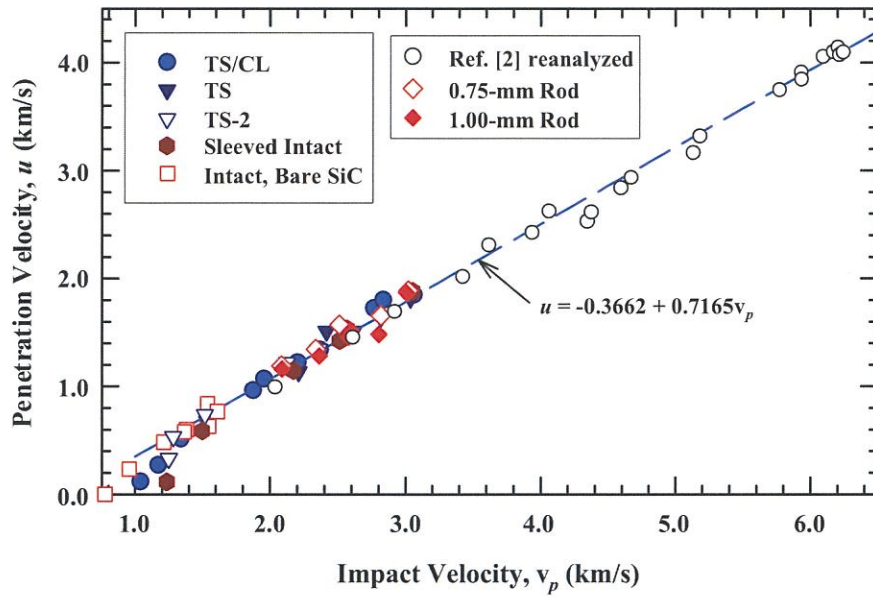


Figure 14. Updated regression fit for u vs. v_p for all SiC-N data.

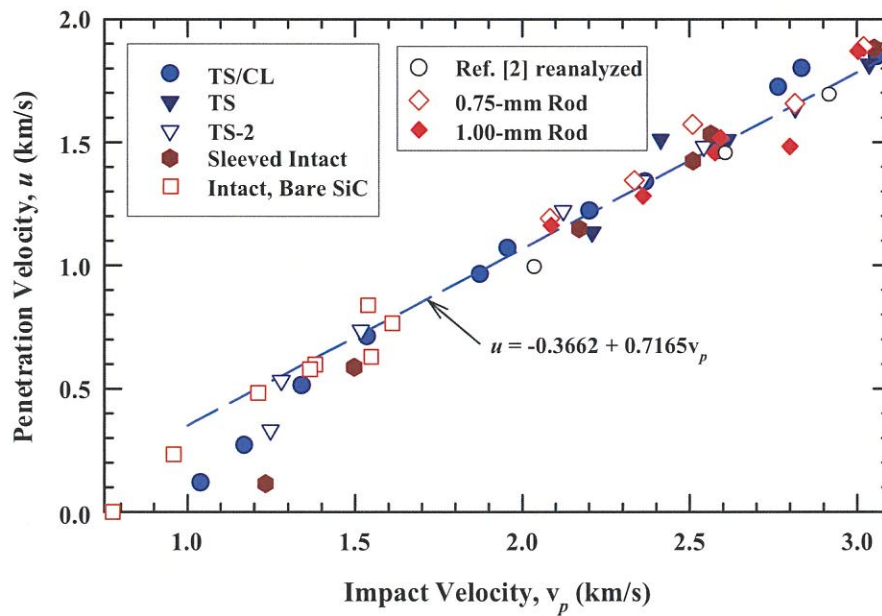


Figure 15. Updated regression fit for u vs. v_p for all SiC-N data, expanded scales.

4.0 Rod Size Effect on Interface Defeat and Buffer Geometry Study

4.1 Introduction

In 2008, experiments were performed to determine the transition velocity from dwell to penetration for gold rods impacting SiC-N [7-8]. The ceramics were either completely bare or had a small copper buffer glued to the front surface of the ceramic. Stable dwell, using the 1.0-mm diameter Au rod, was possible for impact velocities up to approximately 825 m/s on bare SiC ceramic. With a small copper buffer on top of the ceramic, the transition velocity increased to approximately 1540 m/s. However, in an earlier study [9], dwell was observed at a somewhat higher impact velocity (~1620 m/s); this study used the 0.75-mm diameter Au rod. This raised the issue of whether or not there could be a rod-size effect on the dwell-penetration transition velocity. Further, there was interest in determining the influence of different buffer geometries on the transition velocity. Eighteen experiments, with impact velocities between 1.4 km/s and 1.6 km/s, were conducted for these investigations.

The experimental configurations are described in Section 2. The pure gold rods had a diameter of 0.75 mm and 1.0 mm, and lengths of 50 mm and 70 mm, respectively. The buffer types, shown in Fig. 2, consisted of a full cover plate (CP) or cylinders with a diameter of 7 mm (B). A third buffer was introduced, a cruciform (C), to replace buffer B because of buffer separation during launch. The heights of the buffers were 2 mm or 4 mm for the 1.0-mm diameter rod, and 3 mm for the 0.75-mm diameter rod.

4.2 Experimental Data

All experiments are listed by buffer type (CP, B, and C) in Table 2—sorted by increasing impact velocity v_p —where the number after the buffer type indicates the buffer height in mm. The flash X-rays are provided in Appendix B, along with the depths of penetration and rod lengths as measured from the X-ray shadowgraphs. The P - t data are plotted, as are the L_R - t data, for each of the experiments immediately after the respective flash X-ray images. The solid lines, which are the regression fits, denote the range of data used for the regression analyses. The slopes of the linear regressions provide the penetration velocity, u , and the consumption velocity, v_c , which are summarized in Table 2. For each test, the yaw angle of the projectile and the off-center distance of the impact point (oc) were also measured and are listed in Table 2.

Due to the limited number of data pairs for penetration after dwell, and due to cracking during dwell and penetration, results for u and v_c can vary quite substantially for the same impact velocity. This scatter is of a physical origin and not caused by an error in measurement. For tests where there is a dwell to penetration transition, an estimated dwell time can be calculated with the help of the linear regression equation for the penetration depth P into the ceramic versus time t :

$$P = a + ut \quad (10)$$

where u is the penetration velocity. Dwell time t_D is then calculated from the axis intercept a and the time necessary for penetrating the Cu buffer t_{Cu} as:

$$t_D = -a/u - t_{Cu} \quad (11)$$

The time interval t_{Cu} is estimated from hydrodynamic penetration theory as:

$$t_{Cu} = \frac{h_{Cu}}{u_{hydro}} \quad (12)$$

where h_{Cu} is the height of the buffer, and u_{hydro} is given by Eqn. (2).

Table 2. Experimental Results for Dwell and Buffer Geometry Experiments

Exp.	Buffer	Rod [mm]	Yaw [°]	oc [mm]	v_p km/s]	u [km/s]	v_c [km/s]	t_D [μs]
11625	CP2	1.00x70	7.3	5.1	1.487±0.006	-	1.432±0.011	sust.
11638	CP2	1.00x70	3.1	0.8	1.553±0.007	-	1.532	sust.
11640	CP2	1.00x70	0.8	4.2	1.578±0.005	0.693±0.073	0.888±0.079	7
11678	B2	1.00x70	1.9	2.6	1.564±0.007	-	1.518±0.007	sust.
11680	B2	1.00x70	1.6	3.9	1.585±0.004	0.787±0.123	0.775±0.131	24
11624	CP4	1.00x70	5.0	2.8	1.407±0.006	-	1.468	sust.
11639	CP4	1.00x70	0.5	2.6	1.484±0.011	-	1.477±0.004	sust.
11637	CP4	1.00x70	1.5	3.9	1.520±0.008	0.746±0.060	0.763±0.067	19
11641	CP4	1.00x70	1.1	1.1	1.528±0.012	-	1.520	sust.
11671	C4	1.00x70	1.1	2.8	1.525±0.005	-	1.501±0.006	sust.
11674	C4	1.00x70	3.0	2.5	1.549±0.002	-	1.510±0.007	sust.
11672	C4	1.00x70	0.5	2.1	1.552±0.007	0.664	0.864±0.003	21
11673	C4	1.00x70	1.2	1.9	1.555±0.002	0.883	0.726±0.040	24
11643	B4	1.00x70	1.0	3.3	1.570±0.012	0.638±0.069	0.822	3
11675	C3	0.75x50	0.7	1.7	1.571±0.001	-	1.523	sust.
11676	C3	0.75x50	1.8	3.7	1.598±0.004	0.491±0.082	0.967	2
11677	C3	0.75x50	1.8	2.2	1.600±0.004	-	1.594	sust.
11679	C3	0.75x50	2.0	2.1	1.607±0.010	0.621±0.030	1.257	13

4.3 Previous Experimental Results

The test series in Ref. [7-8] investigated interface defeat for bare and buffered SiC-N. The estimated dwell times for the two buffered target configurations with the 4-mm and 2-mm buffer heights are shown in Fig. 16.⁴ The dashed line indicates the time required for a 70-mm long rod to completely erode at the respective impact velocity (ignoring the time it takes for the rod to penetrate the Cu buffer). Three of the experiments showed sustained dwell, but the time for the last X-ray was 40 μs; the vertical arrows denote how much additional time would be required for total interface defeat. For experiments where dwell is followed by penetration, the dwell time of the rod on the ceramic surface was calculated according to Eqn. (11). From these data, the

⁴ The following symbols are used to denote and to distinguish the various types of buffers: open symbol—B or C; solid symbol—CP; the color red—4-mm-thick buffer; the color blue—2-mm-thick buffer.

dwell-penetration transition velocity for the buffered targets was estimated to be approximately 1540 m/s. The available data for the 2-mm cover plate buffer show a relatively large gap between 1.38 km/s and 1.57 km/s. Although the data for 4-mm buffer fills that gap quite well, a thorough examination for each type of buffer seemed desirable.

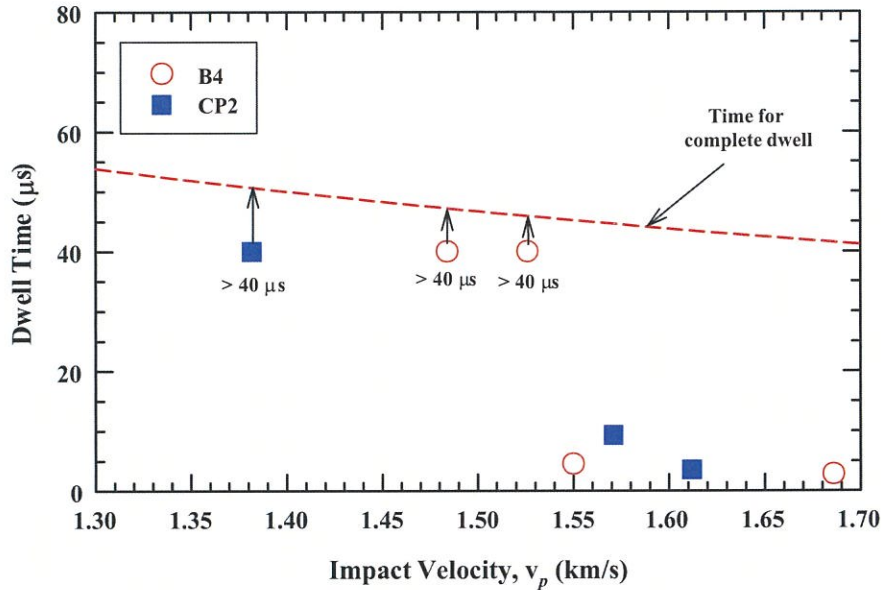


Figure 16. Dwell time vs. impact velocity: original data for buffered targets [7-8].

The post-dwell penetration velocities versus impact velocity are plotted in Fig. 17 for these same experiments. The long dashed line is the regression fit for all the data (see Figs. 14-15), and the dotted lines represent an uncertainty of 1.5σ about the mean response. When sustained dwell is observed, the penetration velocity is zero. The estimated dwell times are shown below each datum for the experiments that transition from dwell to penetration. It is seen that

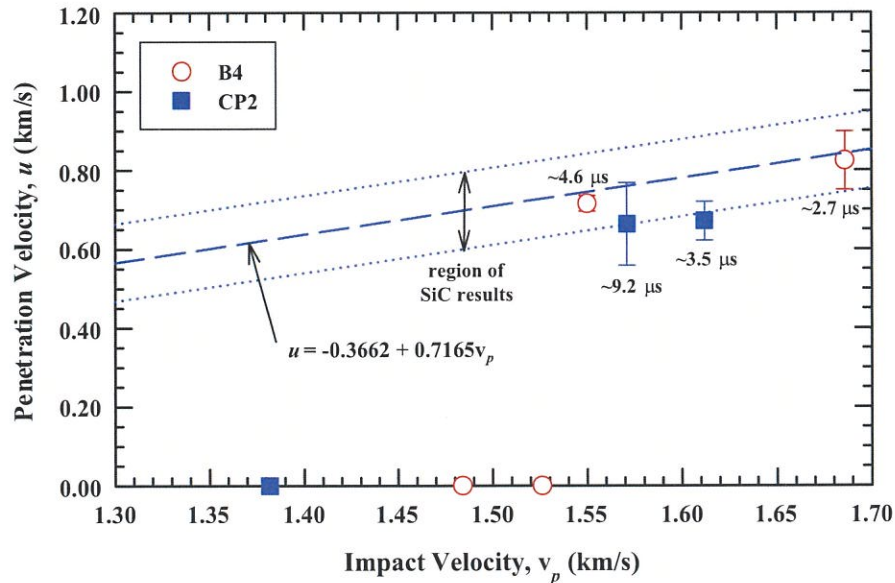


Figure 17. Post-dwell u vs. v_p : original data for buffered targets [7-8].

the post-dwell penetration velocities fall within the scatter band of u vs. v_p that was determined in Section 3.4.

4.4 Results for 2-mm Buffer Height

X-ray images are shown for four experiments in Figs. 18 and 19, all with a 2-mm thick buffer. Experiments with a cover plate (CP), showing dwell (Exp. 11638) and transition to penetration (Exp. 11640) are shown in Fig. 18. The 2-mm thick cover plate bulges after impact, but eventually the cover lifts away from the ceramic surface. Front cracks—presumably conical shaped—can develop in the late phase of dwell but still the rod is completely eroded on the surface. When penetration occurs, the ceramic shows a loose structure with many cracks over the penetrated length. This is usually more readily observed with the optical images, Section 4.7.

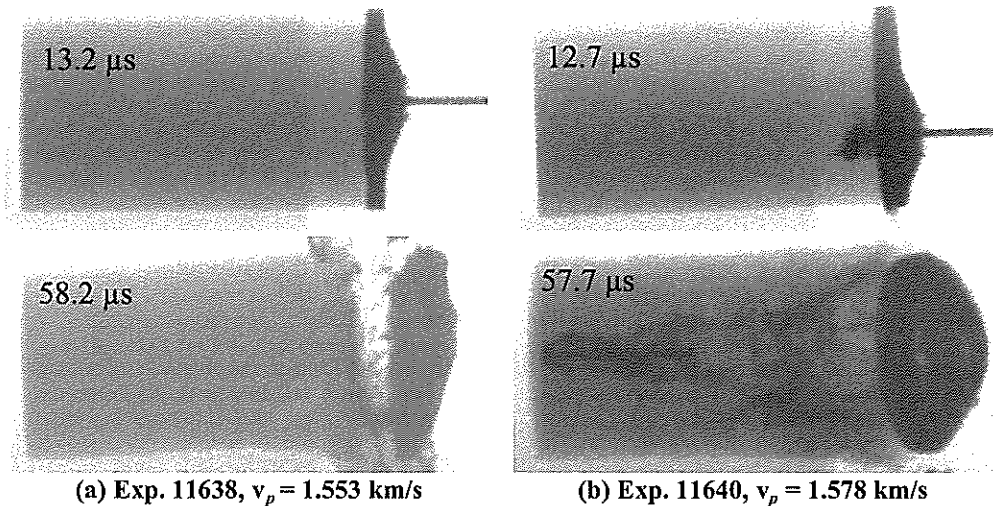


Figure 18. X-ray images for CP2 buffer experiments showing dwell (left), and transition of dwell to penetration (right).

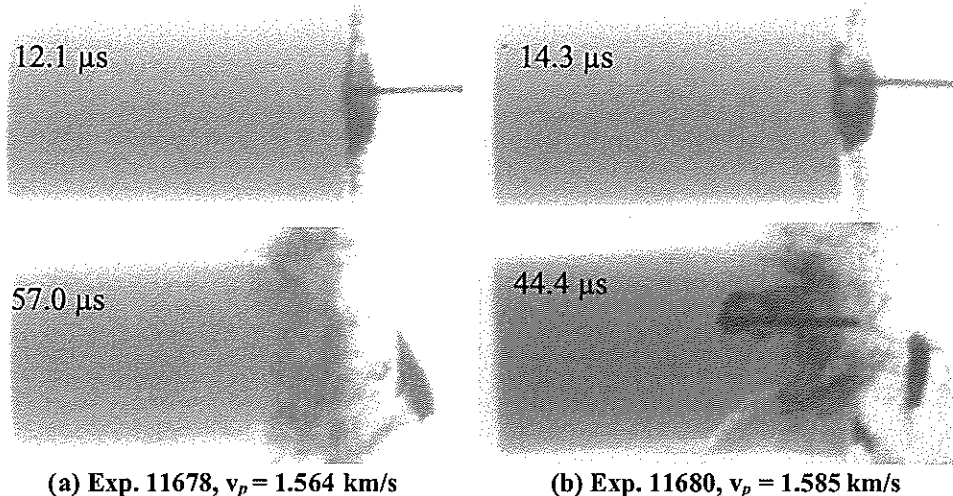


Figure 19. X-ray images for B2 buffer experiments showing dwell (left) and transition of dwell to penetration (right).

Similarly, dwell is observed for an experiment with the small (B) buffer (Exp. 11678) and transition to penetration (Exp. 11680), Fig. 19. The B buffer separates quickly after impact and then no longer influences the dwell process. Again, the ceramic cracks during interaction with

the rod; for dwell, conoidal cracks appear, while for penetration, cracks emanate around the penetrating rod.

Adding these experiments to the previous data, Fig. 20, shows that the results of these new experiments are consistent with the older experimental results. The post-dwell penetration velocities are plotted in Fig. 21. The dwell-penetration transition velocity for the 2-mm thick buffers is 1570 ± 16 m/s, denoted by the bluish shaded region in Fig. 21. (The 4-mm thick buffer data have been removed from Fig. 21, and were not used to obtain an estimate for the transition velocity.) A zone of only 32 m/s covers both dwell and penetration. The B2 configuration,

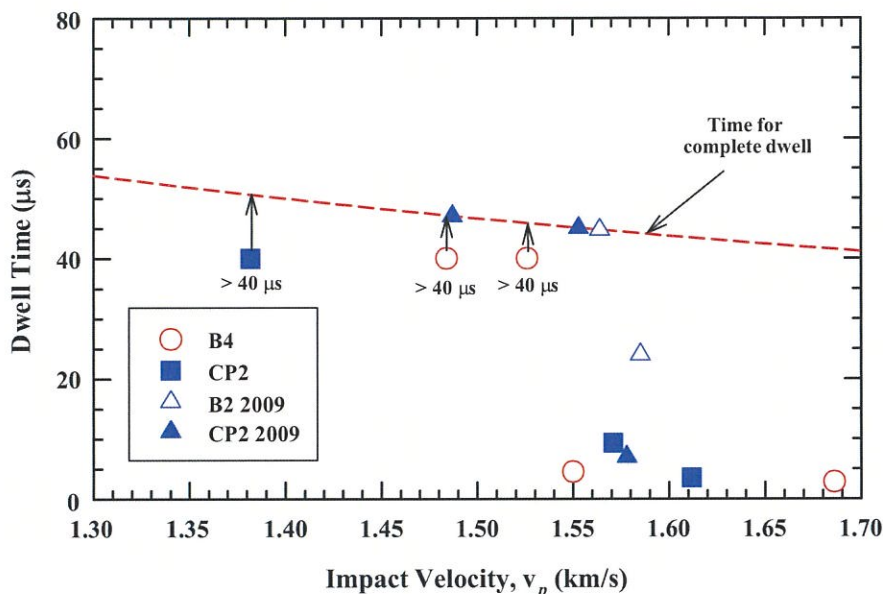


Figure 20. Dwell time vs. impact velocity for 2-mm thick buffers.

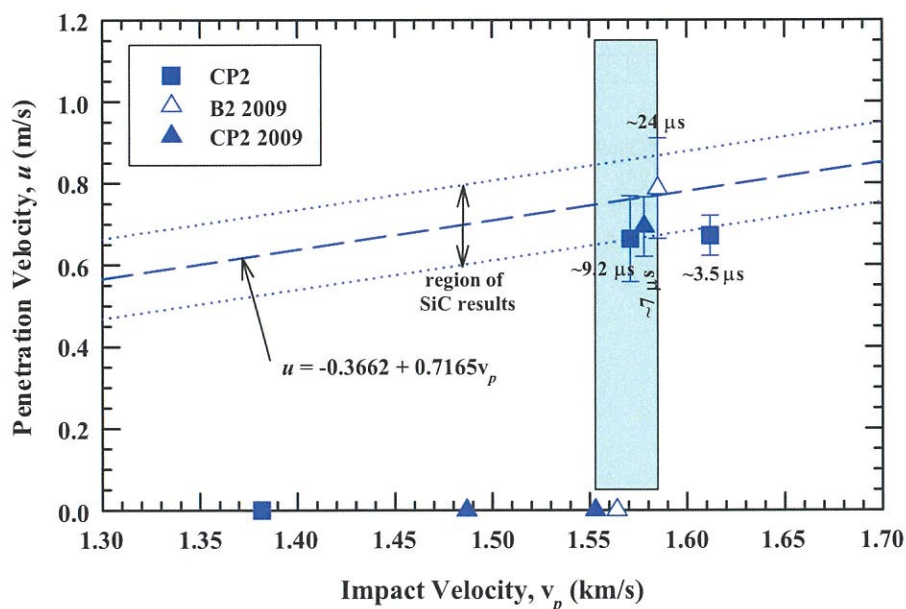


Figure 21. u vs. v_p for 2-mm thick buffer experiments.

perhaps, is slightly better than the CP2 configuration, since there is a longer period of dwell ($\sim 24 \mu\text{s}$) than for the two cover plate experiments, which were at slightly lower impact velocities. However, the data are extremely limited.

4.5 Results for 4-mm Buffer Height

X-ray images using a 4-mm thick buffer are shown in Fig. 22. The 4-mm cover plate bulges less during impact than the thinner 2-mm cover plate (see Fig. 18). The cruciform buffer separates quickly after impact and behaves similarly to the small cylindrical buffer. The results for the experiments with the 4-mm thick buffers are displayed in Fig. 23. As with the B2 and CP2 buffers, there is an indication that the C4 buffer is slightly better than the CP4 buffer since dwell transitions to penetration with the CP4 buffer at a slightly lower impact velocity than for the C4 buffer.

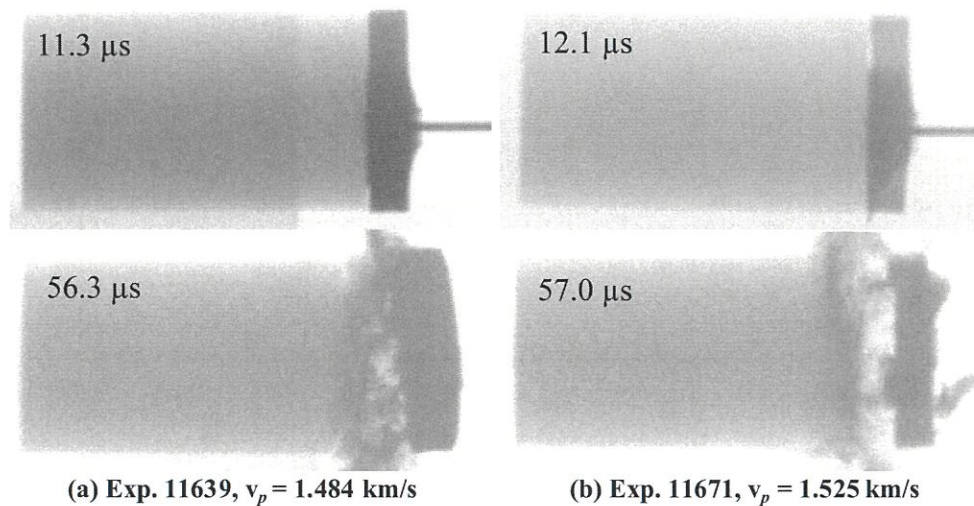


Figure 22. X-ray images for cover plate (left) and cruciform buffer (right).

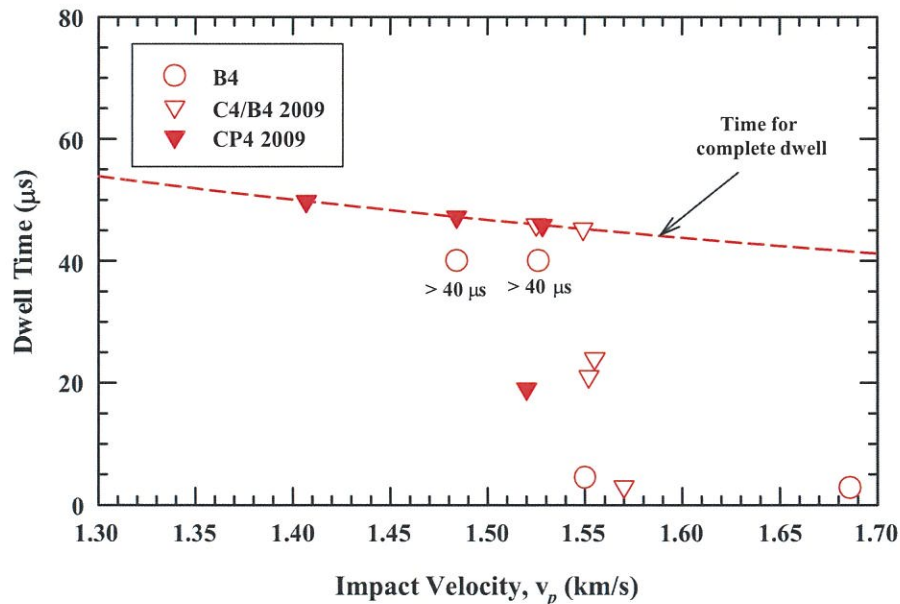


Figure 23. Dwell time vs. impact velocity for 4-mm thick buffers.

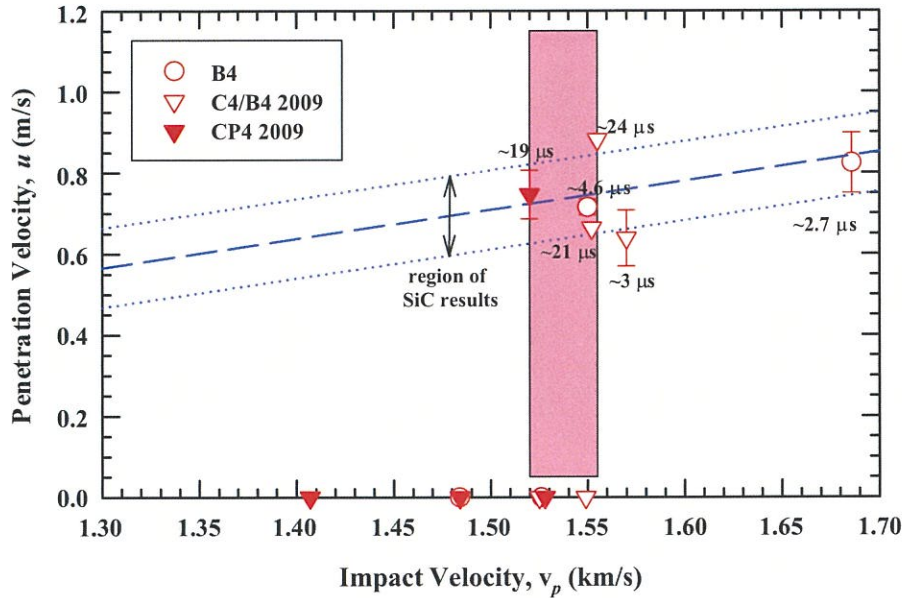


Figure 24. u vs. v_p for 4-mm thick buffer experiments.

All the 4-mm thick buffer results are presented in Fig. 24. The dwell-penetration transition velocity is 1540 ± 18 m/s, and is shown as the reddish shaded region. This transition velocity will be compared to the 2-mm thick buffer in Section 4.8.

4.6 Results for 3-mm Buffer Height (0.75-mm Diameter Rod)

Four experiments were conducted with the 0.75-mm diameter rod. Flash X-ray shadowgraphs showing dwell ($v_p = 1.600$ km/s) and penetration ($v_p = 1.607$ km/s) are shown in Fig. 25. Again, a fracture conoid forms from the top surface and runs to the edge of the ceramic for dwell, while the ceramic is considerably damaged for the penetrating rod.

The dwell times as a function of impact velocity for these 3-mm buffer/0.75-mm rod experiments are plotted in Fig. 26 as the open diamonds. Since the buffer height was 3 mm, the ratio of the buffer height (h) to rod diameter (D_p) is 4, so these experiments can be compared directly with the experiments with the 4-mm thick buffers using the 1.0-mm diameter rod; i.e., $h/D_p = 4$. Therefore, the results for the 4-mm buffer/1-mm rod experiments are also shown. Since the 0.75-mm diameter rods were only 50-mm long, the time for complete dwell is shorter than for the 70-mm diameter rods, as denoted in the figure.⁵ Also shown in the figure are the two preliminary experiments conducted in 2005 [9], denoted by the open upright triangles. These two experiments used a 0.75-mm diameter Au rod that was 50-mm long. The cylindrical buffer for these two experiments had a height of 3 mm and a diameter of 5 mm. Only two X-ray flashes per test were used for these preliminary experiments, and the time of the last flash is denoted in the figure. For both experiments, dwell was still on-going at the time of the last flash.

⁵ As mentioned previously, the time for complete dwell ignores the time required to penetrate the buffer.

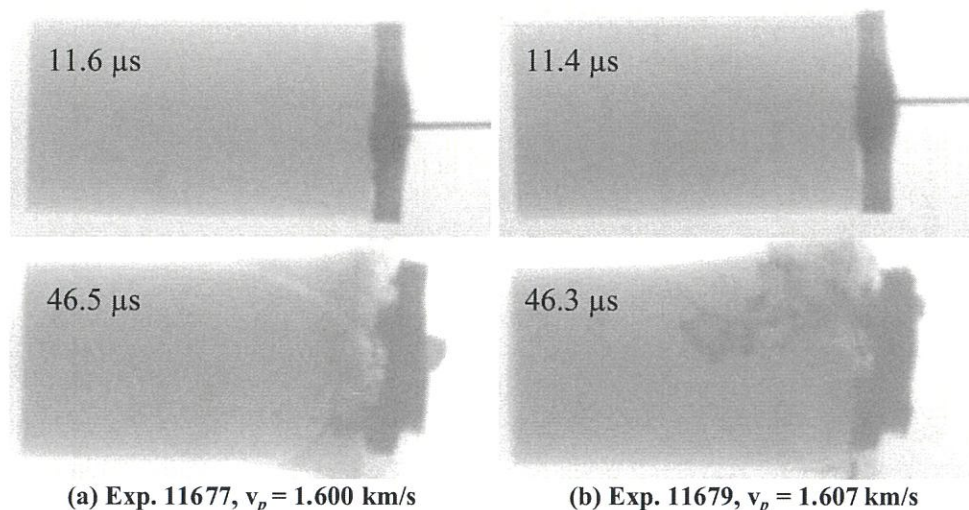
(a) Exp. 11677, $v_p = 1.600$ km/s(b) Exp. 11679, $v_p = 1.607$ km/s

Figure 25. X-ray images for the 0.75-mm diameter rod showing dwell (left) and transition from dwell to penetration (right) using the C buffer configuration.

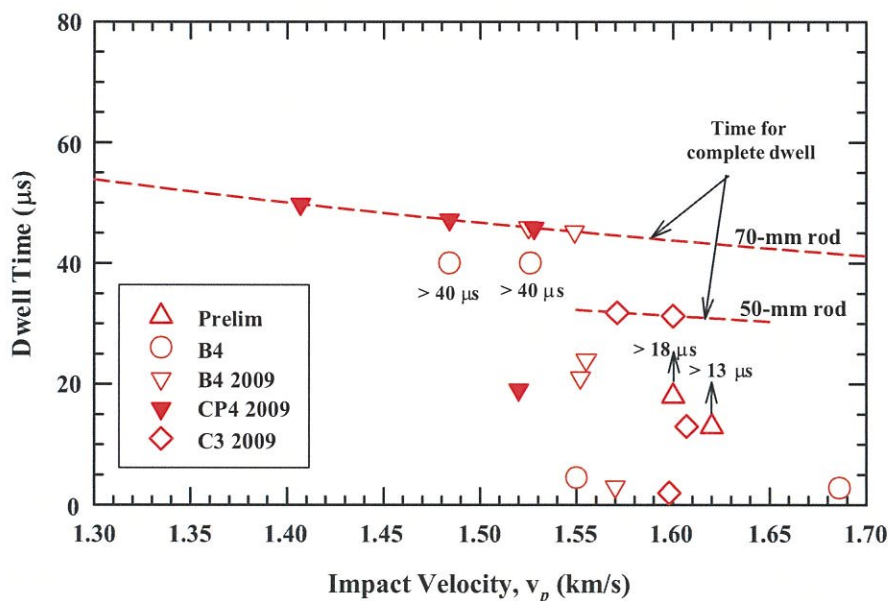


Figure 26. Dwell time vs. impact velocity for $h/D_p = 4$ experiments.

The new data are consistent with the preliminary data, and indicate that the 0.75-mm diameter rod will sustain dwell at a slightly higher impact velocity than the 1.0-mm diameter rod. The post-dwell penetration velocities are shown in Fig. 27. The two preliminary experiments (open, upright triangles) are shown with a very low penetration velocity only to provide an offset from the open diamond data. Because there were no late time X-rays, however, it is unknown if one or both of these experiments might have transitioned to penetration. For example, one of the C3 datum (open diamond) at approximately 1.62 km/s had a dwell time of ~ 13 μ s before transitioning to penetration.

The average dwell-penetration transition velocity for the 0.75-mm rods is 1605 ± 18 m/s, denoted by the yellow region in Fig. 27. This transition velocity will be compared to the other transition velocities in Section 4.8.

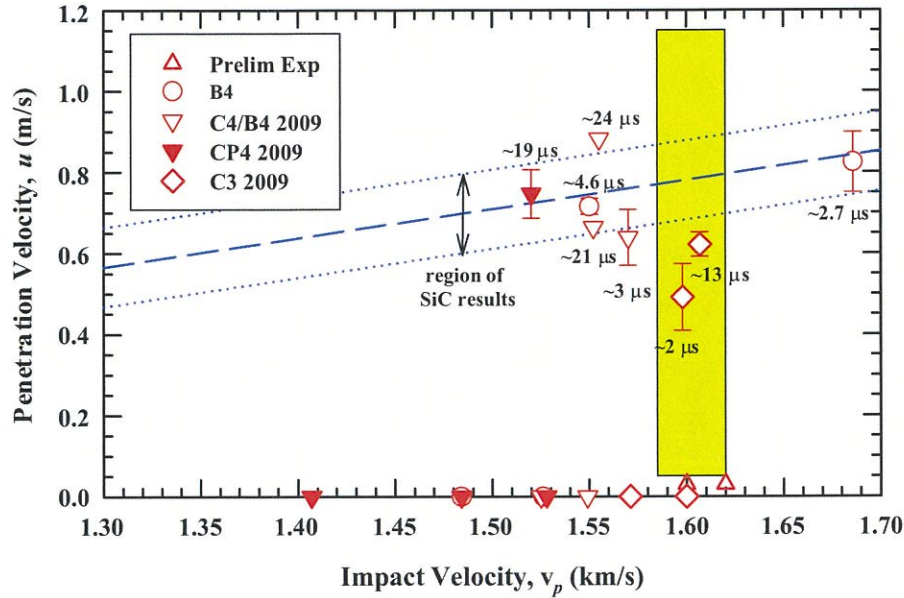


Figure 27. u vs. v_p for $h/D_p = 4$ experiments.

An interesting observation is that the post-dwell penetration velocities of the 0.75-mm rods lie below all the other post-dwell data. Although it was concluded in Section 3.3.3 that there did not appear to be any scale-size (rod diameter) effect on penetration velocity, there was one datum with the 0.75-mm rod, at ~ 2.7 km/s, that had a very low penetration velocity (see Fig. 15). However, it is noted that there is usually only a few (sometimes only two) data points (X-ray flashes) to determine u and v_c after the onset of penetration. Additionally, there is a consistency check, which is that $u + v_c$ should equal v_p [8,10]. This consistency check is violated for some of the u - v_c pairs in Table 2, thereby bringing into question the accuracy of the u - v_c data when calculated from a minimum number of points.

4.7 Use of Optical Diagnostics

As described in Section 2.4, two different diagnostic methods were used for imaging the experiments, flash radiography and a high-speed video camera capable of a frame rate of 1 million frames per second (fps). The videos were taken at 500 kfps with a single-frame exposure time of $0.5 \mu\text{s}$. Whereas the X-ray images show the *in-situ* position of the rod with respect to the ceramic very clearly and are absolutely necessary for determination of depth of penetration for a penetrating rod, the video imaging provide an overall external view of the response of the ceramic surface and development of cracks during impact.

Representative video images are shown in Fig. 28. The two experiments in Fig. 28, using the C3 buffer, are the same two experiments for which flash X-rays are shown in Fig. 25. It is observed that during dwell that the ceramic stays compact but with conoidal cracks extending from the front surface to the side of the ceramic (better seen in Fig. 25). However, for penetration, the ceramic undergoes extensive cracking, and presumably, rod material flows from inside the ceramic through some of the cracks, which is the bright feature a little above the middle of the ceramic cylinder in the lower right image of Fig. 28. In general, it was therefore possible to judge from the visual behavior of the ceramic if dwell or penetration occurred, as

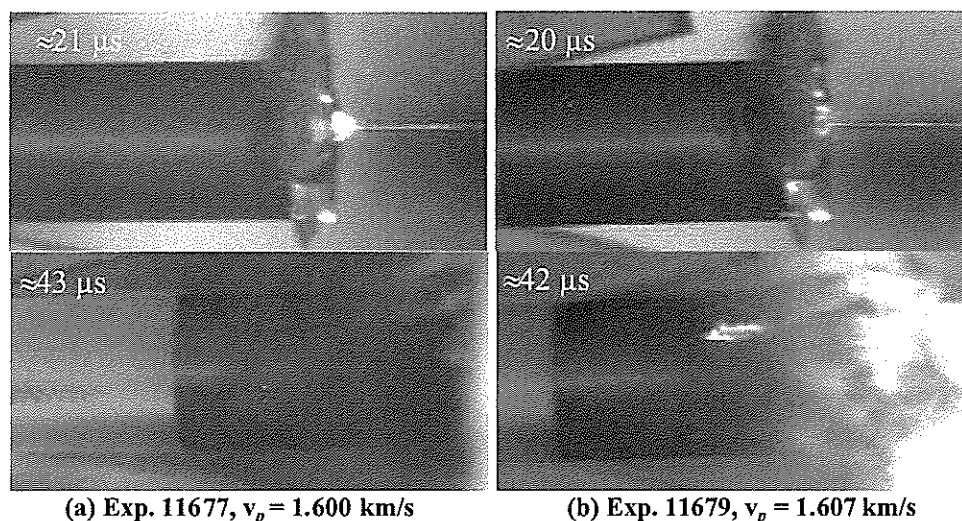


Figure 28. Video images for the 0.75-mm diameter rod showing dwell (left) and transition from dwell to penetration (right).

confirmed by flash radiography. This means that for certain applications, where the use of X-ray diagnostics might not be possible, optical diagnostics can still provide relevant information about the impact response.

4.8 Comparison of Dwell-Penetration Transition Velocities

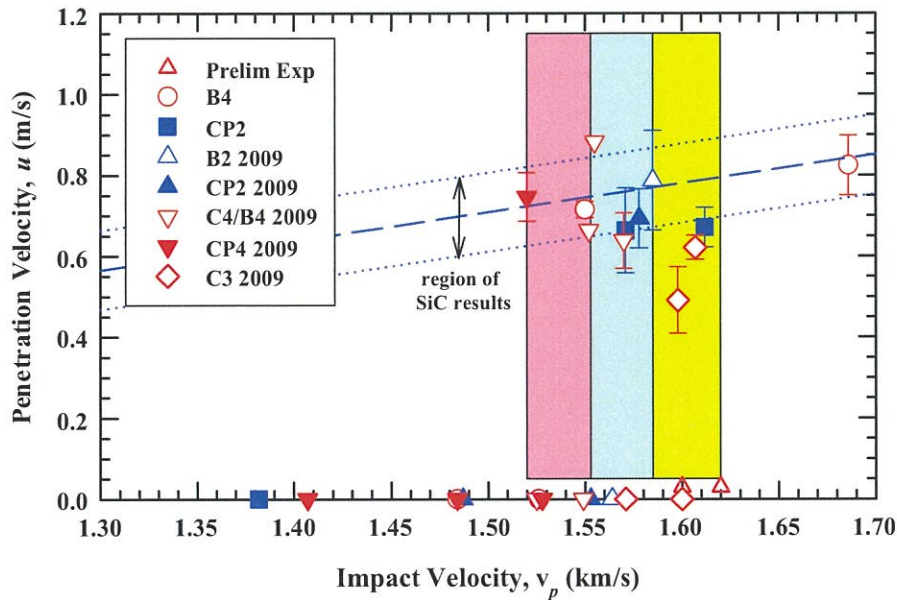
The dwell-penetration transition velocities for the three sets of experimental conditions are summarized in Table 3. These results are also plotted in Fig. 29, denoted by the shaded regions.⁶ The averages and uncertainties/spread are estimates based on the limited experimental data. Since this transition can be viewed physically as an instability condition, it is reasonable to expect that the transition velocity is not a well-defined number; rather, it represents an average or statistical response. The physical behavior of the dwell-penetration transition velocity probably can be viewed as analogous to a V_{50} . For V_{50} , the instability condition is failure of the rear surface of the target with perforation by the residual projectile. Thus, when the probability of perforation is plotted versus impact velocity, the probability has an S-shaped response, going from 0 (no perforation, i.e., partial penetration) to 1 (perforation, i.e., complete penetration) as the impact velocity increases. V_{50} is the impact velocity for which there is a 50% probability of perforation. It is possible, that is, there is a certain probability, that there can be a perforation below V_{50} , just as there is a probability that there is no perforation above V_{50} . The further away the impact velocity is from V_{50} , the less likely there will be a complete penetration or partial penetration for impact velocities lower than or higher than V_{50} , respectively. For example, see the experimental results described in Anderson, *et al.* [22]. With these thoughts in mind, the results shown in Table 3 and Fig. 29 can be considered reasonable estimates for the dwell-penetration transition velocity based on the limited experimental data discussed above.

Examining Table 3 and Fig. 29, it is observed that the transition velocity for the 4-mm thick buffer (reddish region in Fig. 29) is approximately 30 m/s less than that for the 2-mm thick buffer (bluish region in Fig. 29). This is an indication that the thicker cover plate may influence

⁶ Although there exists a small amount of overlap between adjacent transition intervals, the plotting routine does not explicitly show the overlap, that is, a color dominates a second color in the overlap region.

Table 3. Summary of Dwell-Penetration Transition Velocities

Buffer	Rod Diameter [mm]	h/D_p [-]	Transition Velocity [m/s]
B2, CP2	1.0	2.0	1570±16
B4/C4, B4	1.0	4.0	1540±18
C3	0.75	4.0	1605±18

**Figure 29. Comparison of the dwell-penetration transition velocities for variations in buffer height and rod diameter.**

the flow of rod material at the buffer/ceramic interface. It is also noted, within the very limited 4-mm thick buffer data, that the B4/C4 configuration is slightly more effective than the cover plate (CP4) configuration. The B4/C4 has a slightly higher dwell-penetration transition velocity, and even if not complete interface defeat, dwell times can be longer (Fig. 23). These two observations—the slightly detrimental effect of a full cover plate and a detrimental effect of a thicker cover plate—have been predicted by numerical simulations by Holmquist, *et al.* [10].

The spread in the transition velocity for the 0.75-mm rod is displayed as the yellow region in Fig. 29. The results show that for the same h/D_p ratio (4.0), that the small diameter rod has a transition velocity of approximately 65 m/s higher than that for the 1.0-mm rod. Further, these results are in agreement with the preliminary experiments described in Ref. [9]. As mentioned previously, Andersson, *et al.*, [11], suggested that there was a rod-diameter effect for the dwell-penetration transition velocity.

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5.0 Early Penetration Phase

5.1 Introduction and Background

Experiments were conducted to investigate the dwell-penetration transition velocity for Au rods impacting SiC-N [7-8]. The transition velocity for bare SiC-N is ~ 825 m/s, and it was shown experimentally that dwell times were very short at impact velocities greater than 100 m/s higher than the transition velocity. However, the analysis procedures described in Section 4.2 predict a finite amount of dwell time, even for rather large velocities above the transition velocity. An example is shown in Fig. 30, which is from Ref. [8]. This particular experiment was a “buffer experiment” in which the rod missed the buffer (“MB”) and impacted the bare ceramic. The impact velocity of 1.365 km/s was much too high for a bare target to achieve dwell. Nevertheless, it can be seen that early-time penetration resistance must be quite high since extrapolation of the penetration-time data does not go through the 0/0 coordinate, as shown in Fig. 30.⁷ A t_d of $4.2 \mu\text{s}$ —Eqns. (10-12)—is calculated for Exp. 11359. As there are no X-ray images at short times after impact, we cannot differentiate between a very large penetration resistance versus some dwell followed by penetration. Nevertheless, these data are consistent with the interpretation that the penetration resistance of SiC-N is very large immediately after impact.

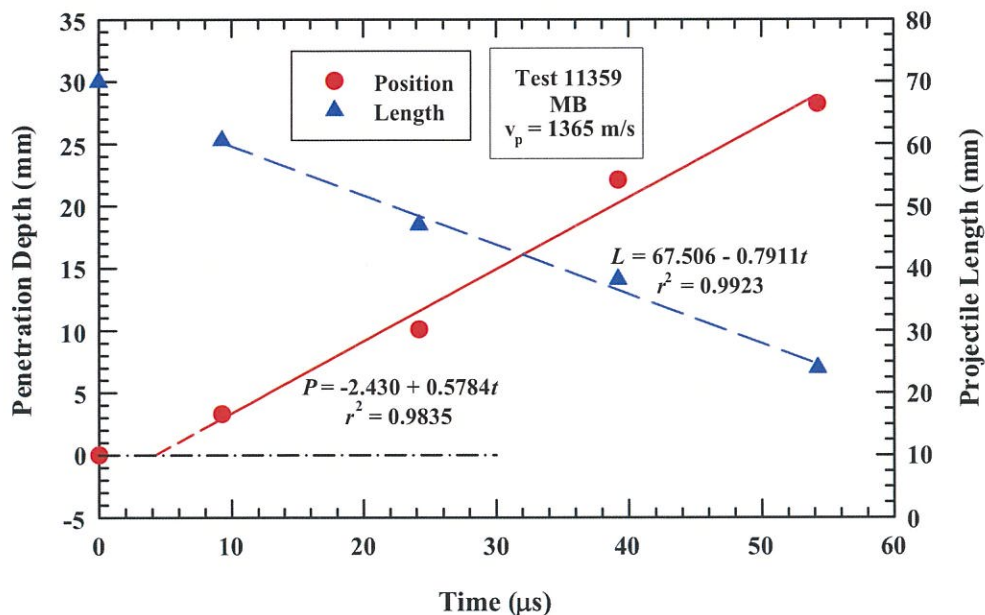


Figure 30. Analysis of Exp. 11359, indicating high penetration resistance at early time [8].

Some of the experiments conducted to determine the effect of the rod diameter (e.g., see Appendix A, Exp. 11558), which had an early-time flash X-ray (at $\sim 5 \mu\text{s}$ after impact), indicated that penetration rate into SiC is slower during the first several microseconds after impact than for a later, steady-state penetration phase. But for all these earlier test series, at best only one data point for the early phase of penetration was available per experiment.

⁷ The penetration-time response in Fig. 30 is contrasted to that of the high velocity experiments (impact velocities greater than ~ 3.0 km/s) that are described in Ref. [2], where the extrapolated penetration-time data tend to pass through, to a good first approximation, the 0/0 point.

To investigate the first few microseconds of penetration itself and to obtain a better understanding of the penetration-time data for the early phase of the penetration, four additional experiments at ~ 1.5 km/s and ~ 2.1 km/s impact velocity were performed against bare SiC-N cylinders. The Au rods were 1.0 mm in diameter and 70-mm long. The SiC-N cylinders had a diameter of 20 mm, and were 35-mm long. Three of the five X-ray tubes (see Fig. 3) monitored the first few microseconds after impact. Additionally, one X-ray image each was taken prior to impact and one X-ray was taken after the rod had penetrated about one-half of the ceramic. A high-speed video camera monitored the impact process optically. Other details of the experiments are described in Section 2.

5.2 Results for Early-Time Penetration Experiments

The four experiments are listed Table 4. The total yaw angle and the off-centered distance from the intended impact point (oc) were directly measured in the experiments and are given in Table 4, along with the impact velocity v_p . The penetration-time (P - t) data for the experiments are listed in Table 5.

Table 4. Experimental Results for Early-Time Penetration Experiments

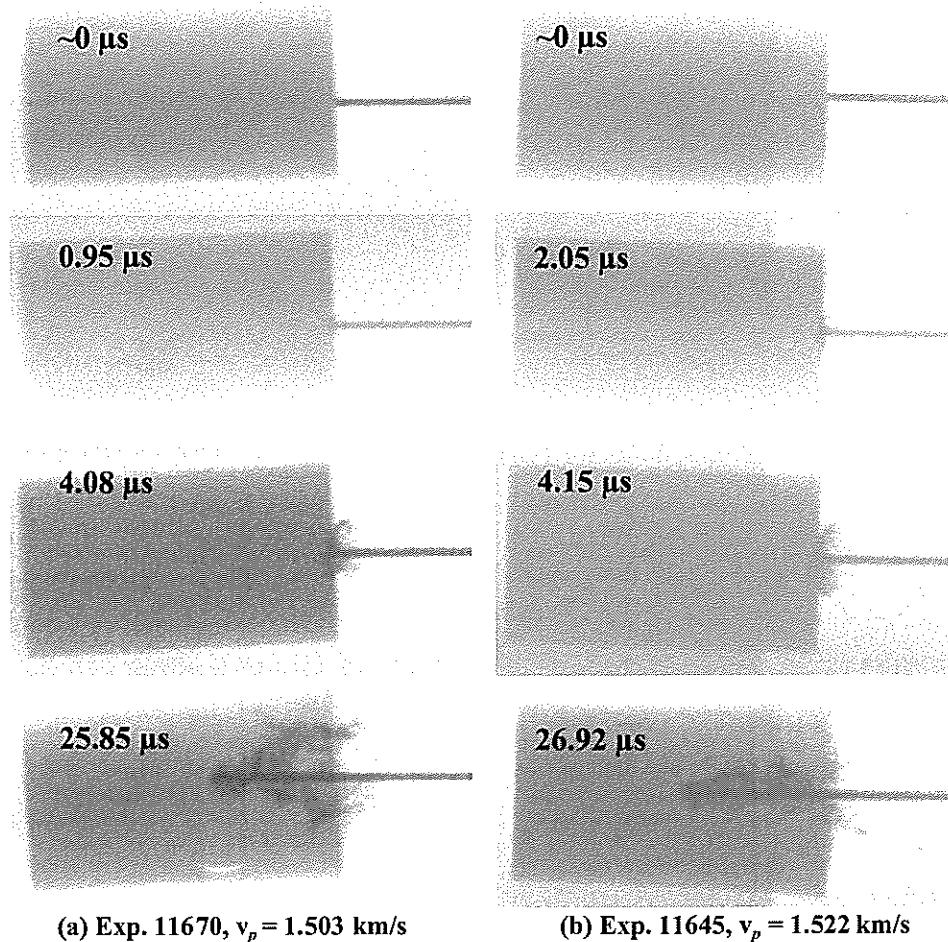
Exp.	Rod [mm]	Yaw [°]	oc [mm]	v_p [km/s]
11670	1.00x70	3.3	2.8	1.503 ± 0.008
11645	1.00x70	0.4	0.8	1.522 ± 0.011
11656	1.00x70	3.2	2.6	2.102 ± 0.006
11655	1.00x70	2.2	3.4	2.117 ± 0.004

Table 5. Position-Time Data for Early-Time Penetration Experiments

Exp.	1.50 km/s			Exp.	2.10 km/s		
	t after imp [μ s]	Pen. depth [mm]	Rod length [mm]		t after imp [μ s]	Pen. depth [mm]	Rod length [mm]
11670	0.00	0.00	70.07	11656	0.00	0.00	69.99
	0.95	1.04	69.01		0.90	1.24	68.96
	4.08	1.61	65.00		3.00	2.52	66.02
	25.85	14.83	45.52		5.14	3.93	62.62
					14.92	15.25	53.59
11645	0.00	0.00	69.96	11655	0.00	0.00	70.05
	2.05	0.66	67.44		0.70	1.00	69.38
	4.15	1.46	65.05		2.73	2.54	66.71
	26.92	16.57	45.26		14.67	15.30	53.99

All experiments produced at least two X-ray images for the early penetration phase. Images taken at or shortly before impact were not taken into evaluation, i.e., the 0/0 point is not included in the evaluation of the data (the reason for not including the 0/0 will be discussed later in the section). The X-ray images for the four experiments are shown in Figs. 31 and 32. Rod material flows primarily radially, at or near the surface of the ceramic, for a few microseconds before forming a penetration channel. An interpretation for this behavior is that at impact the ceramic is

undamaged and the penetration resistance is quite high while the ceramic material transitions from intact to damaged material. In analogy to glass [12-14], once damage is initiated, a damage front then propagates into the ceramic, and this damage front propagates considerably faster than the rod is penetrating; thus, later in time, the rod is penetrating already damaged material.

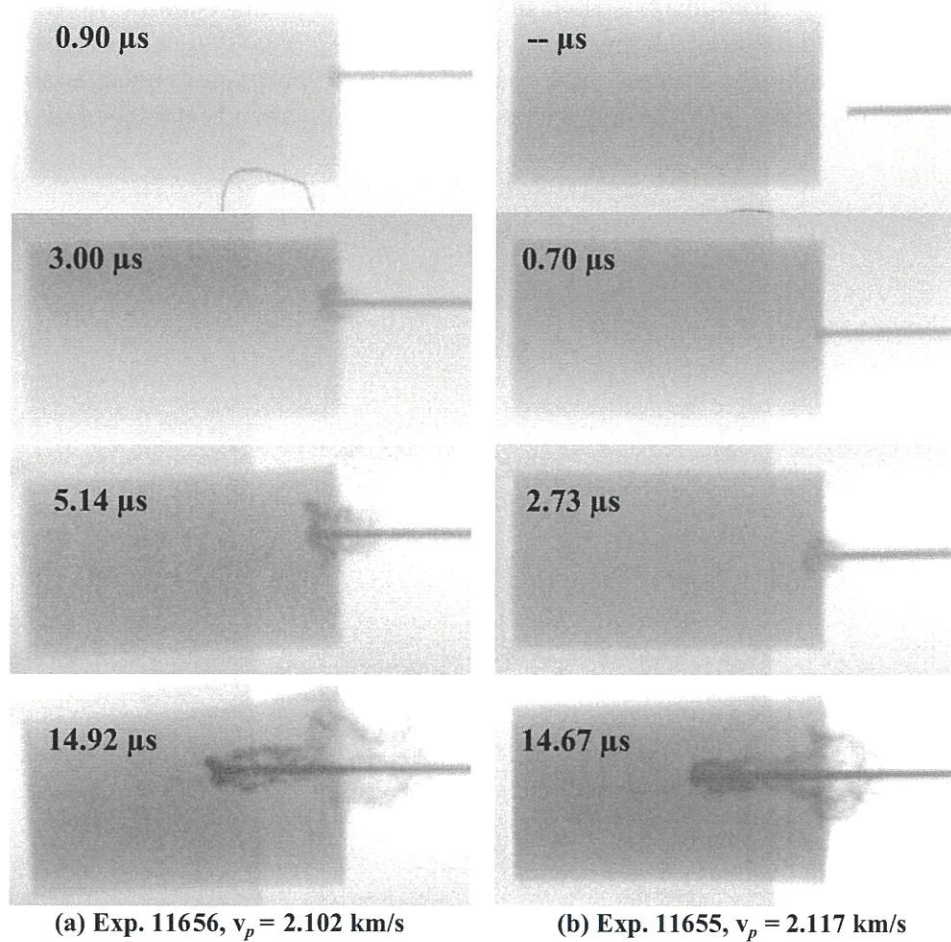
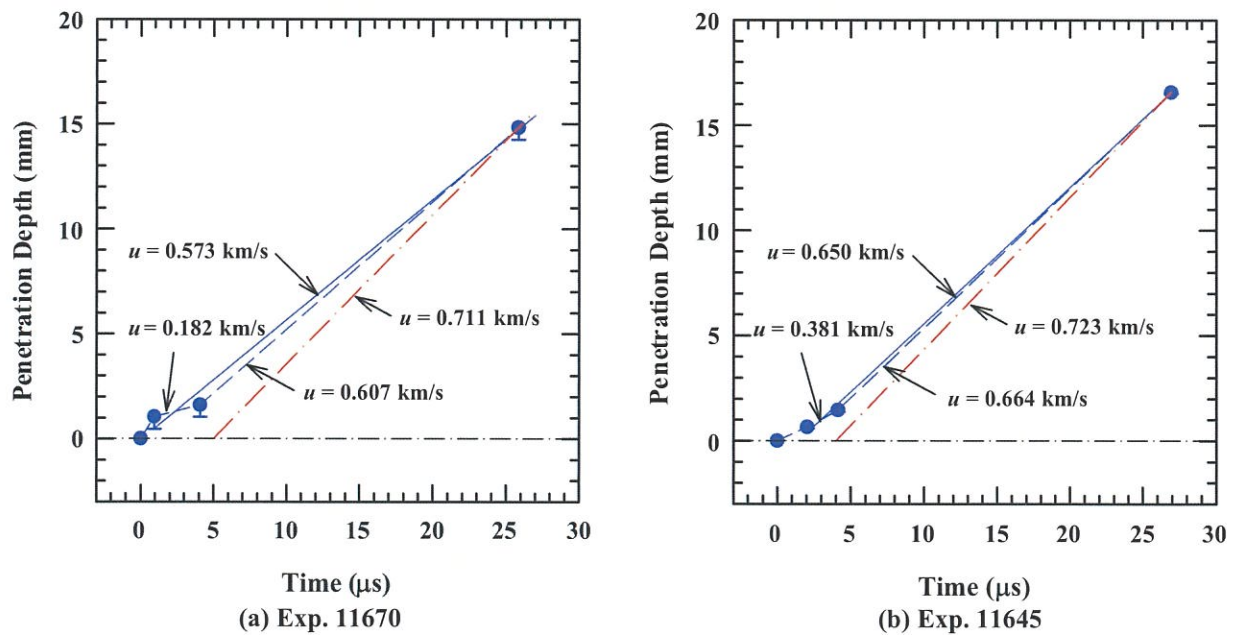


(a) Exp. 11670, $v_p = 1.503$ km/s

(b) Exp. 11645, $v_p = 1.522$ km/s

Figure 31. X-ray images for experiments at $v_p \approx 1.50$ km/s.

The penetration-time data are plotted in Figs. 33 and 34. Each diagram shows three or four data points, which are connected by short dashed lines. The early penetration phase (up to 5 μ s after impact) tends to show a smaller slope (that is, a lower penetration velocity u) than the later penetration phase. Four slopes, i.e., four u 's, are shown in each figure. One slope is calculated from the first two or three data points (but not including 0/0); this u is always the lowest penetration velocity for the experiment. A second u is calculated from a linear regression of all the data. The third u is calculated from the last two data points of the data set. The fourth u (shown as the dashed-dot line) is the penetration velocity, as calculated from the regression fit shown in Fig. 15—Eqn. (9)—based on the impact velocity. The P - t response for this u is calculated to go through the data point at the time of the last X-ray. The various penetration velocities are summarized in Table 6.

Figure 32. X-ray images for experiments at $v_p \approx 2.10$ km/s.Figure 33. Penetration-time data for $v_p \approx 1.5$ km/s; various calculated penetration velocities are shown in the graphs.

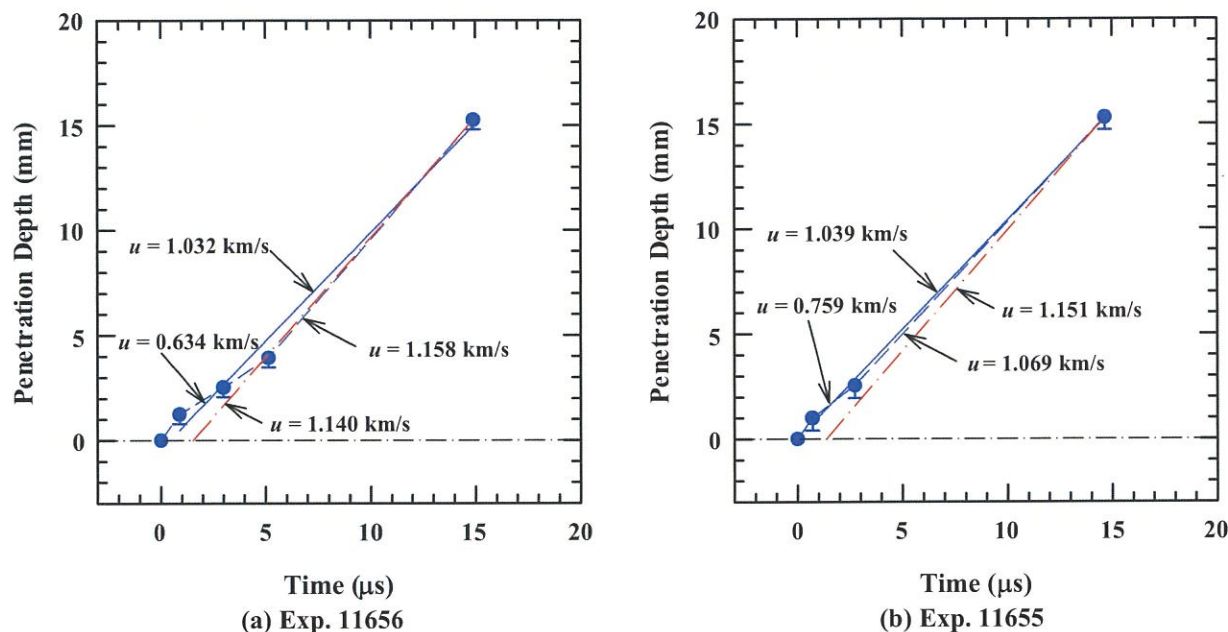


Figure 34. Penetration-time data for $v_p \approx 2.1$ km/s; various calculated penetration velocities are shown in the graphs.

Table 6. Summary of Calculated Penetration Velocities

Exp.	v_p [km/s]	u -First Pts [km/s]	u -Regression [km/s]	u -Last 2 Pts [km/s]	u -Eqn. (9) [km/s]	t_D [μs]
11670	1.503 ± 0.008	0.182	0.573	0.607	0.711	5.0
11645	1.522 ± 0.011	0.381	0.650	0.664	0.723	4.0
11656	2.102 ± 0.006	0.634	1.032	1.158	1.140	1.5
11655	2.117 ± 0.004	0.759	1.039	1.069	1.151	1.4

The penetration velocities calculated from the last two data points (the fifth column in Table 6) are plotted as the “+” sign in Fig. 35 (one of the “+” signs is difficult to see because it lies on top of the hexagon symbol at $v_p \approx 1.5$ km/s). It is seen that the penetration velocities calculated from these last two data points fall within the scatter of the other experimental data. The u 's from column six of Table 6 would fall on the regression line since that was how they were determined.

If there were only late-time P - t data, then an extrapolation of the slope back to 0 penetration depth provides an estimate for a hypothesized dwell time, which is listed in the last column of Table 6. This dwell time is calculated using Eqns. (10-11), with $t_{Cu} = 0$. The P - t response is assumed to be the red dot-dashed line in Figs. 33 and 34. Where it was inferred previously that there might be dwell, even at ~ 2 km/s, it is now seen that there is no dwell for bare SiC at these higher impact velocities; instead, the penetration resistance is very high initially (low penetration velocity), which was not directly observed in earlier experiments because the first X-ray flash was taken after the rod had established a quasi-steady-state penetration rate.

The point 0/0 was not included in the foregoing analyses. Theoretically, penetration starts at time $t = 0$, i.e., the penetration-time curve should start at point 0/0. It has been shown that the

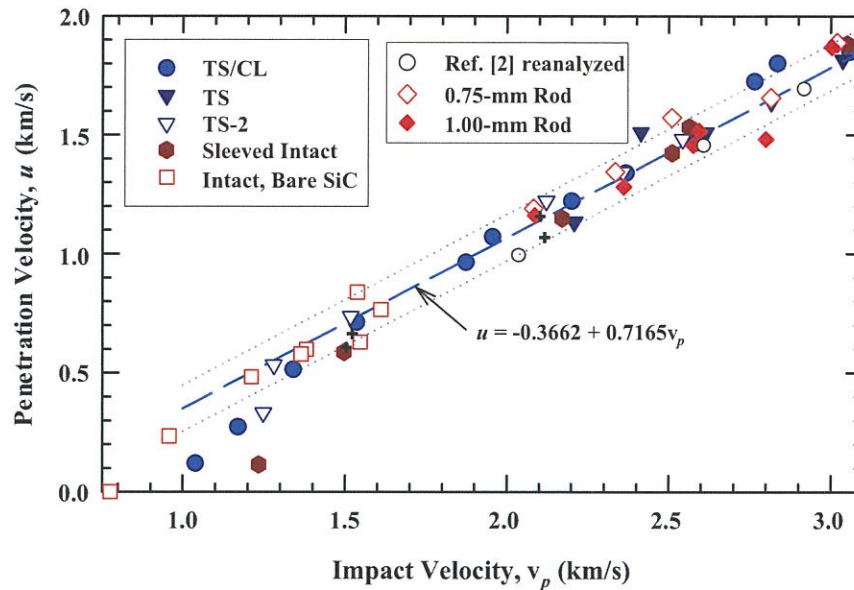


Figure 35. Comparison of penetration velocities calculated from last two points with previous data.

penetration resistance is very high initially (penetration velocity is very low), but examining the data for these experiments, there appears to be an inconsistency with the penetration rate between the point 0/0 and the first flash X-ray that shows penetration. For three of the four experiments (Exps. 11670, 11656, and 11655), the penetration rate from 0/0 to the first X-ray time is very high, and then decreases significantly before increasing again. This behavior does not seem physically plausible. In contrast, the results of Exp. 11645 show, what seems to us, a more logical behavior, namely, the initial penetration velocity is low (i.e., high SiC penetration resistance) and increases relatively rapidly with time to achieve a steady-state value.

Experiments 11670, 11656, and 11655 have some yaw, while Exp. 11645 has very low yaw (Table 4). Yaw influences the measured penetration depths because penetration depth is measured from the rear of the ceramic (see Fig. 9). A good estimate for the effect of yaw on the penetration depth can be obtained by rotating the ceramic cylinder about its center of gravity. The projected length of the ceramic then is longer than without yaw by the product of the ceramic radius and the sine of the yaw angle. Yaw angles of 3° can result in an error of about 0.5 mm, i.e., the penetration depth of the rod seems deeper than it really is. The vertical lines shown below the data points in Figs. 33 and 34 denote the corrections to the position data due to yaw. These corrections seem to account for most of the “anomalously” high penetration velocity using the 0/0 point. Additionally, yaw affects the estimated time of impact. Given these uncertainties, the analysis does not include the 0/0 point. Thus, in addition to the high penetration resistance at very early times after impact, the effect of yaw can affect interpretation of the 0/0 point. However, since the penetration velocity is the slope of the P - t response, u is not affected by the yaw measurement bias so long as the 0/0 point is not included. This provides an additional reason for the decision that was made in Section 3.4 to not include the 0/0 point in estimating the penetration velocity as a function of impact velocity, Figs. 14 and 15 (and Fig. 35).

6.0 Conclusions

The experiments with scaled gold rods impacting bare SiC cylinders, with impact velocities between 2 km/s and 3 km/s, provided several interesting results and helped to resolve some open questions concerning earlier test series done with sleeved SiC ceramics. The most important findings are as follow.

- A scaling effect of the penetration velocity for different rod diameters, within data scatter, is not observed.
- A thorough examination of the analysis process used to determine the penetration (and rod consumption) rate after impact revealed that the first test series done in 2004 [2] used a different method of regression analysis than all subsequent test series. The Ref. [2] regression analysis forced the regression to go through the 0/0 point.
- The sleeved experiments [3-4], as well as later experiments [5-6], did not include the 0/0 point in the analysis. Thus, due to the different regression methods, results from 2004 are not directly comparable to later experiments.
- When the 2004 data are analyzed similarly to the more recent data, the “old” data *are consistent* with the more recent data. They align the different findings of earlier reports and combine them into a coherent picture.
- There are no differences, within data scatter, for the penetration velocity of intact (bare or sleeved) ceramic, predamaged (thermally shocked, TS) ceramic, or *in-situ* comminuted (thermally shock with load/reload cycles, TS/CL) ceramic.
- A regression analysis was performed on the complete set of data to generate an updated u versus v_p relationship for the penetration velocity of Au rods into SiC-N:

$$u = -0.3662 + 0.7165v_p \quad \sim 1.2 \text{ km/s} < v_p < 6.25 \text{ km/s}$$

with a standard deviation of 65.1 m/s. Thus, for several experiments at nominally the same impact velocity, there can be a fairly large spread in the expected penetration velocity.

Impact experiments were conducted to determine dwell-to-penetration transition velocities for unconfined SiC ceramic impacting long gold rods. The ceramics had a relatively thin copper buffer on the front with varying geometries. The significant results from these experiments are as follow.

- The experimental results show that for a 1-mm diameter rod and a buffer height of 2 mm ($h/D_p = 2.0$), transition from sustained dwell to penetration occurred at 1570 ± 16 m/s. The transition zone from complete dwell to penetration is very narrow, i.e., only 32 m/s.
- When the h/D_p ratio is increased to 4.0 (a 4-mm thick buffer), the transition velocity decreases ~ 30 m/s to 1540 ± 18 m/s. There is a

slight indication that the full cover plate degrades performance slightly more than a small diameter buffer. It appears that the cover plate influences the flow of rod material at the buffer-ceramic interface.

- When the rod diameter is decreased to 0.75 mm, with $h/D_p = 4.0$ (all with the cruciform buffer), the transition velocity increased to 1605 ± 18 m/s. Thus, at these relatively small rod dimensions, there appears to be a size effect for the dwell-penetration transition velocity. An extrapolation, though, to large rod diameters cannot be made from these experiments.

Four experiments, two each at nominal impact velocities of 1.5 km/s and 2.1 km/s, were conducted to investigate penetration at very early times after impact. These impact velocities are well above the dwell-penetration transition velocity for bare SiC-N (~ 825 m/s). The important observations are as follow.

- The penetration velocity is quite low immediately after impact. After a few microseconds, the penetration velocity increases significantly.
- If only late time ($> \sim 5 \mu\text{s}$) data are used to estimate the penetration velocity, the intercept of the P - t regression line with the time-axis is a few microseconds after time "0". This was interpreted as a short dwell period in previous analyses [8,10].
- It was shown in these experiments that the rod does not dwell at impact velocities above the dwell-transition velocity. The apparent short dwell period that was hypothesized previously is due instead to a high penetration resistance during the first few microseconds after impact.
- Because of the high penetration resistance immediately after impact, the data point 0/0 should not be used in regression analyses to determine the penetration velocity (and erosion rate) for relatively long penetration times.
- Yaw of the ceramic cylinder induces a measurement bias in the depth of penetration (since the analysis procedure uses the back of the ceramic as a fiducial). For the experiments here, 3° of yaw could induce 0.5 mm error in the depth of penetration. However, since the penetration velocity is the slope of the P - t response, u is not affected by this bias.

It is hypothesized that the high penetration resistance observed at very early times after impact is due to the transition of initially intact ceramic to damaged (comminuted) ceramic. A damage front propagates away from the projectile and this damage front propagates faster than the rod penetrates. Thus, after the few microseconds, the rod is penetrating failed (comminuted) ceramic. This phenomenology is consistent with the initially large penetration resistance during the first few microseconds after impact, and the observation that the steady-state penetration velocity for intact, predamaged (TS), and *in-situ* damaged (TS/CL) ceramic are the same.

The results of these experiments, combined with the data from previous sets of experiments, provide a coherent and fairly extensive database for the penetration resistance (dwell, the dwell-

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penetration transition velocity, and no-dwell/post-dwell penetration velocity) as a function of impact velocity for an armor ceramic material, specifically, SiC-N. The impact velocities cover a very large range, from subordnance velocities (< 800 m/s) to hypervelocities (6.2 km/s). The data also include the effect of using a buffer material on the dwell-penetration transition velocity and effects of buffer geometry.

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7.0 Acknowledgements

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Appendix A: Data for Bare Intact Ceramic Penetration Experiments

The appendix contains the position-time data of the rod into the ceramic as well as the X-ray images for each of the experiments. Table A-1 provides the times of the X-ray flashes. Time zero is impact on the surface of the ceramic. Table A-2 gives the depth of penetration and the rod length at the corresponding times after impact. Graphical representations of the data as measured from the X-rays are presented for each experiment.

Table A-1. X-ray Times (μ s) Before/After Impact for Bare Intact Ceramic Penetration Experiments

Exp	1	2	3	4	5
11546	-4.303	5.618	12.711	24.753	26.606
11547	-4.857	5.124	12.084	19.187	26.182
11549	-4.700	4.190	10.225	15.255	20.147
11550	-4.260	4.663	10.648	15.832	20.630
11551	-4.121	3.899	8.929	13.918	18.873
11552	-4.022	3.799	8.872	14.049	19.027
11554	-2.924	4.894	8.979	14.131	18.933
11555	-3.556	4.317	8.580	13.448	18.407
11556	-3.749	4.270	8.304	13.392	18.305
11557	-4.205	3.675	7.809	11.812	15.793
11558	-2.770	4.995	10.296	15.079	21.146

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Table A-2. Position-Time Data for Bare Intact SiC-N Experiments

	<i>t</i> after impact [μ s]	Pen. Depth [mm]	Rod Length [mm]		<i>t</i> after impact [μ s]	Pen. Depth [mm]	Rod Length [mm]
11546	26.61	28.32	42.54	11554	18.93	29.83	26.52
	24.75	25.93	44.31		14.13	22.09	31.80
	12.71	11.55	54.29		8.98	13.54	38.10
	5.62	4.03	62.13		4.89	6.58	42.57
	0.00	0.00	70.00		0.00	0.00	49.82
11547	26.18	30.02	25.34	11555	18.41	26.77	25.46
	19.19	21.25	31.17		13.45	19.58	32.03
	12.08	13.41	37.69		8.58	12.57	38.48
	5.12	4.73	43.10		4.32	5.81	43.54
	0.00	0.00	49.76		0.00	0.00	50.21
11549	20.15	24.89	47.24	11556	18.31	33.66	27.93
	15.25	18.31	52.23		13.39	24.41	33.42
	10.22	12.49	57.87		8.30	14.71	39.22
	4.19	4.23	63.94		4.27	7.19	43.95
	0.00	0.00	70.10		0.00	0.00	49.82
11550	20.63	24.81	26.44	11557	15.79	28.52	31.10
	15.83	18.53	30.92		11.81	21.25	35.76
	10.65	11.03	36.10		7.81	13.71	40.23
	4.66	3.49	42.24		3.68	5.89	44.56
	0.00	0.00	49.86		0.00	0.00	50.06
11551	18.87	26.54	48.22	11558	21.15	30.79	27.90
	13.92	19.04	52.99		15.08	22.23	33.45
	8.93	11.87	58.43		10.30	14.04	37.99
	3.90	4.68	64.56		4.99	5.57	42.67
	0.00	0.00	70.18		0.00	0.00	49.96
11552	19.03	27.82	28.70				
	14.05	20.42	34.00				
	8.87	12.41	38.83				
	3.80	4.76	45.13				
	0.00	0.00	50.22				

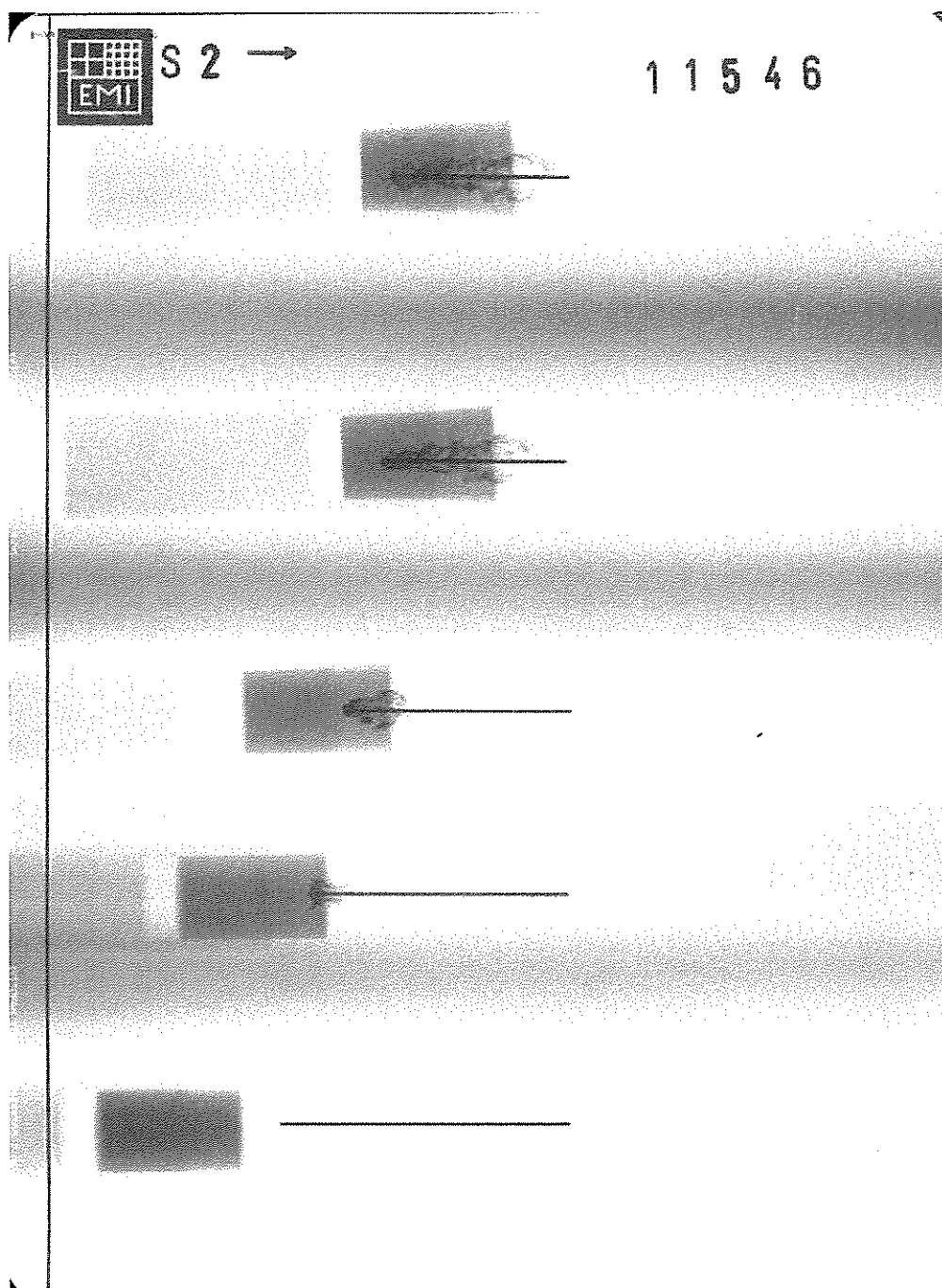


Figure A-1. X-ray picture for Exp. 11546: $v_p = 2.086$ km/s.

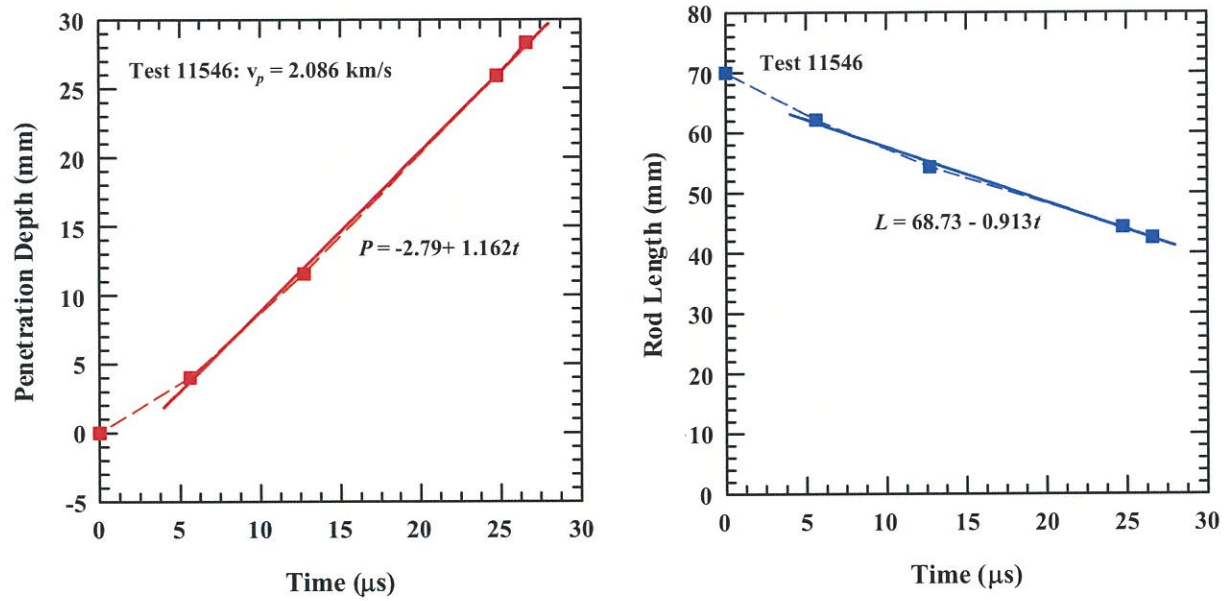


Figure A-2. Penetration vs. time and rod length vs. time for Exp. 11546: $v_p = 2.086$ km/s.

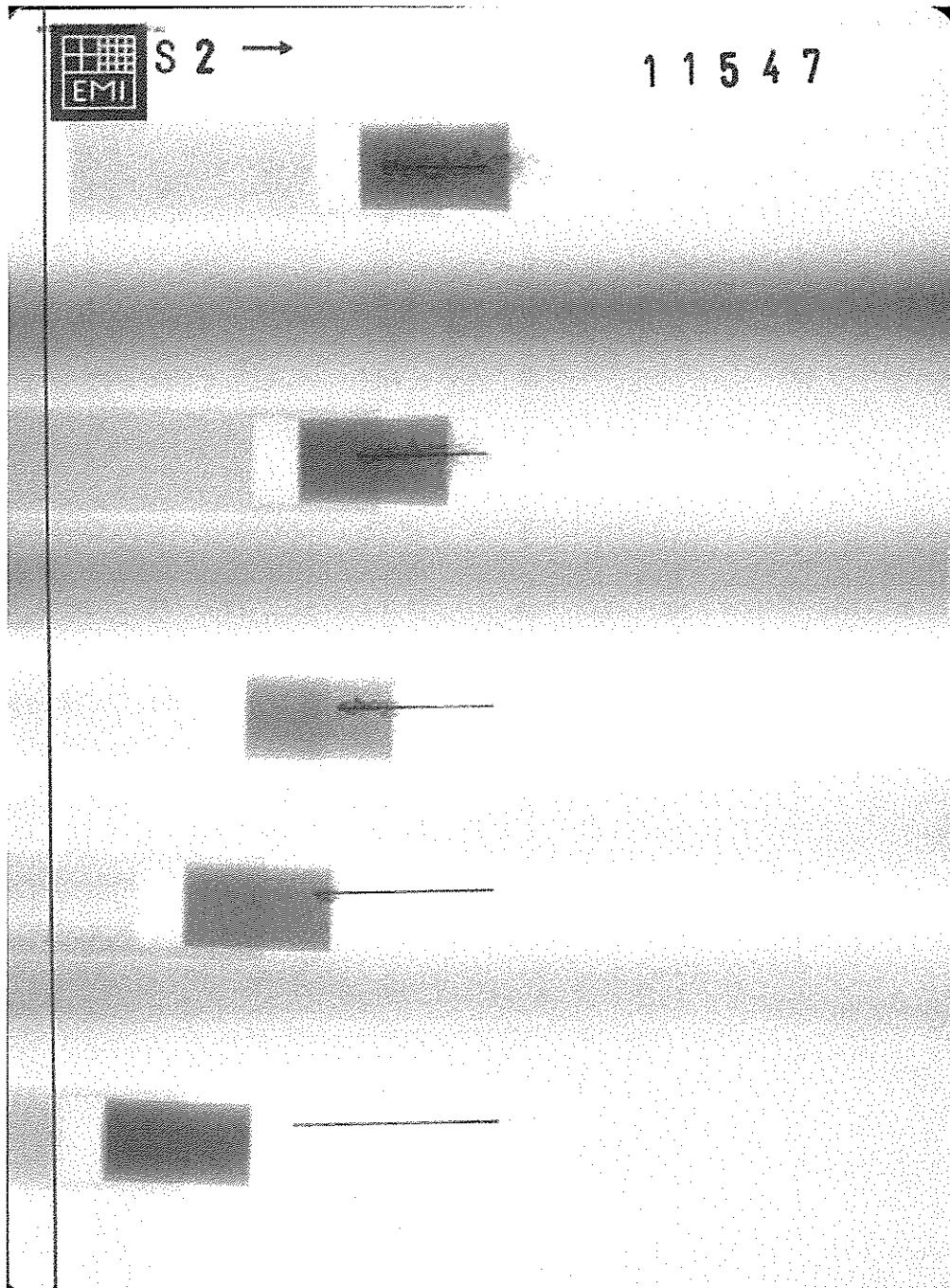


Figure A-3. X-ray picture for Exp. 11547: $v_p = 2.082$ km/s.

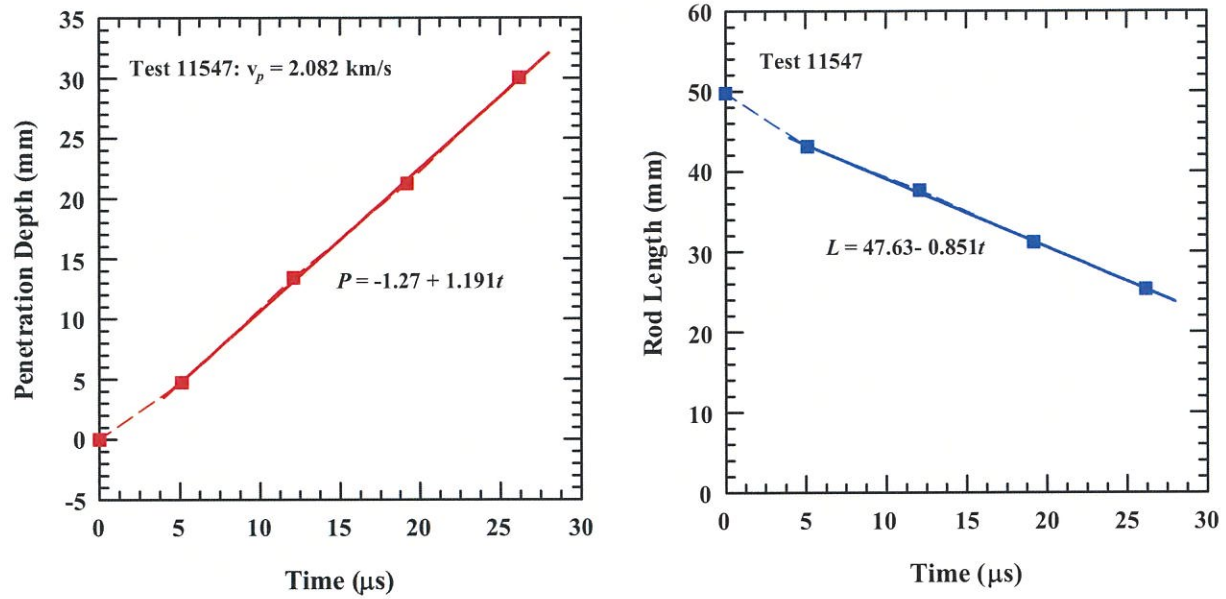


Figure A-4. Penetration vs. time and rod length vs. time for Exp. 11547: $v_p = 2.082$ km/s.

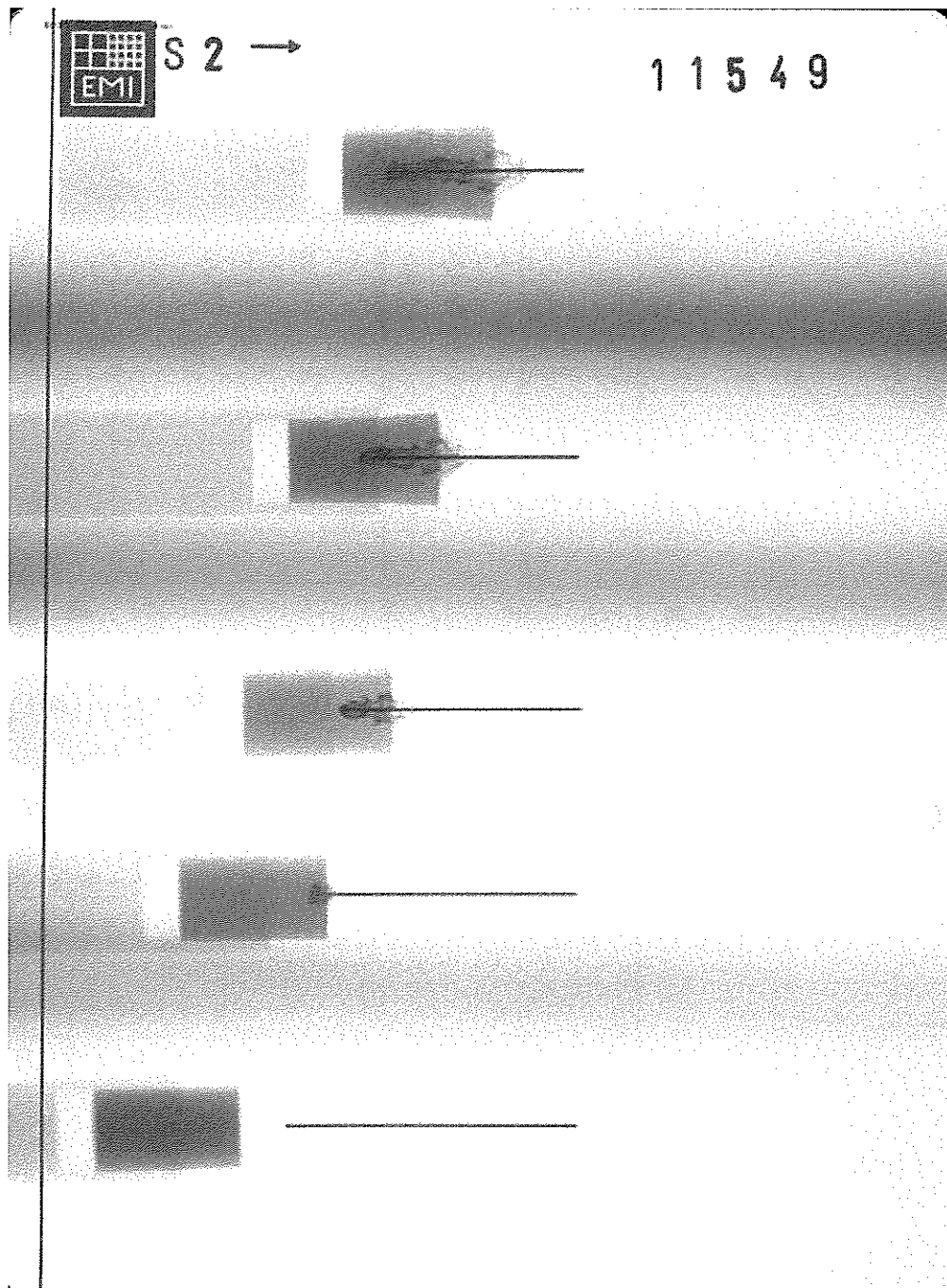


Figure A-5. X-ray picture for Exp. 11549: $v_p = 2.360$ m/s.

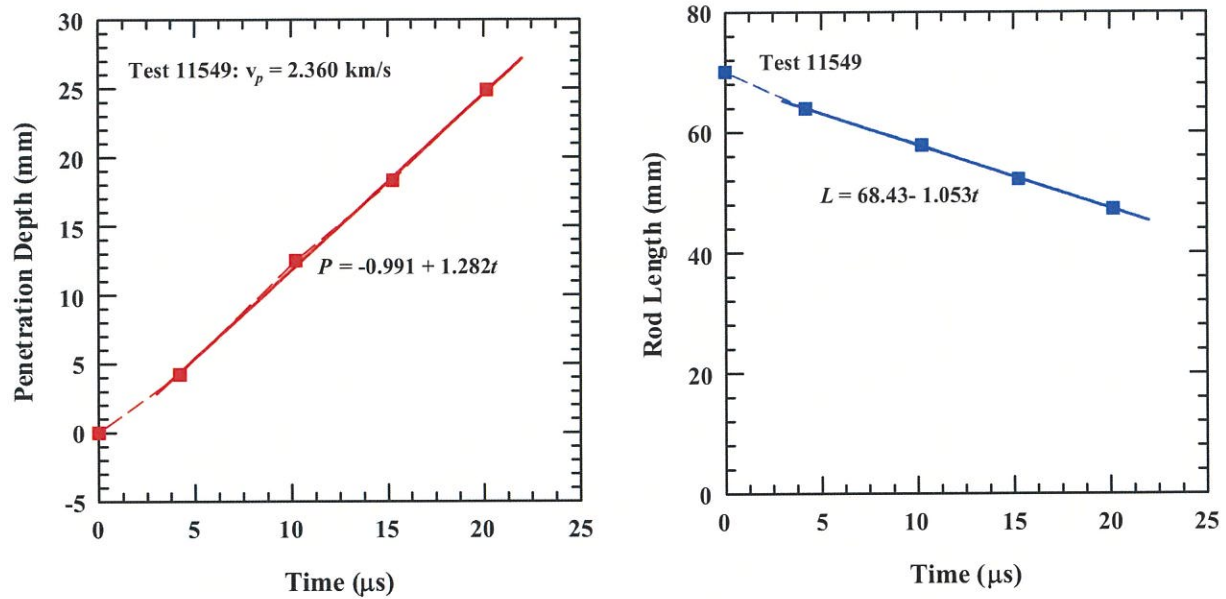


Figure A-6. Penetration vs. time and rod length vs. time for Exp. 11549: $v_p = 2.360$ km/s.

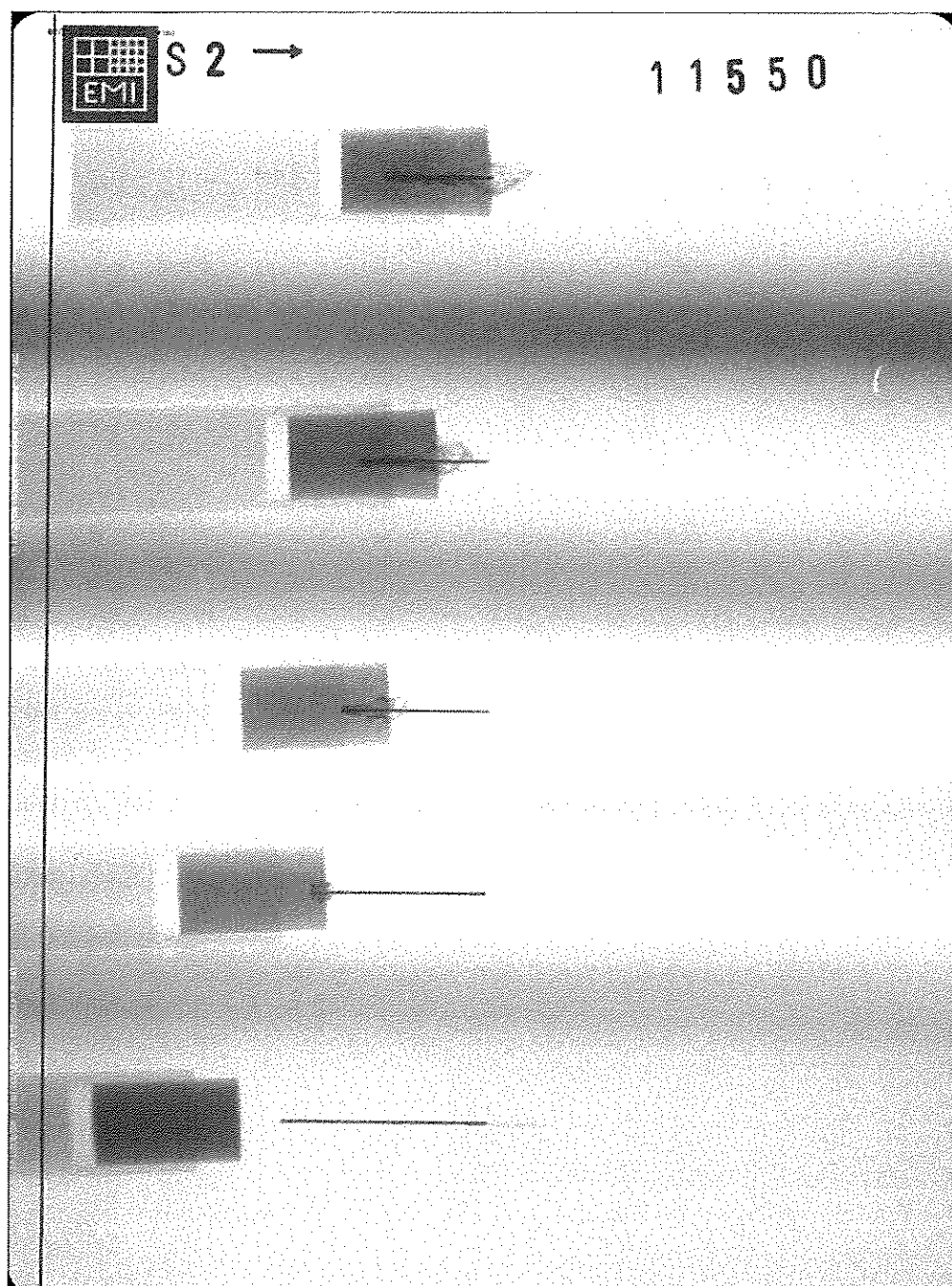


Figure A-7. X-ray picture for Exp. 11550: $v_p = 2.334$ km/s.

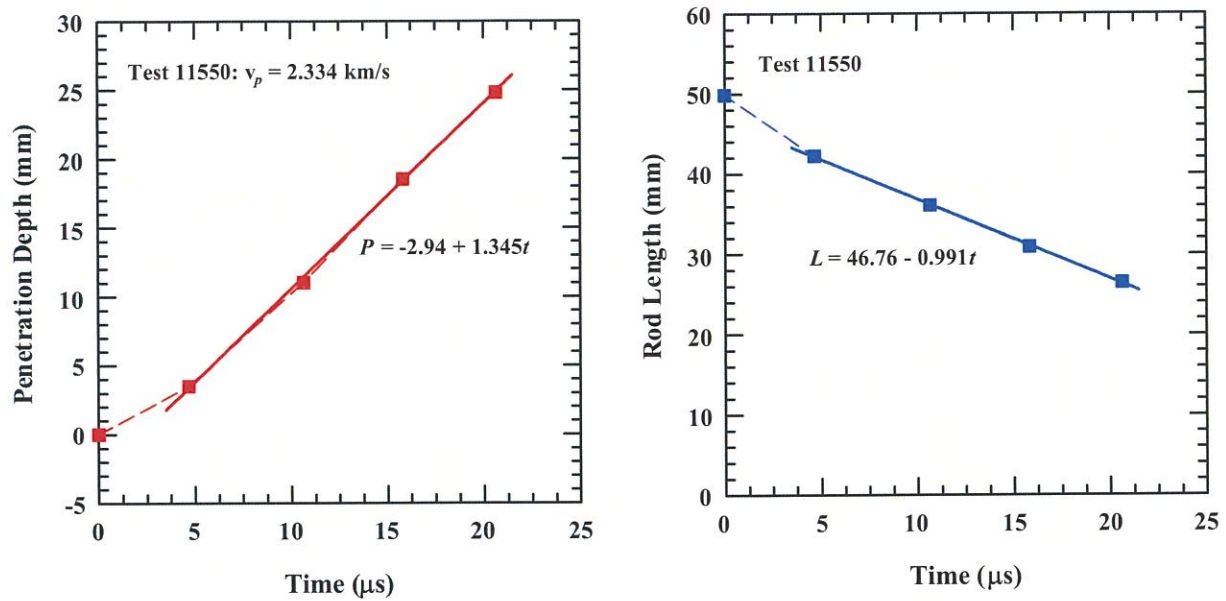


Figure A-8. Penetration vs. time and rod length vs. time for Exp. 11550: $v_p = 2.334$ km/s.

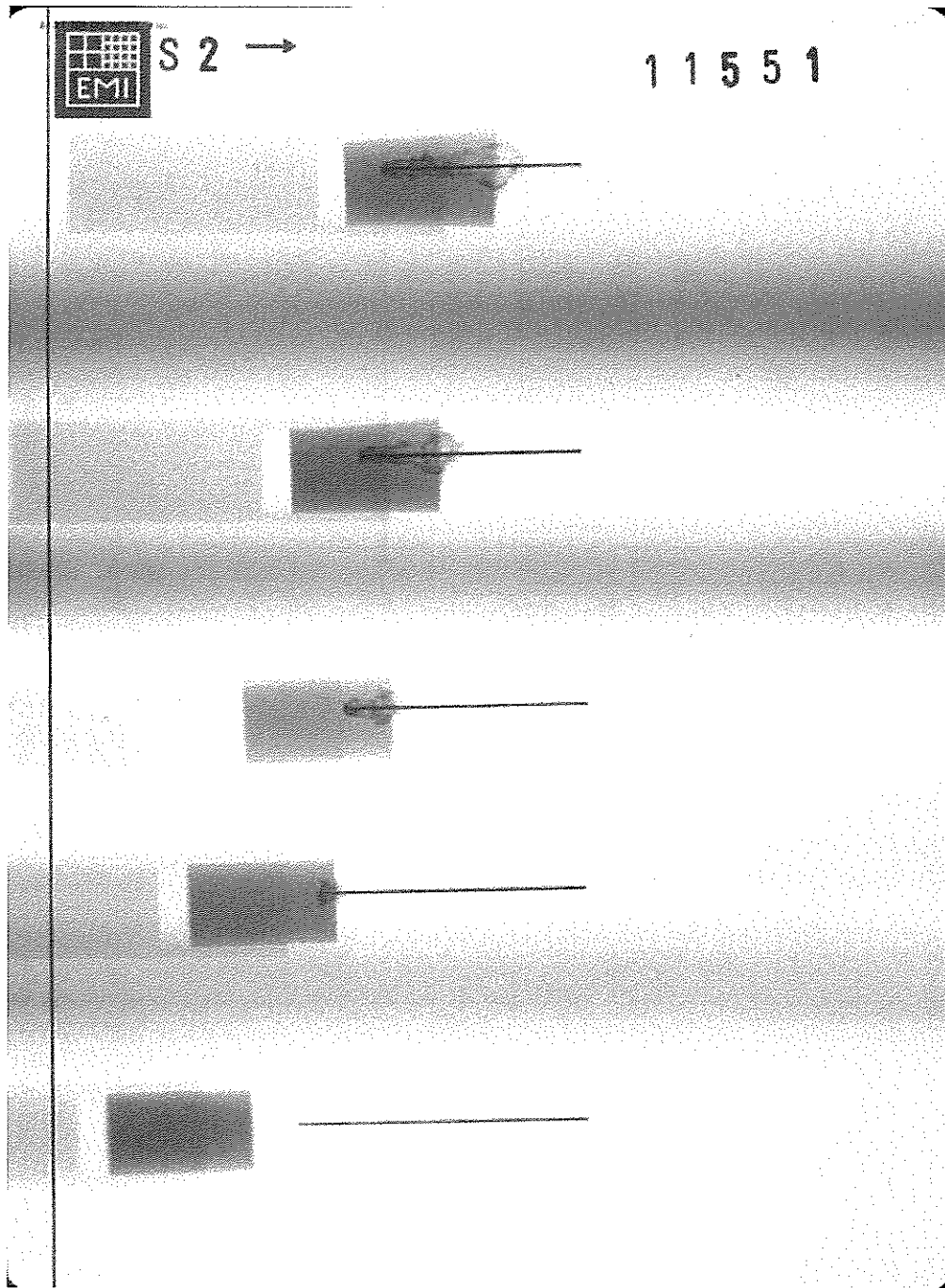


Figure A-9. X-ray picture for Exp. 11551: $v_p = 2.576$ km/s.

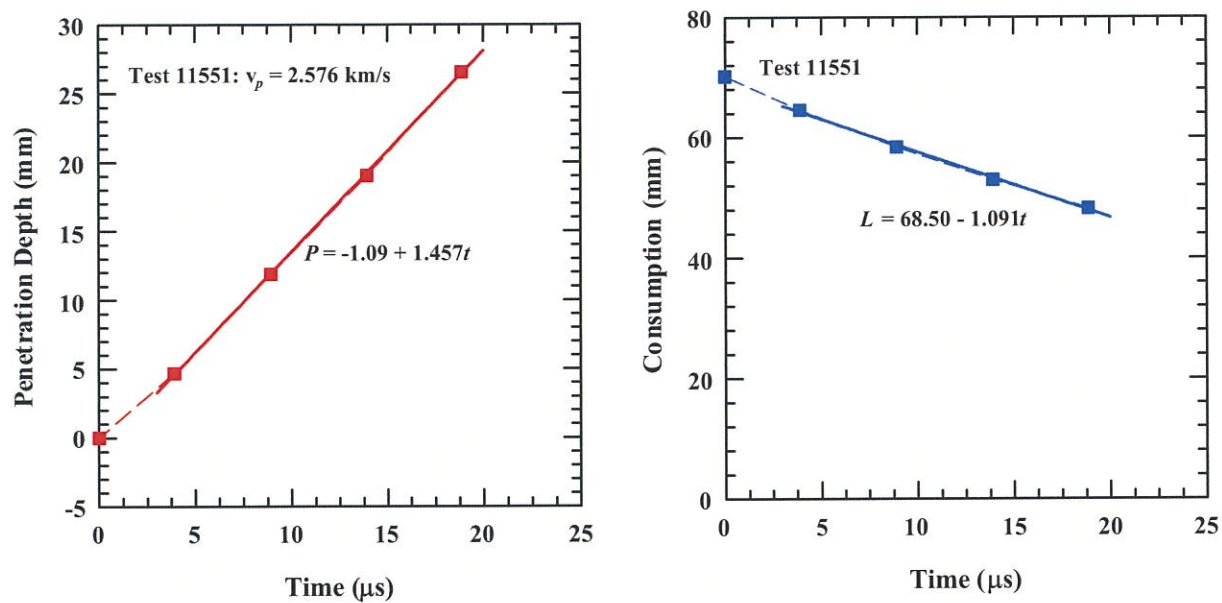


Figure A-10. Penetration vs. time and rod length vs. time for Exp. 11551: $v_p = 2.576$ km/s.

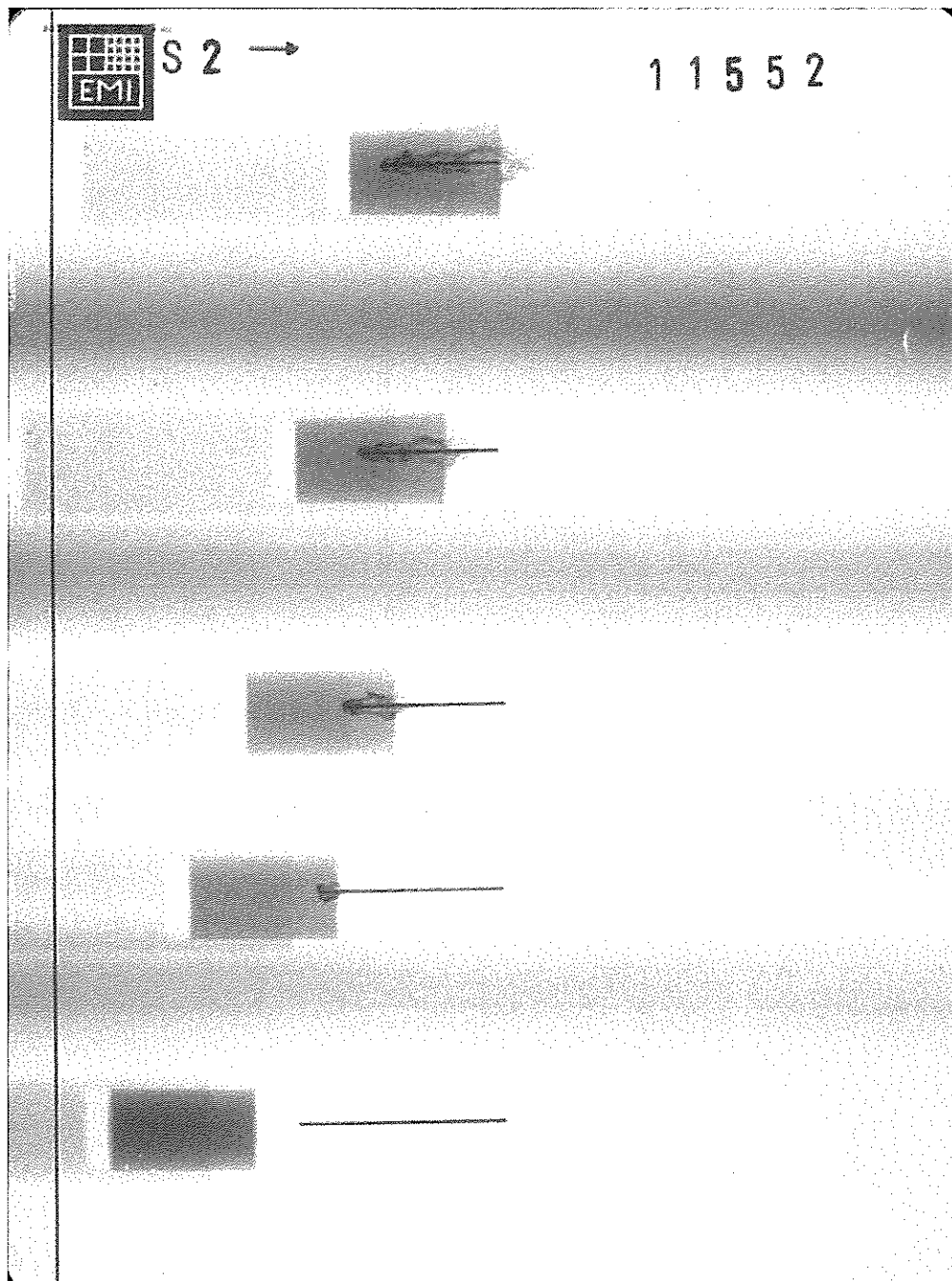


Figure A-11. X-ray picture for Exp. 11552: $v_p = 2.594$ km/s.

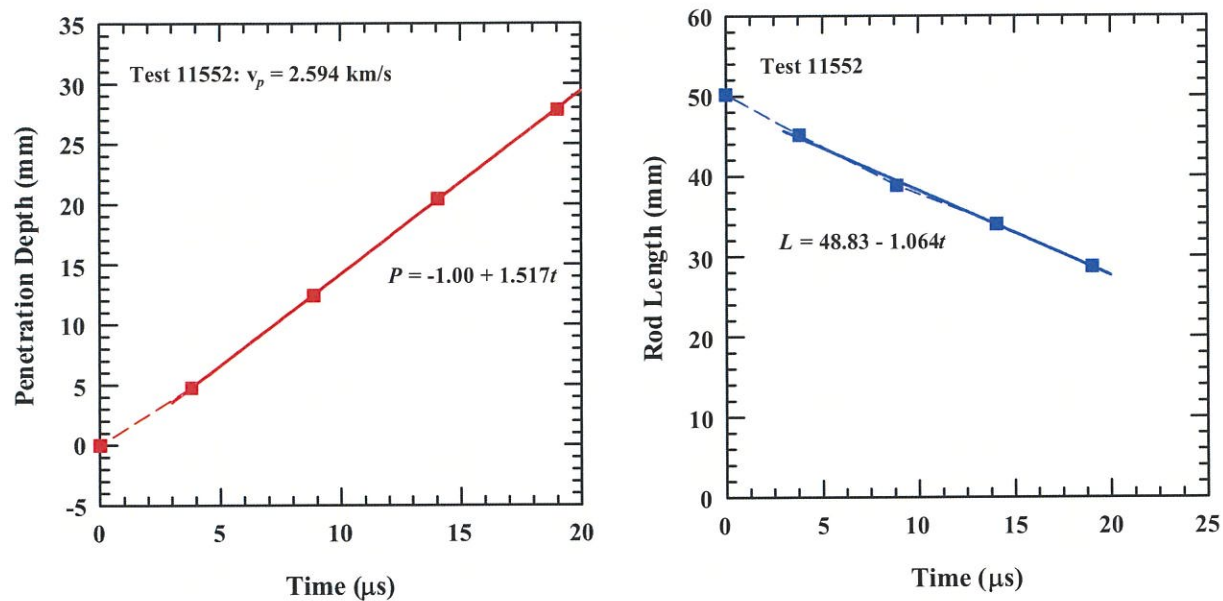


Figure A-12. Penetration vs. time and rod length vs. time for Exp. 11552: $v_p = 2.594$ km/s.

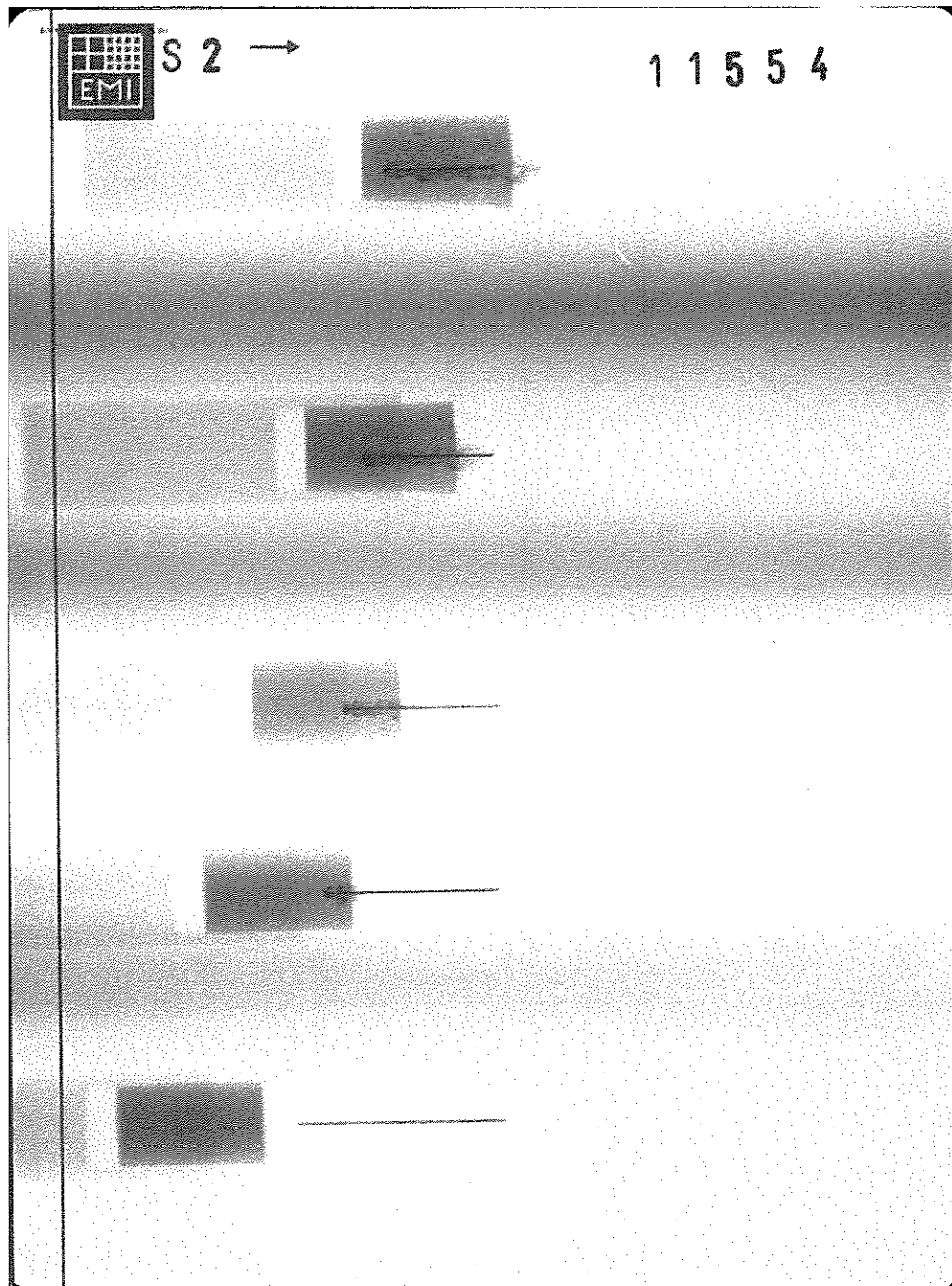


Figure A-13. X-ray picture for Exp. 11554: $v_p = 2.815$ km/s.

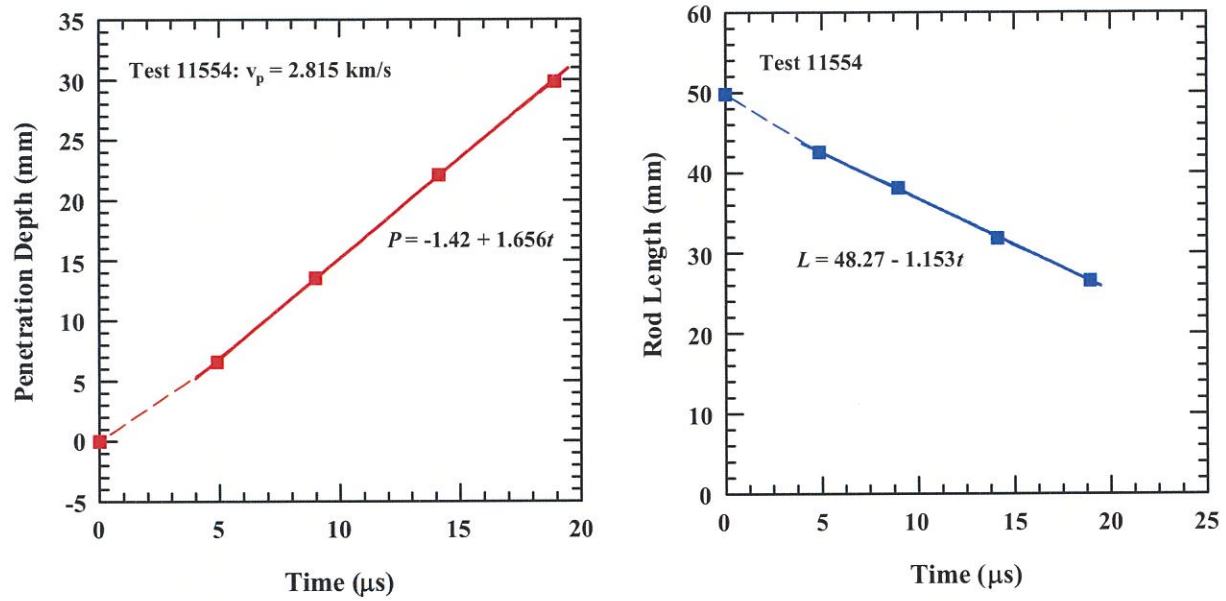


Figure A-14. Penetration vs. time and rod length vs. time for Exp. 11554: $v_p = 2.815 \text{ km/s}$.



Figure A-15. X-ray picture for Exp. 11555: $v_p = 2.800$ km/s.

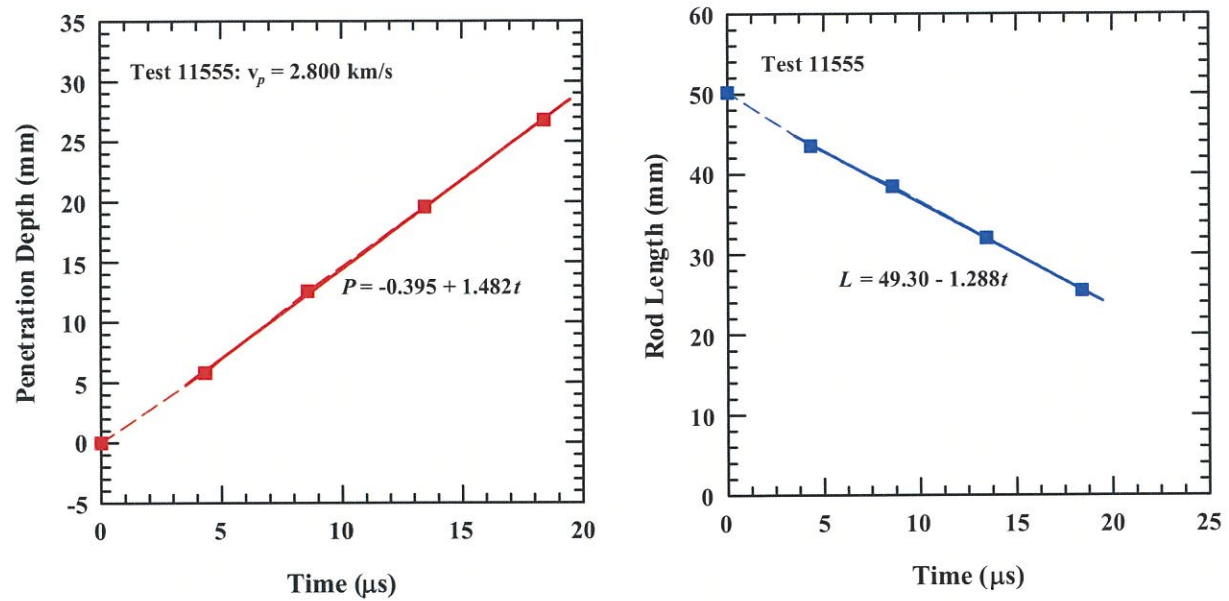


Figure A-16. Penetration vs. time and rod length vs. time for Exp. 11555: $v_p = 2.800$ km/s.

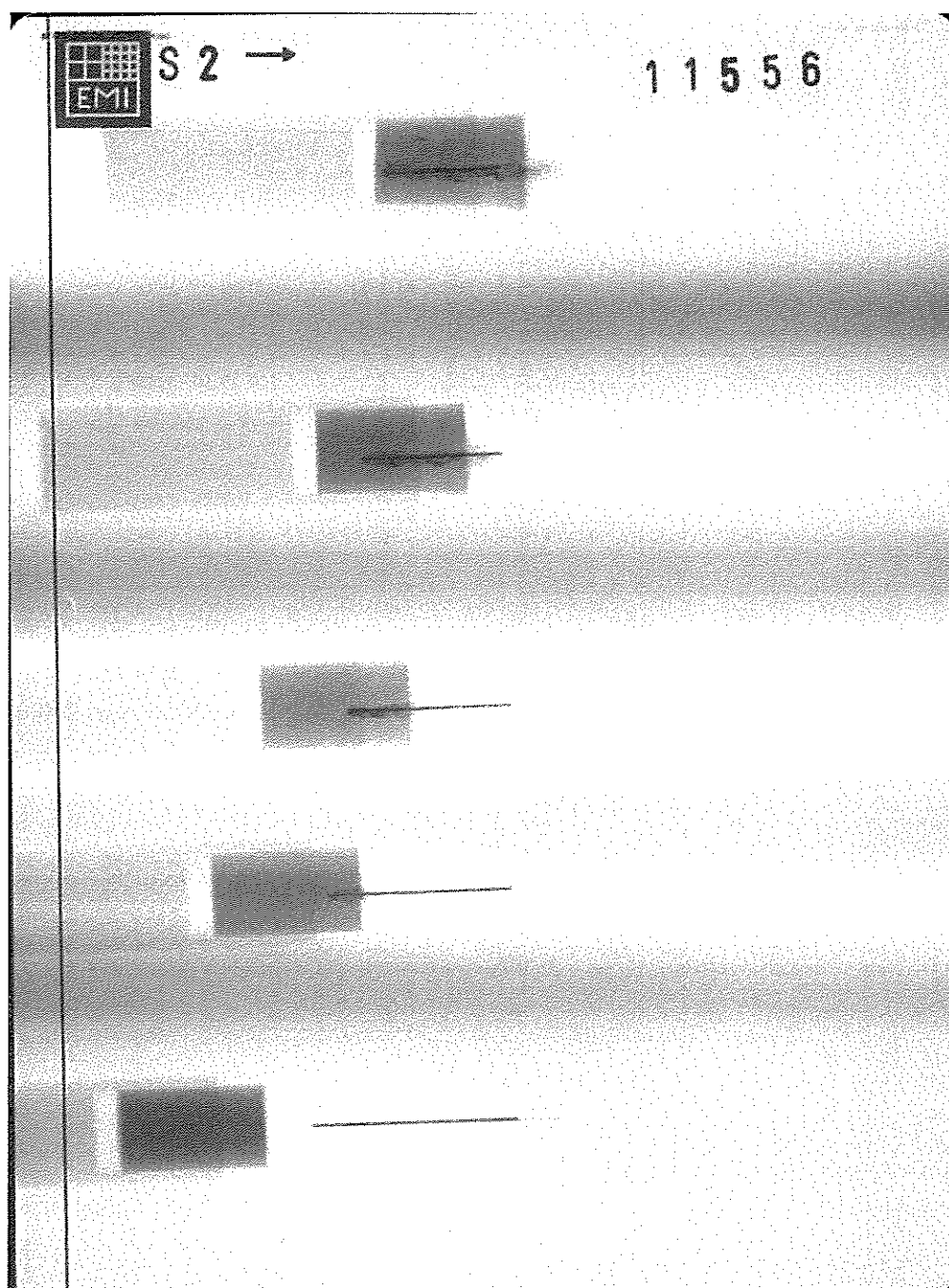


Figure A-17. X-ray picture for Exp. 11556: $v_p = 3.020$ km/s.

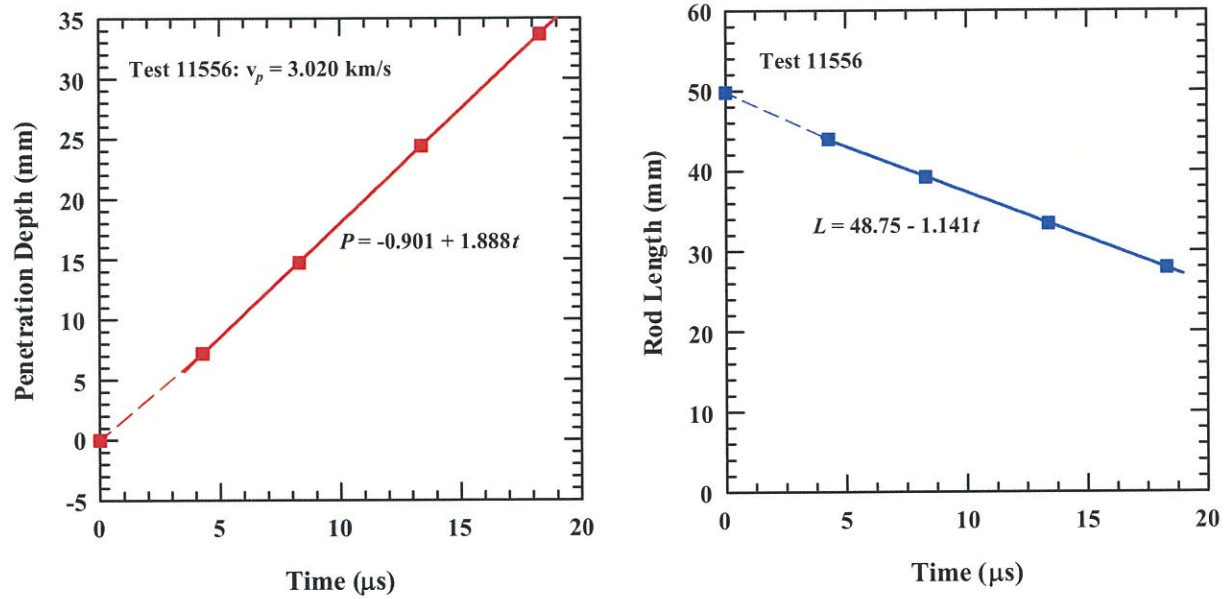


Figure A-18. Penetration vs. time and rod length vs. time for Exp. 11556: $v_p = 3.020$ km/s.

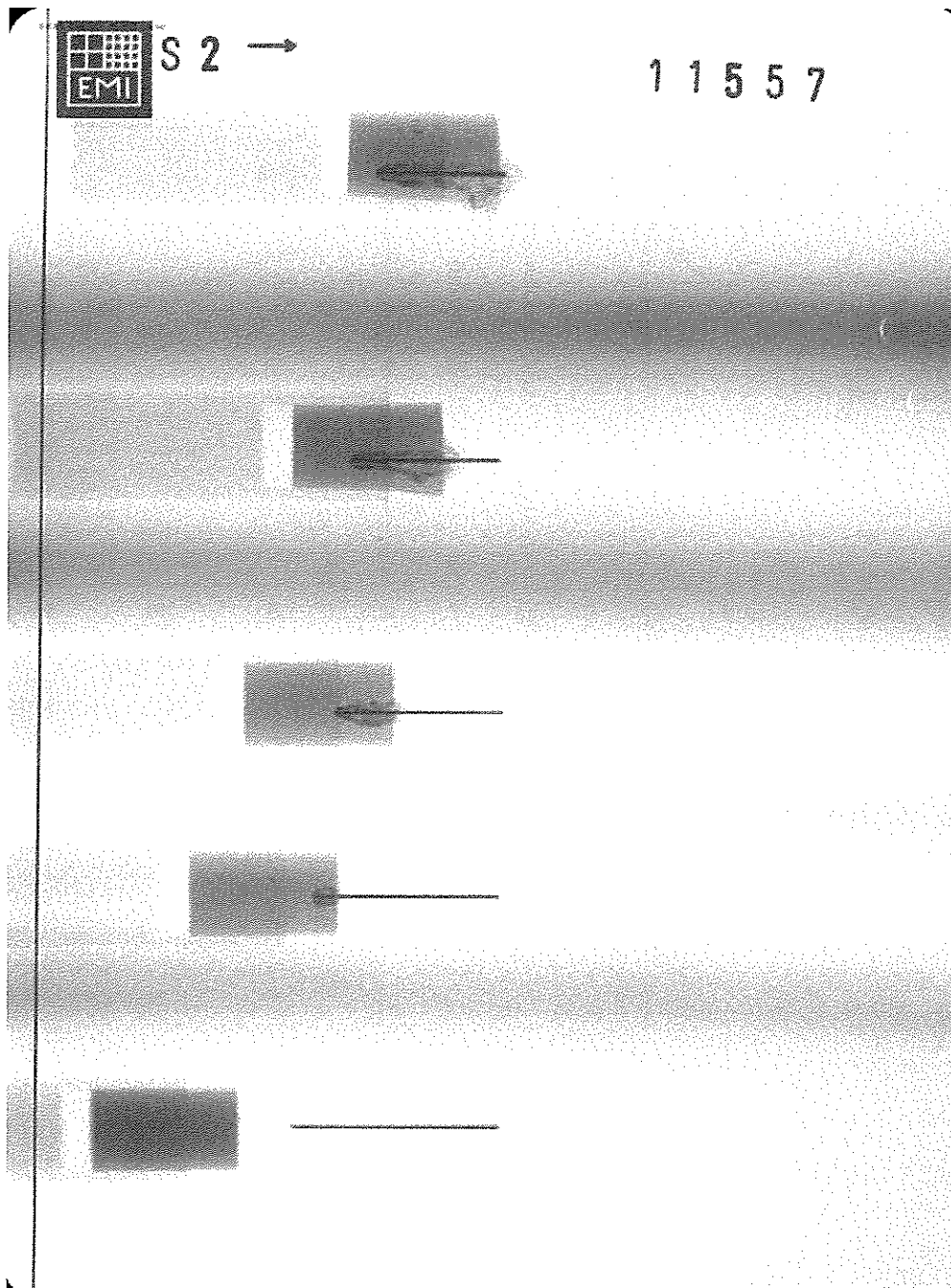


Figure A-19. X-ray picture for Exp. 11557: $v_p = 3.003$ km/s.

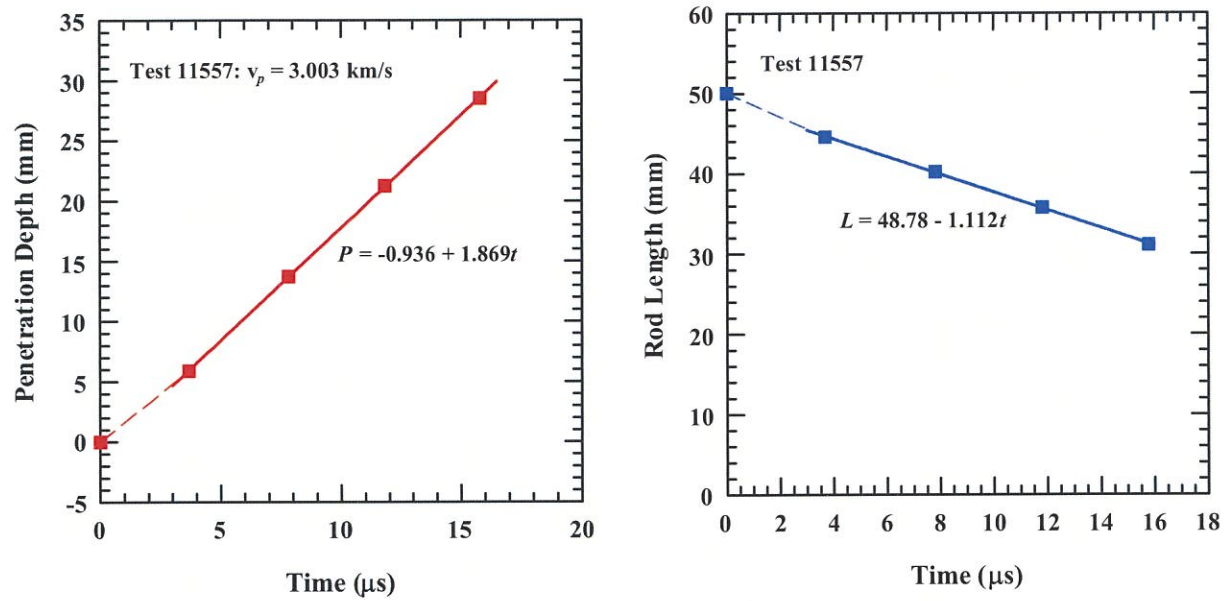


Figure A-20. Penetration vs. time and rod length vs. time for Exp. 11557: $v_p = 3.003$ km/s.

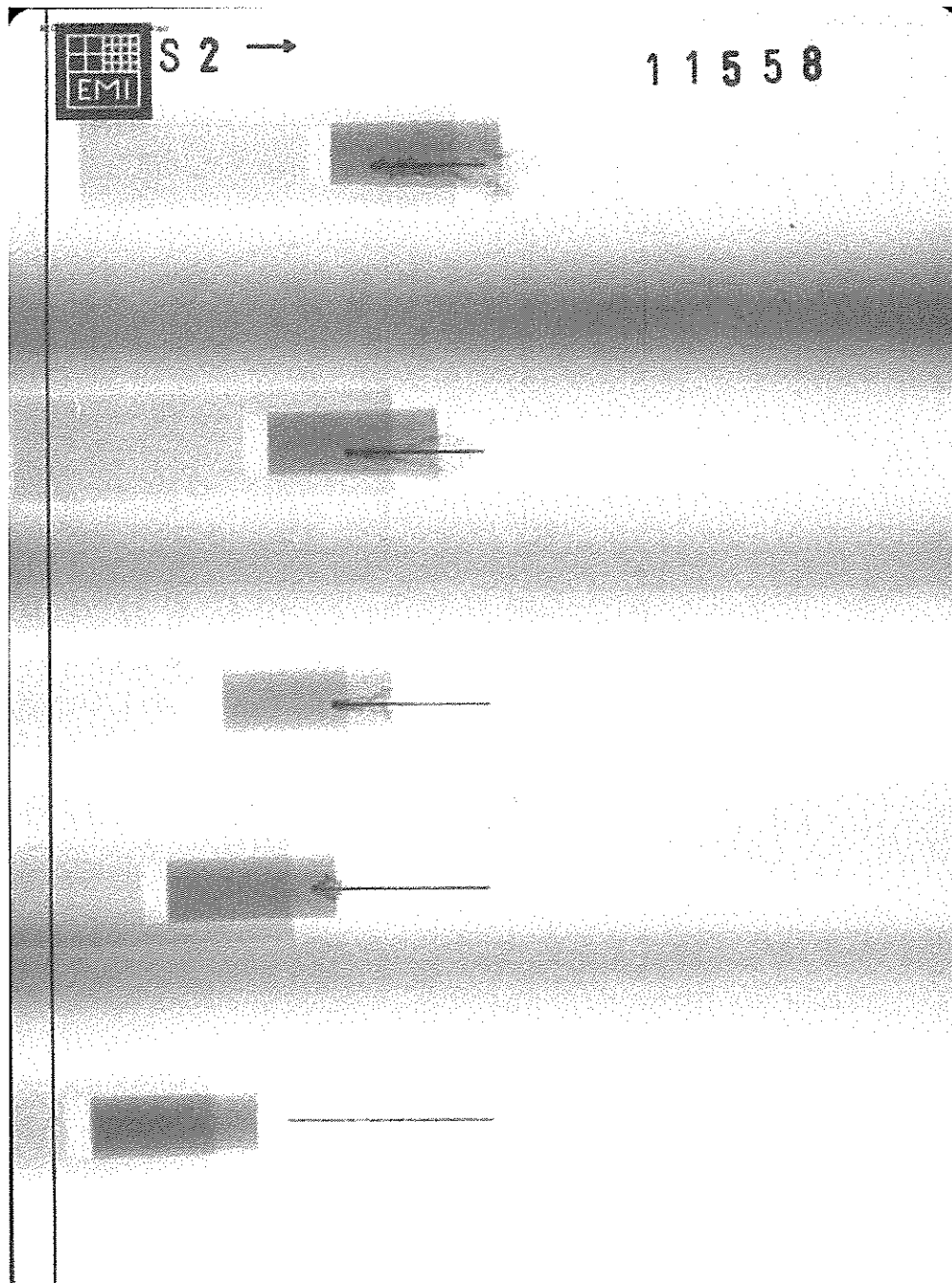


Figure A-21. X-ray picture for Exp. 11558: 15-mm Ø SiC-N from 2002, $v_p = 2.510$ km/s.

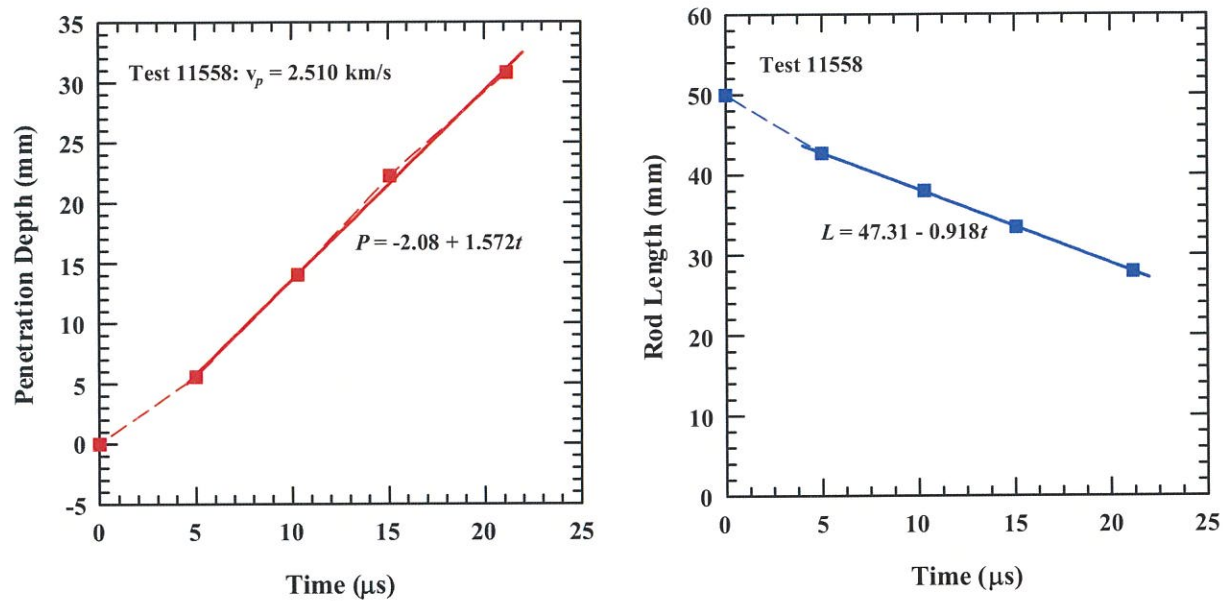


Figure A-22. Penetration vs. time and rod length vs. time for Exp. 11558: $v_p = 2.510$ km/s.

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Appendix B: Data for Rod Size and Buffer Experiments

The appendix contains the position-time data of the rod into the ceramic as well as the X-ray images for each of the experiments. Table B-1 provides the time of the X-ray flashes. Time zero is impact on the surface of the cover plate. The position "0" is the top surface of the ceramic (the cover plate/ceramic interface). Thus, the surface of the cover plate has a negative spatial coordinate. Table B-2 gives the depth of penetration and rod lengths at the corresponding times after impact. Graphical representations of the data as measured from the X-rays are presented for each experiment.

Table B-1. X-ray Times (μ s) for Rod Size and Buffer Experiments

Exp./frame	1	2	3	4	5
11624	-12.285	3.605	18.613	33.834	48.483
11625	-11.206	8.640	23.811	38.960	53.680
11637	-8.032	12.051	27.116	42.243	57.009
11638	-6.779	13.148	28.299	43.402	58.164
11639	-8.637	11.296	26.399	41.582	56.347
11640	-7.311	12.696	27.825	42.981	57.712
11641	-8.489	11.497	26.583	41.732	56.503
11643	-5.521	14.507	29.526	44.630	59.452
11671	-7.901	12.146	27.213	42.328	57.041
11672	-9.606	10.362	25.271	40.308	55.192
11673	-7.933	12.054	27.052	41.956	56.955
11674	-9.387	10.587	25.579	40.649	55.572
11675	-9.473	10.660	25.537	40.621	55.536
11676	-9.707	10.426	25.303	40.387	55.307
11677	-8.548	11.567	21.464	31.544	46.468
11678	-7.898	12.139	27.067	42.115	57.007
11679	-8.658	11.370	21.412	31.374	46.298
11680	-5.813	14.340	29.269	44.356	8.222

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Table B-2. Position-Time Data for Size Effect and Buffer Experiments

	<i>t</i> after imp. [μs]	Pen. depth [mm]	Rod length [mm]		<i>t</i> after imp. [μs]	Pen. depth [mm]	Rod length [mm]
CP2 buffer				CP4 buffer			
11625	53.68	-	0.00	11624	48.48	-	0.00
	38.96	-	15.17		33.83	-	25.60
	23.81	-	36.57		18.61	-	47.95
	8.64	-	58.60		3.60	-	0.13
	0.00	-2.02	70.01		0.00	-4.05	70.04
11638	58.16	-	-0.25	11639	56.35	-	-0.08
	43.40	-	-0.13		41.58	-	12.37
	28.30	-	28.51		26.40	-	34.69
	13.15	-	51.73		11.30	-	57.10
	0.00	-2.07	70.01		0.00	-4.06	70.11
11640	57.71	34.83	15.77	11637	57.01	25.25	12.42
	42.98	21.83	25.56		42.24	12.67	21.95
	27.82	10.40	38.33		27.12	2.92	35.21
	12.70	3.94	55.92		12.05	0.43	55.61
	0.00	-2.06	70.10		0.00	-4.06	70.01
B2 buffer				11641	56.50	-	-0.10
11678	57.01	-	0.01		41.73	-	-0.07
	42.12	-	7.58		26.58	-	33.61
	27.07	-	30.25		11.50	-	56.53
	12.14	-	53.10		0.00	-4.04	70.06
	0.00	-2.05	70.06	C4 buffer			
11680	59.22	27.05	5.43	11671	57.04	-	0.00
	44.36	12.79	14.33		42.33	-	10.10
	29.27	3.47	28.64		27.21	-	32.62
	14.34	0.79	49.98		12.15	-	55.40
	0.00	-2.22	70.09		0.00	-4.00	69.99
C3 buffer				11674	55.57	-	-0.18
11675	55.54	-	-0.09		40.65	-	12.25
	40.62	-	0.08		25.58	-	34.84
	25.54	-	13.79		10.59	-	57.65
	10.66	-	36.44		0.00	-4.00	70.11
	0.00	-3.01	50.30	11672	55.19	20.15	8.76
11676	55.31	20.46	-0.07		40.31	10.27	21.55
	40.39	17.38	0.20		25.27	-	34.62
	25.30	9.98	22.37		10.36	-	57.86
	10.43	-	36.76		0.00	-4.00	70.05
	0.00	-2.91	50.28	11673	56.95	25.28	10.69
11677	46.47	-	-0.12		41.96	12.05	20.54
	31.54	-	0.26		27.05	-	32.40
	21.46	-	19.27		12.05	-	55.20
	11.57	-	35.05		0.00	-4.01	70.02
	0.00	-3.00	50.28	B4 Buffer			
11679	46.30	18.63	-0.09	11643	59.45	35.14	-0.14
	31.37	8.75	-0.02		44.63	23.41	-0.22
	21.41	3.26	22.47		29.53	15.57	43.24
	11.37	-	35.09		14.51	4.20	55.58
	0.00	-3.00	50.32		0.00	-4.02	69.97

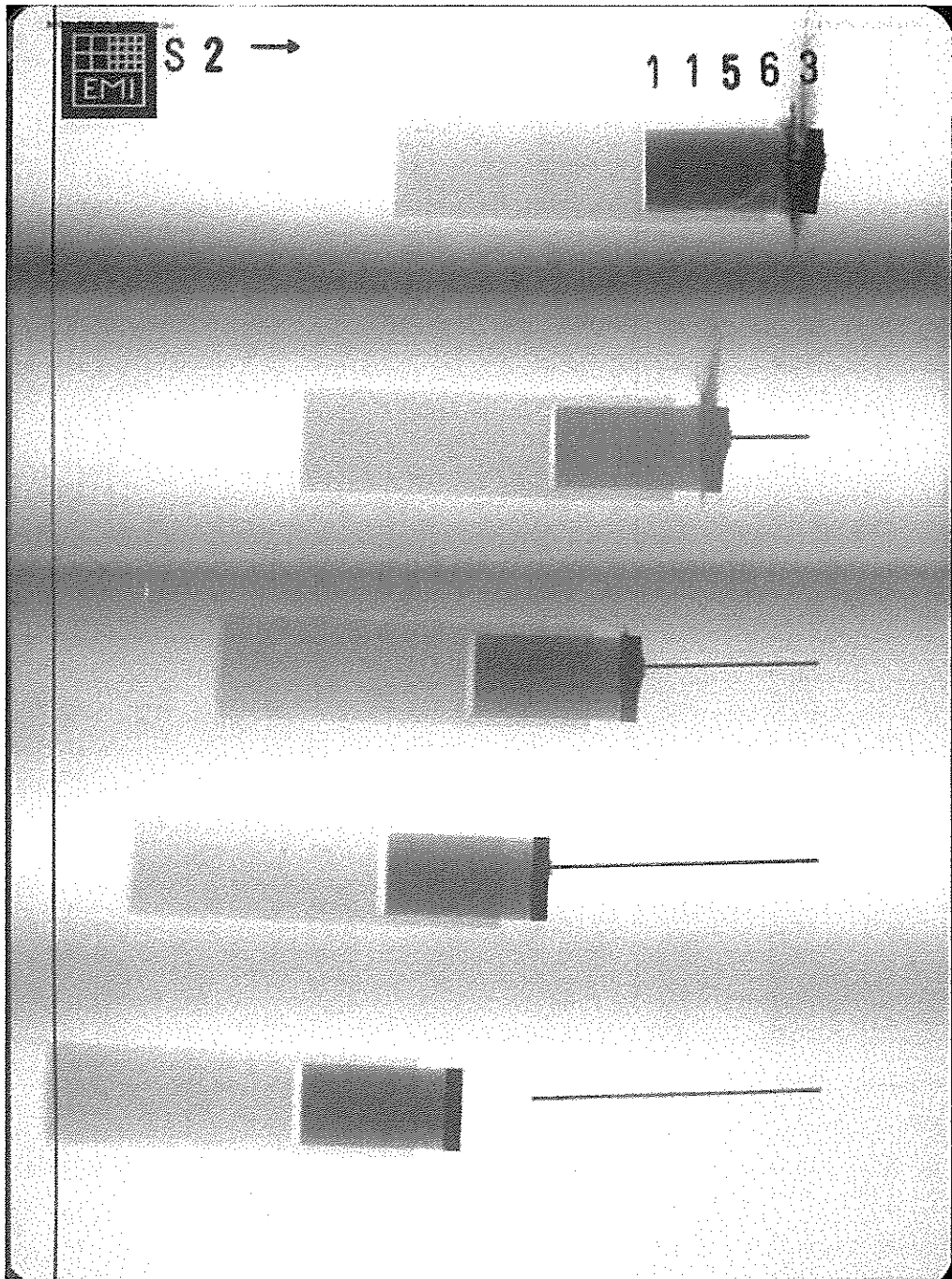


Figure B-1. X-ray picture for Exp. 11624 (X-ray shows a wrong number):
CP4 buffer, $v_p = 1.407$ km/s.

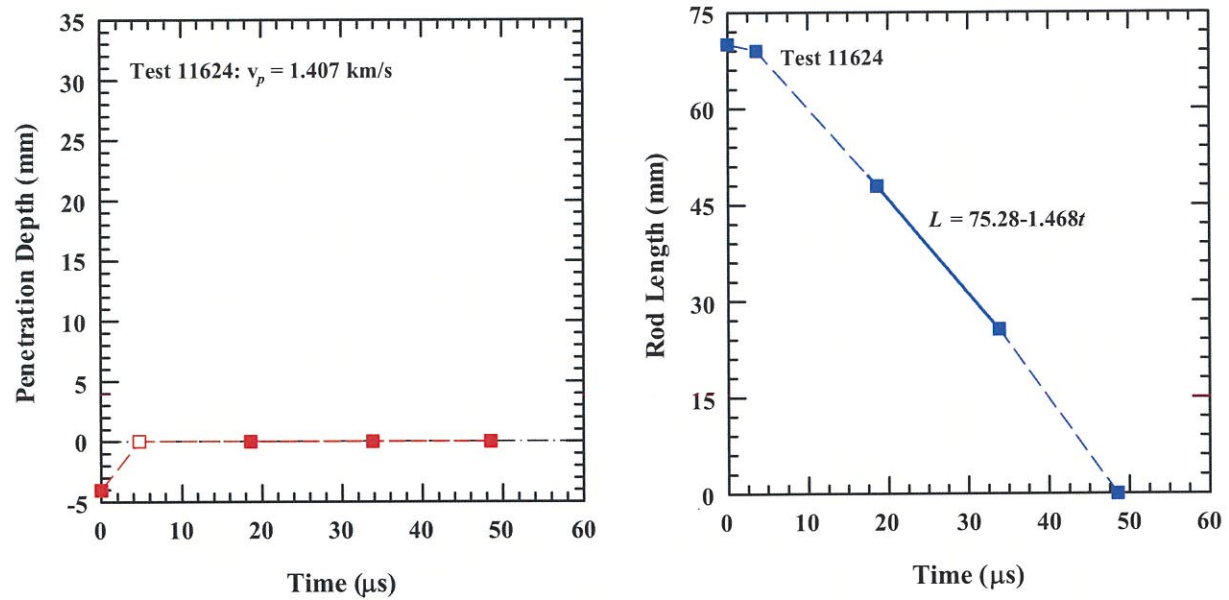


Figure B-2. Penetration vs. time and rod length vs. time for Exp. 11624: $v_p = 1.407$ km/s.

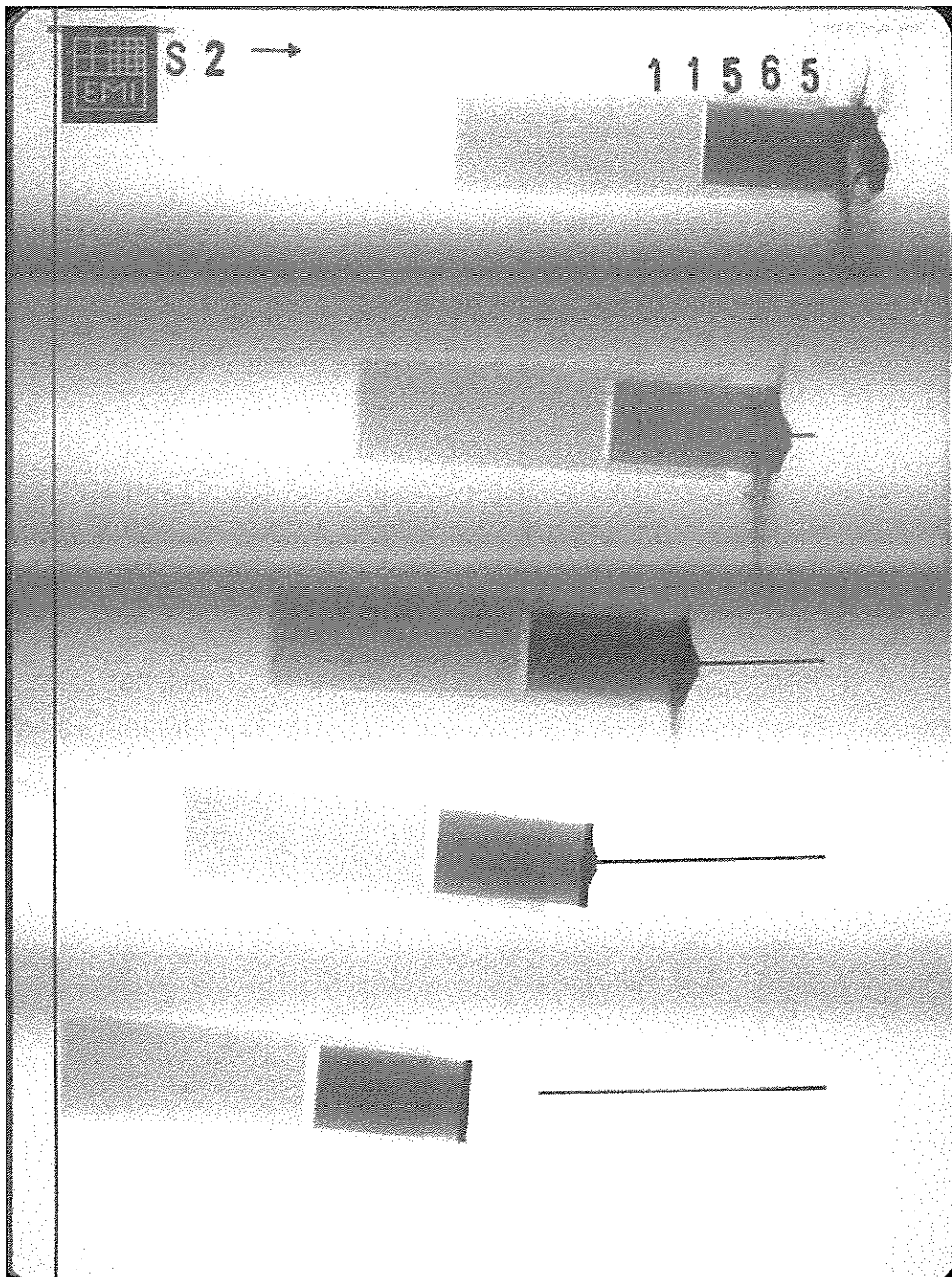


Figure B-3. X-ray picture for Exp. 11625 (X-ray shows an incorrect number):
CP2 buffer, $v_p = 1.487$ km/s.

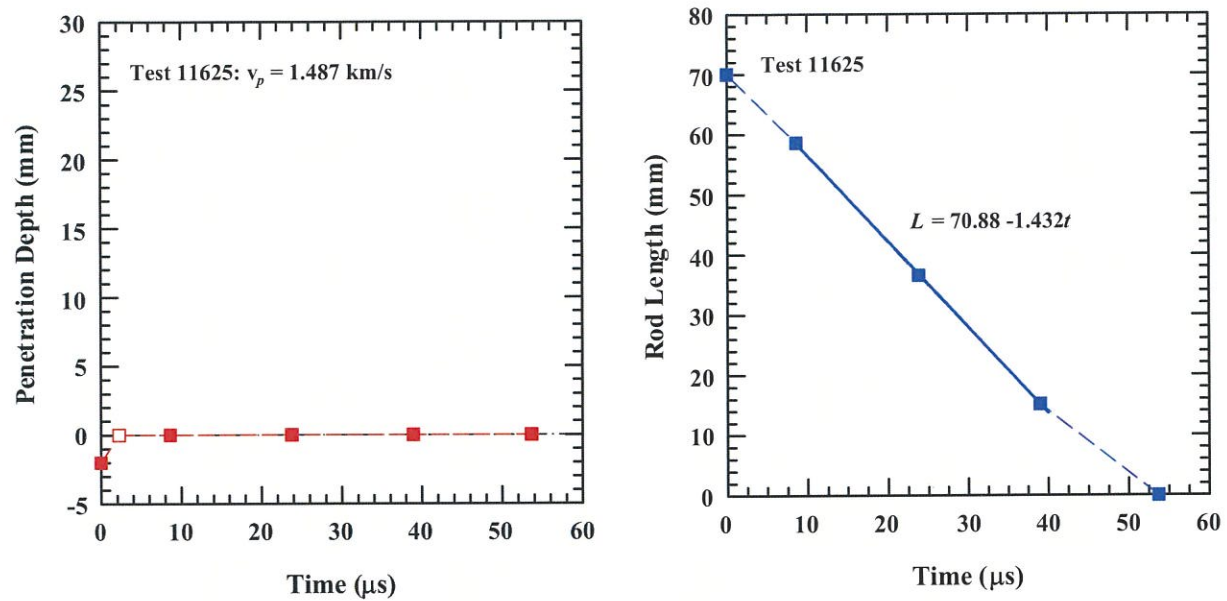


Figure B-4. Penetration vs. time and rod length vs. time for Exp. 11625: $v_p = 1.487$ km/s.

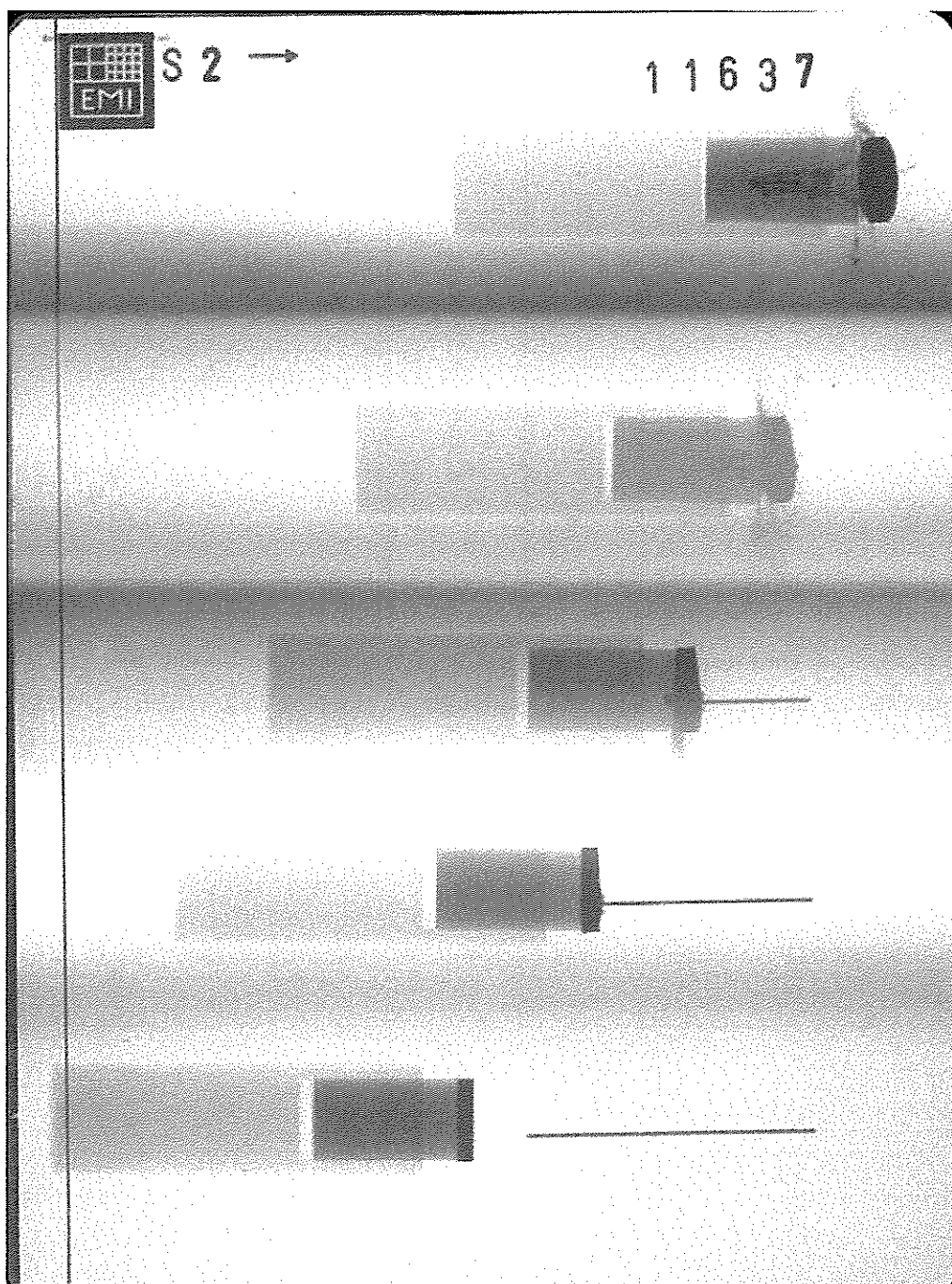


Figure B-5. X-ray picture for Exp. 11637: CP4 buffer, $v_p = 1.520$ km/s.

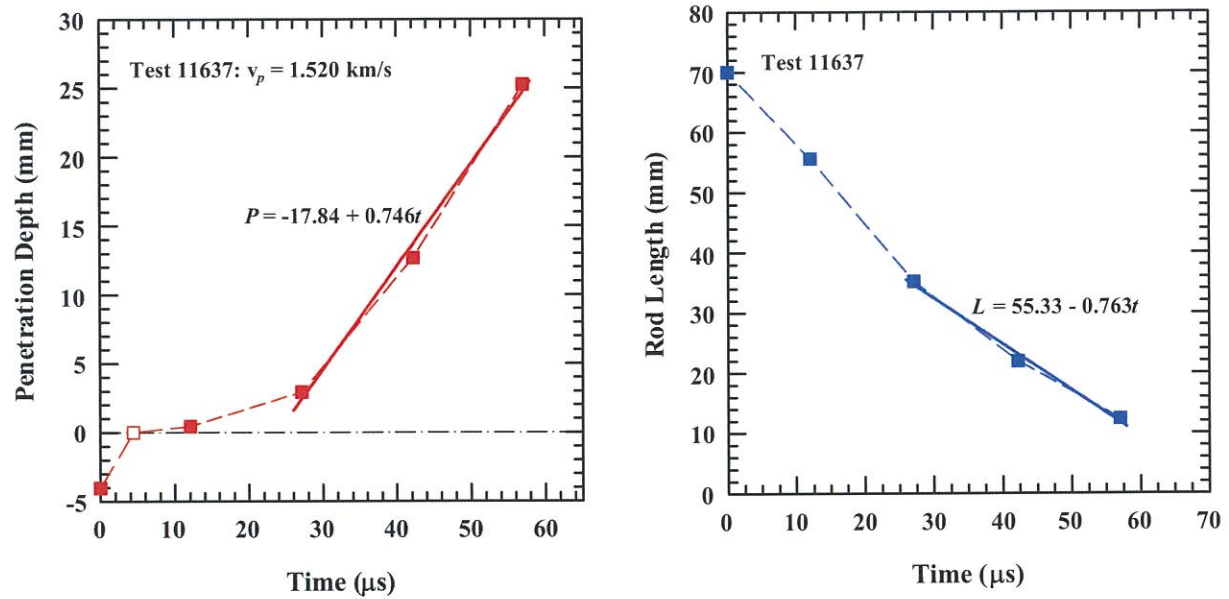


Figure B-6. Penetration vs. time and rod length vs. time for Exp. 11637: $v_p = 1.520$ km/s.

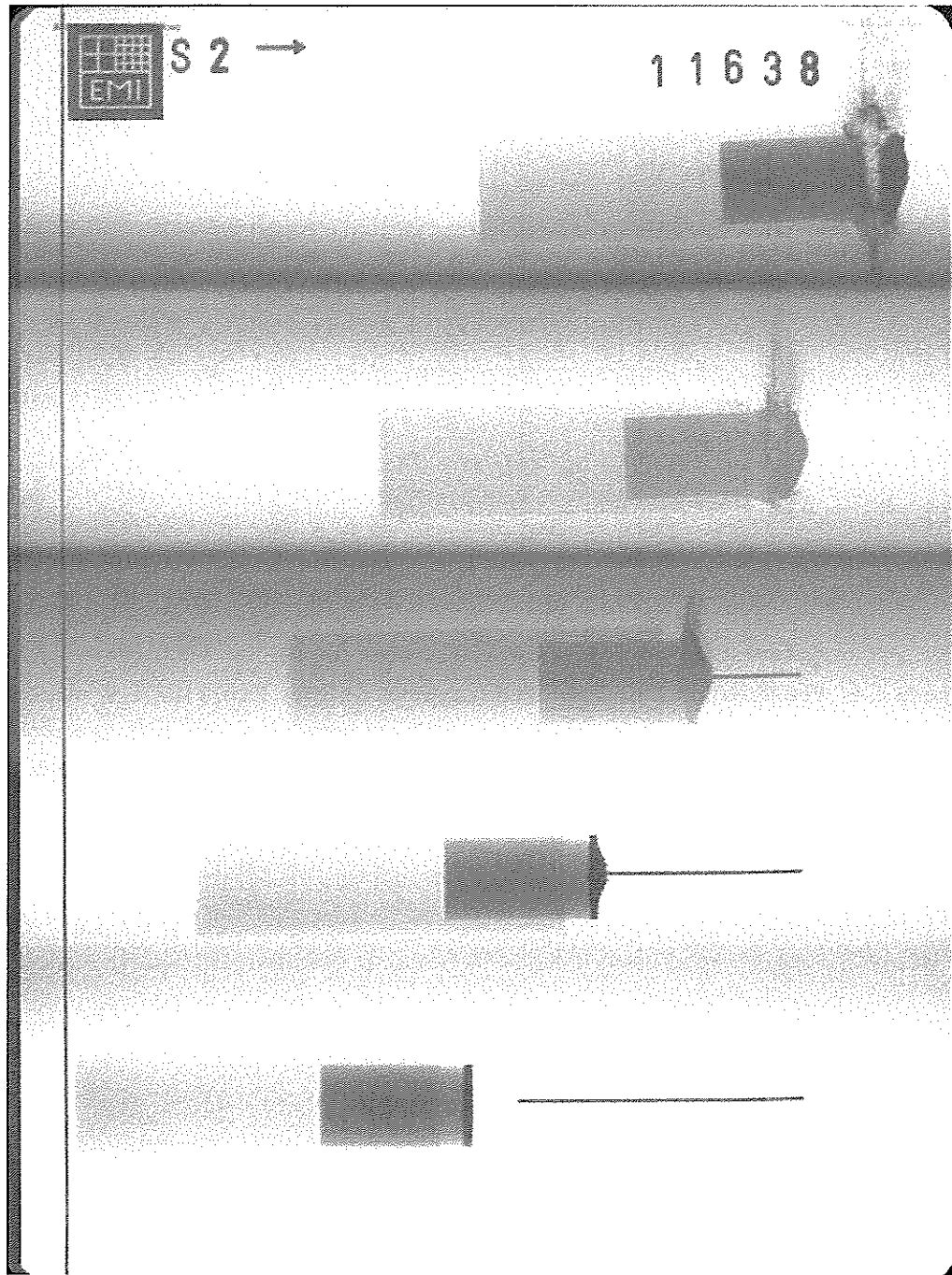


Figure B-7. X-ray picture for Exp. 11638: CP2 buffer, $v_p = 1.553$ km/s.

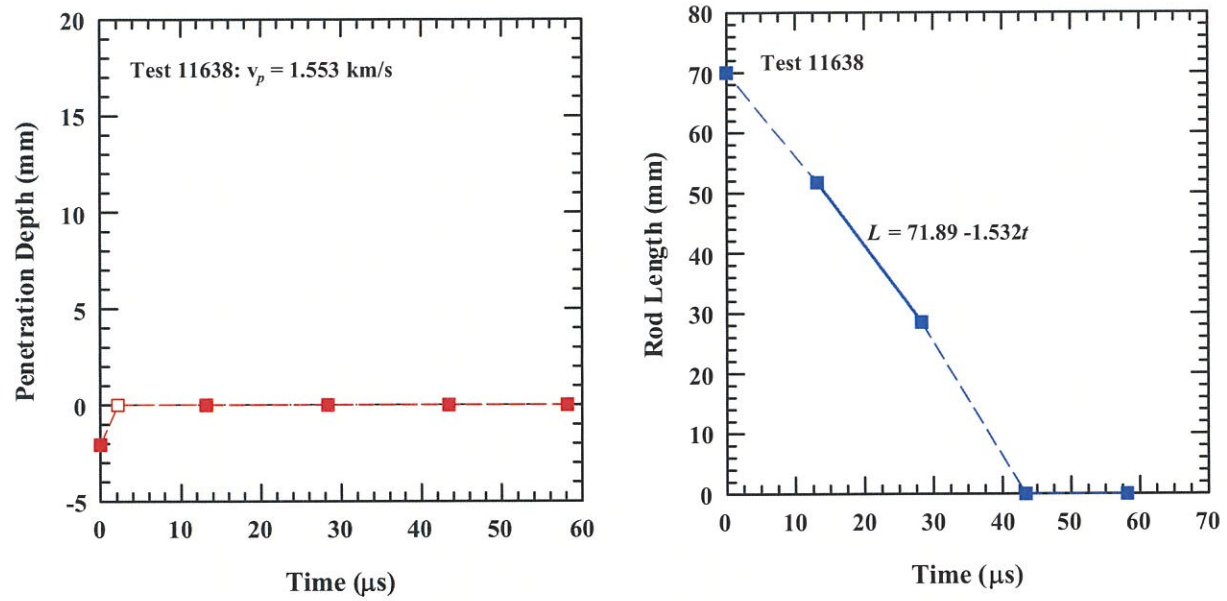


Figure B-8. Penetration vs. time and rod length vs. time for Exp. 11638: $v_p = 1.553$ km/s.

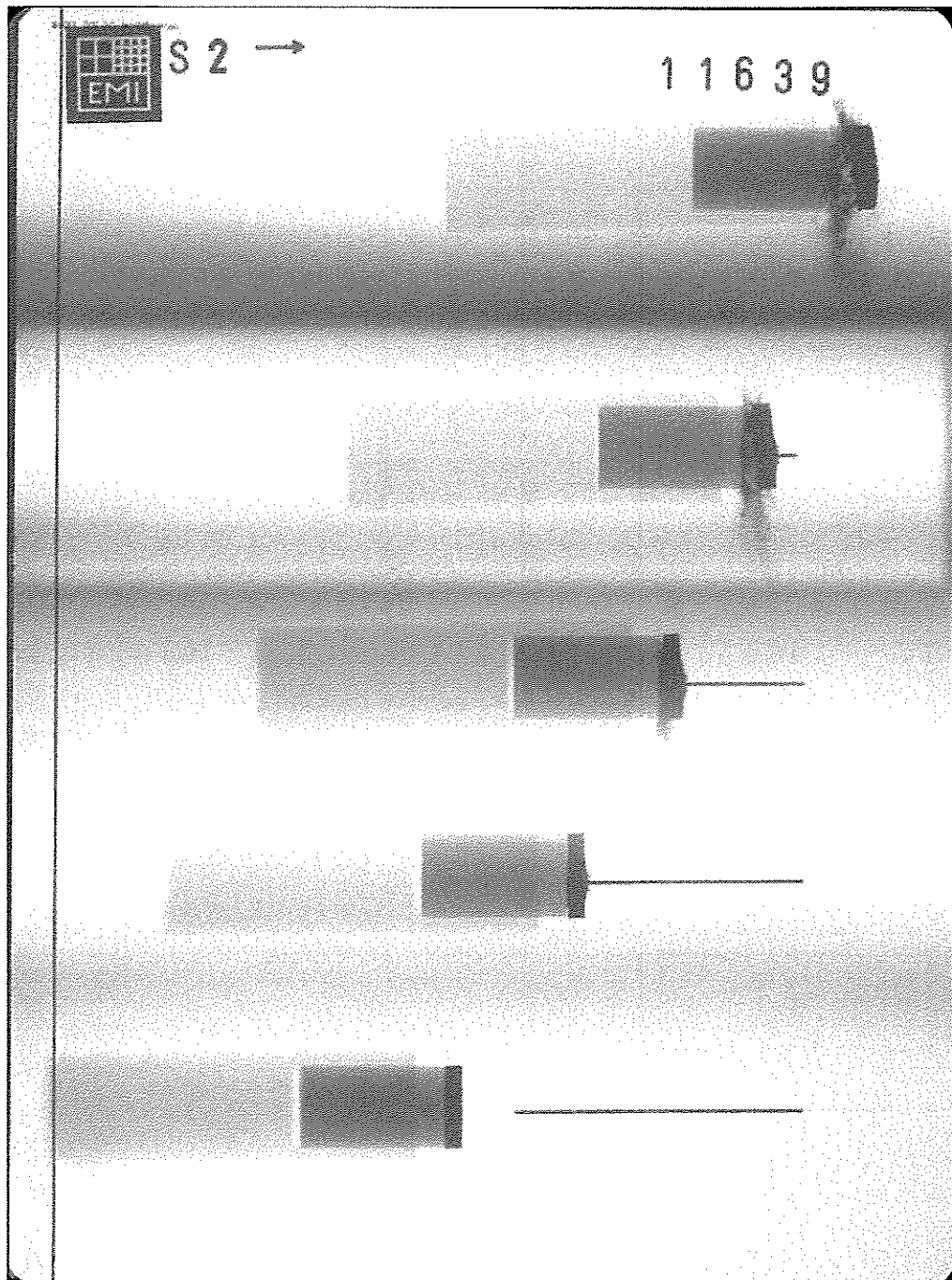


Figure B-9. X-ray picture for Exp. 11639: CP4 buffer, $v_p = 1.484$ km/s.

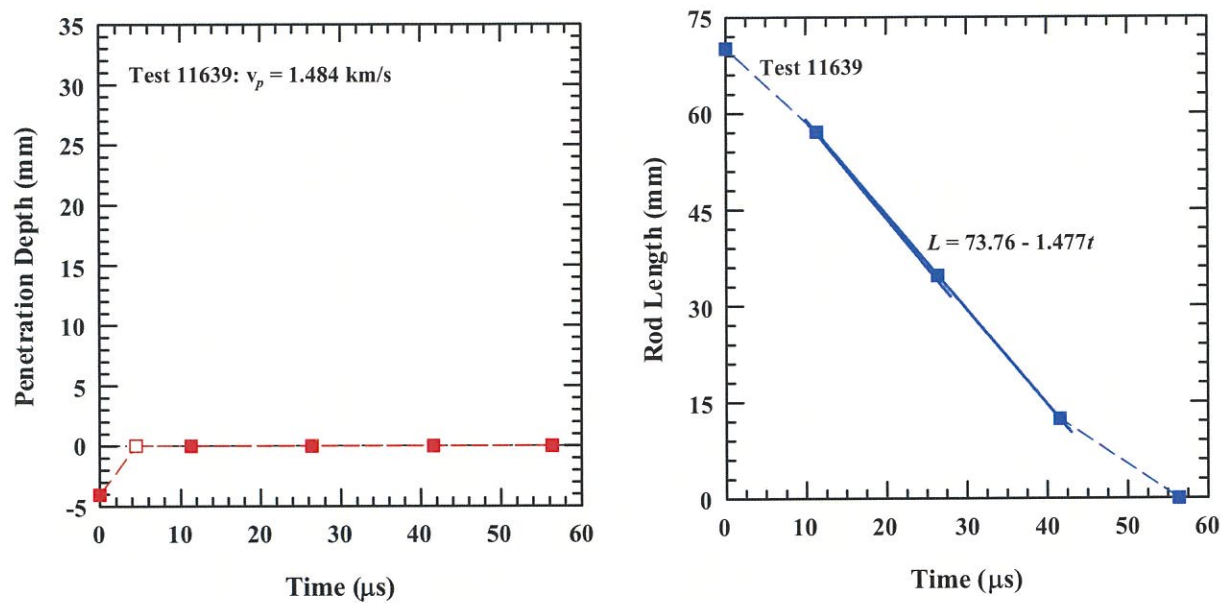


Figure B-10. Penetration vs. time and rod length vs. time for Exp. 11639: $v_p = 1.484$ km/s.

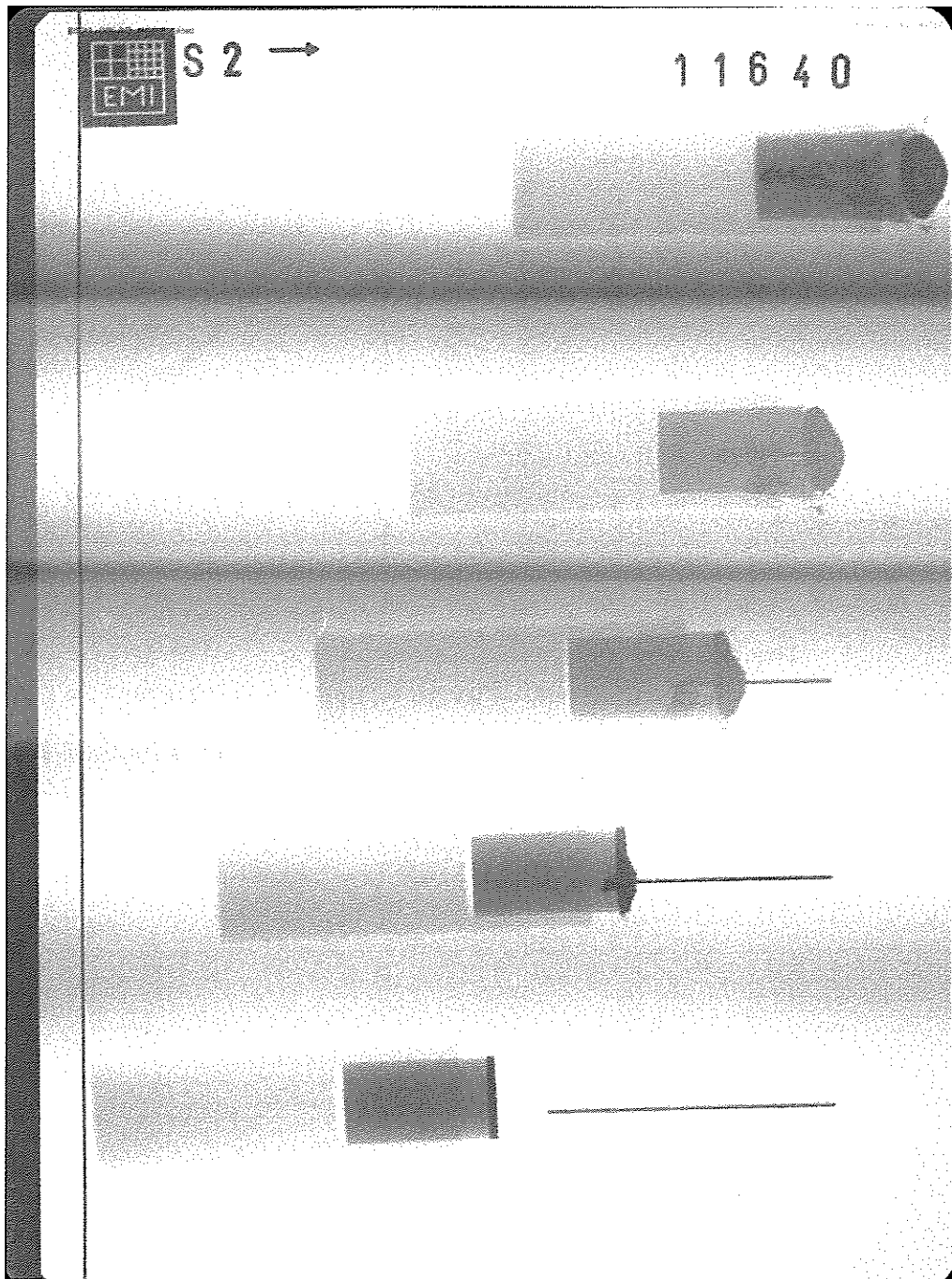


Figure B-11. X-ray picture for Exp. 11640: CP2 buffer, $v_p = 1.578$ km/s.

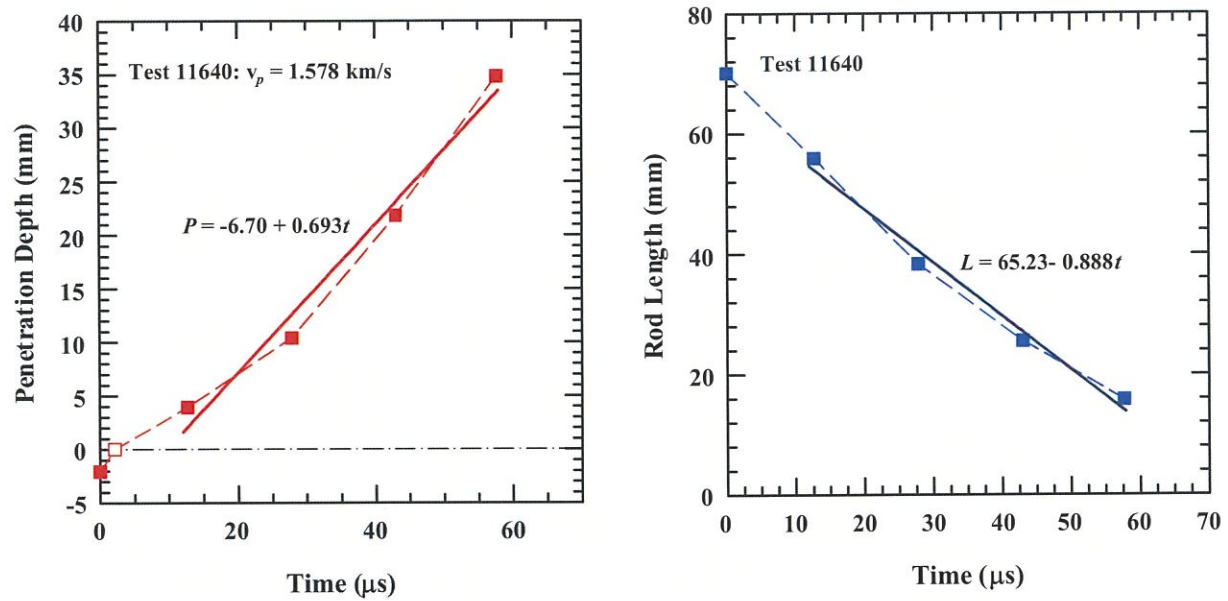


Figure B-12. Penetration vs. time and rod length vs. time for Exp. 11640: $v_p = 1.578$ km/s.

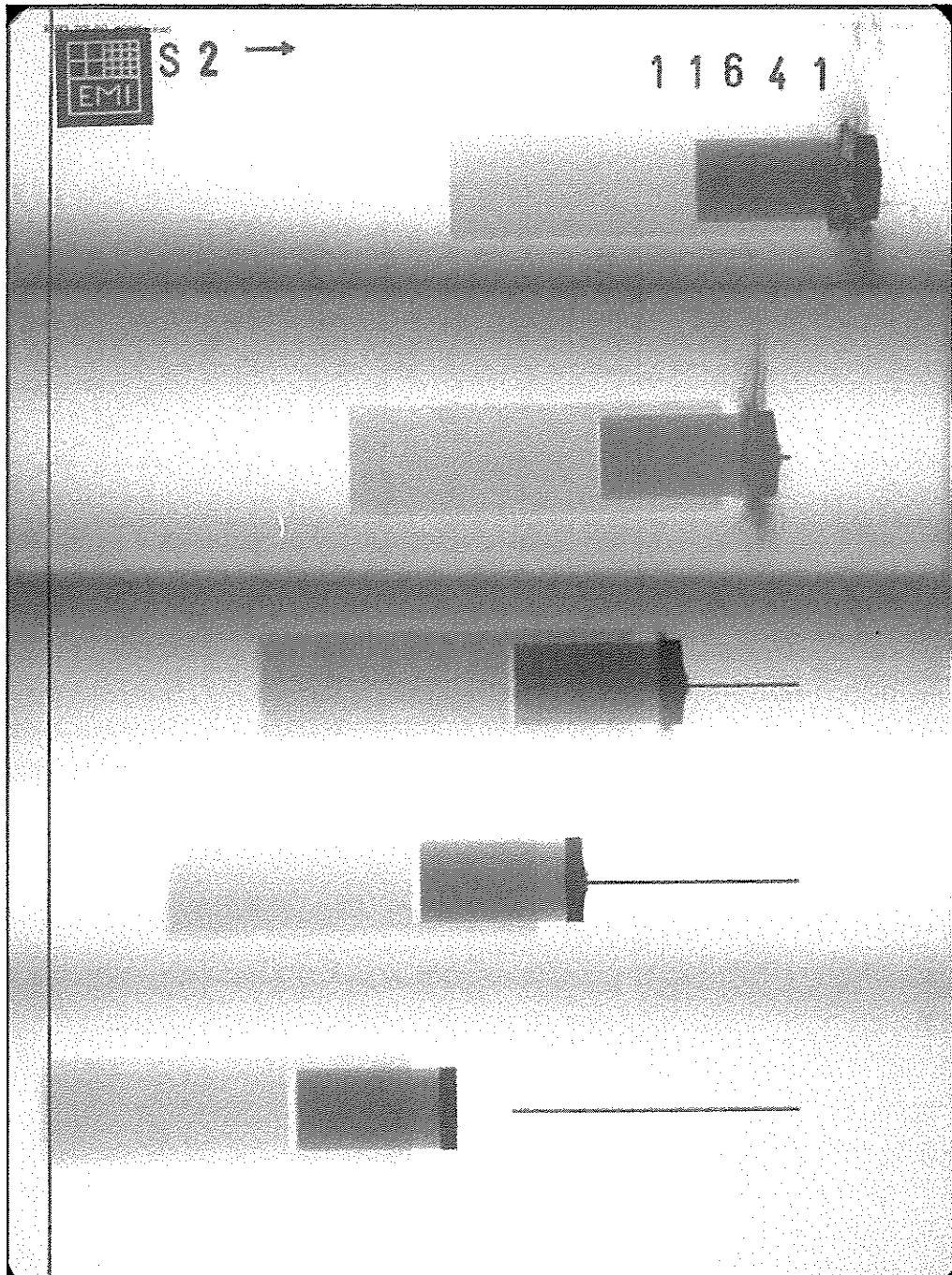


Figure B-13. X-ray picture for Exp. 11641: CP4 buffer, $v_p = 1.528$ km/s.

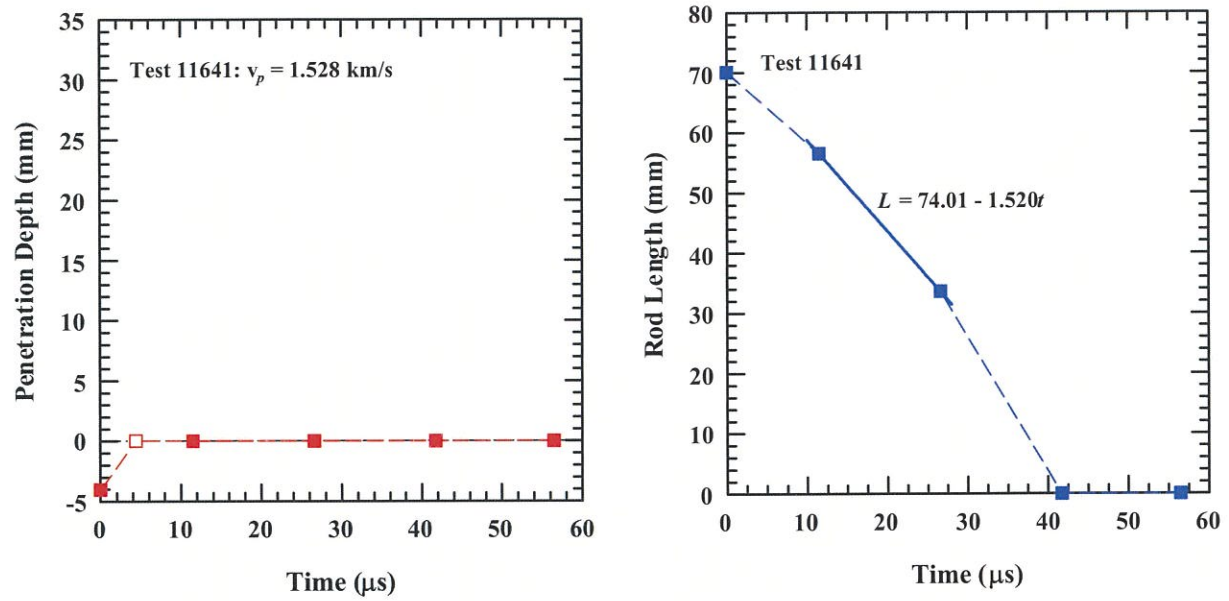


Figure B-14. Penetration vs. time and rod length vs. time for Exp. 11641: $v_p = 1.528$ km/s.

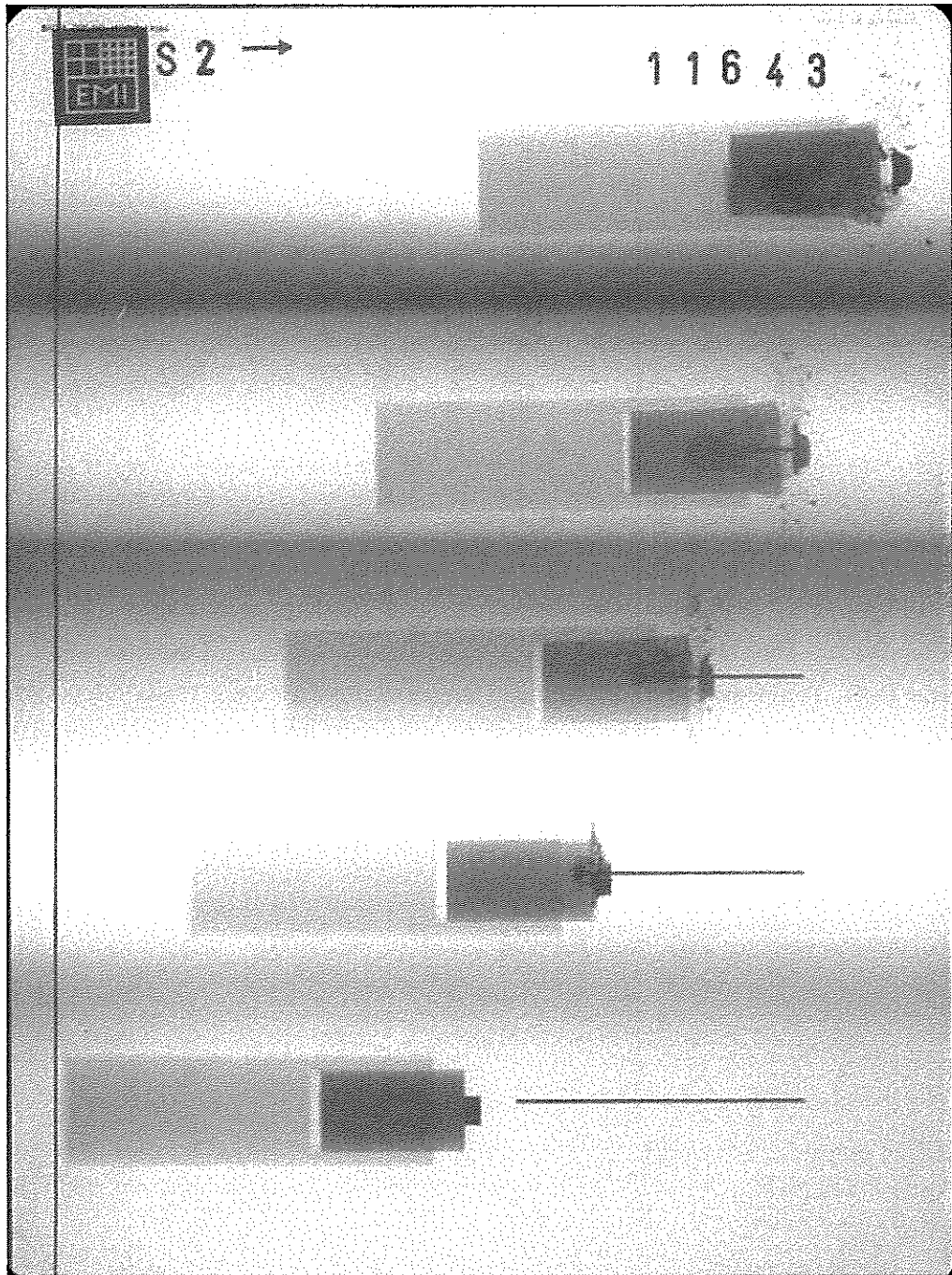


Figure B-15. X-ray picture for Exp. 11643: B4 buffer, $v_p = 1.570$ km/s.

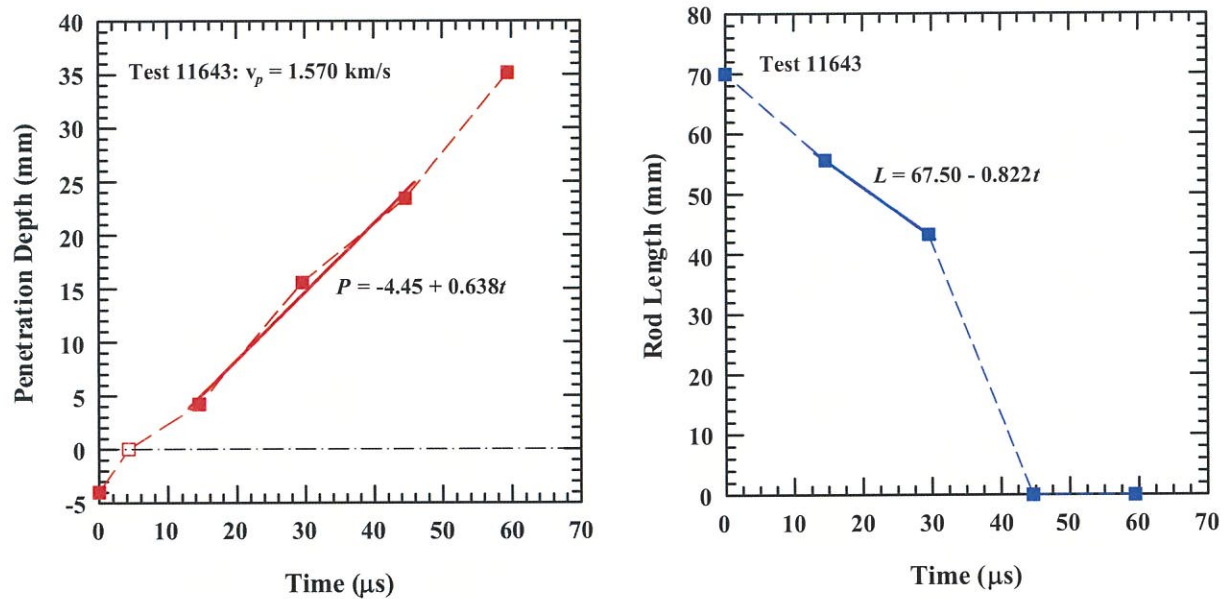


Figure B-16. Penetration vs. time and rod length vs. time for Exp. 11643: $v_p = 1.570$ km/s.

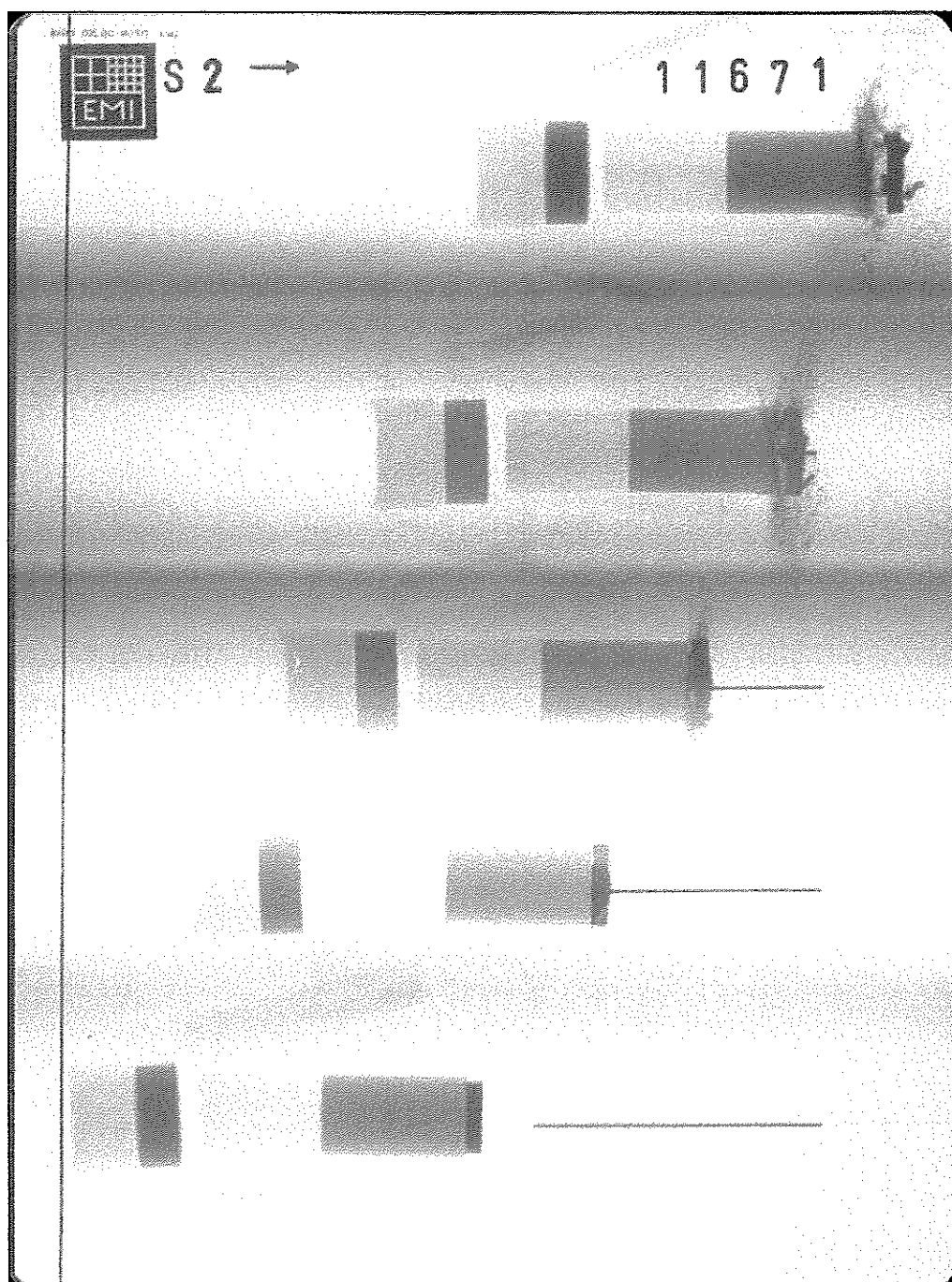


Figure B-17. X-ray picture for Exp. 11671: C4 buffer, $v_p = 1.525$ km/s.

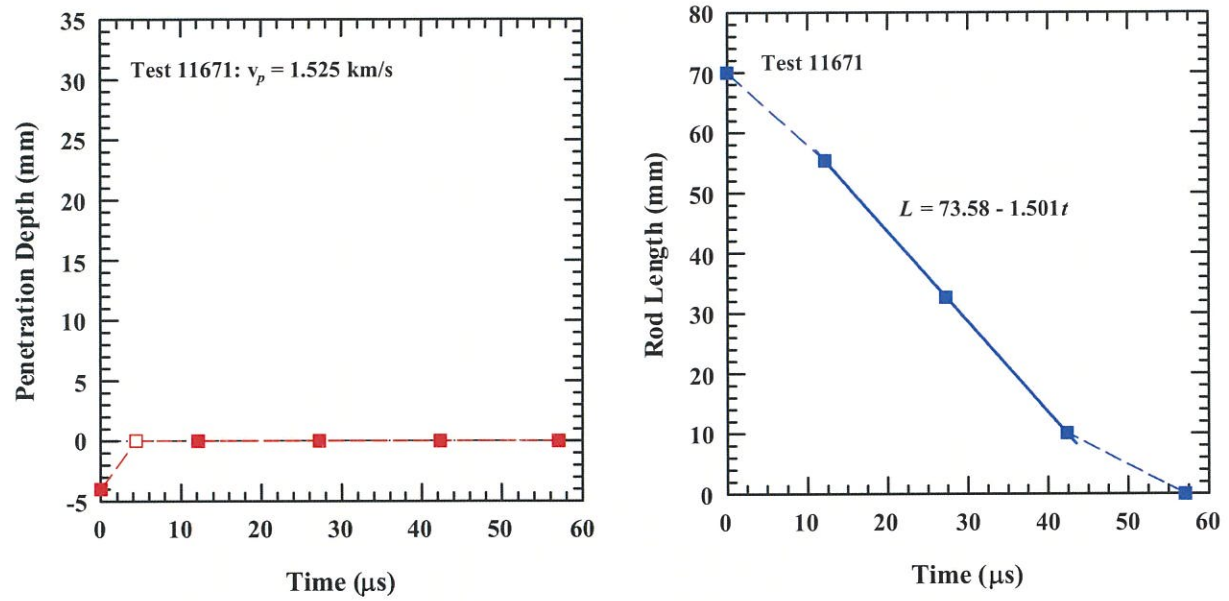


Figure B-18. Penetration vs. time and rod length vs. time for Exp. 11671: $v_p = 1.525$ km/s.

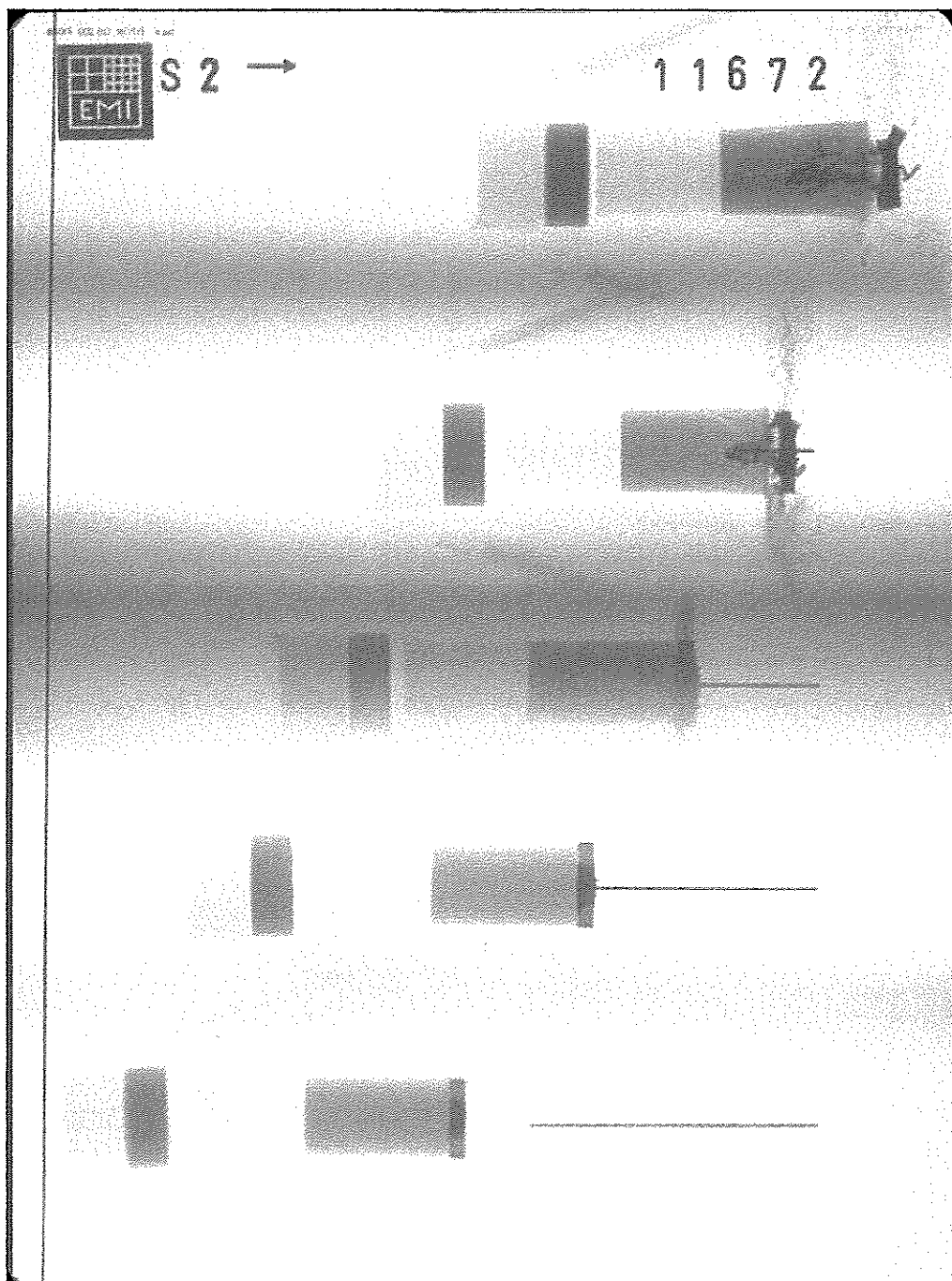


Figure B-19. X-ray picture for Exp. 11672: C4 buffer, $v_p = 1.552$ km/s.

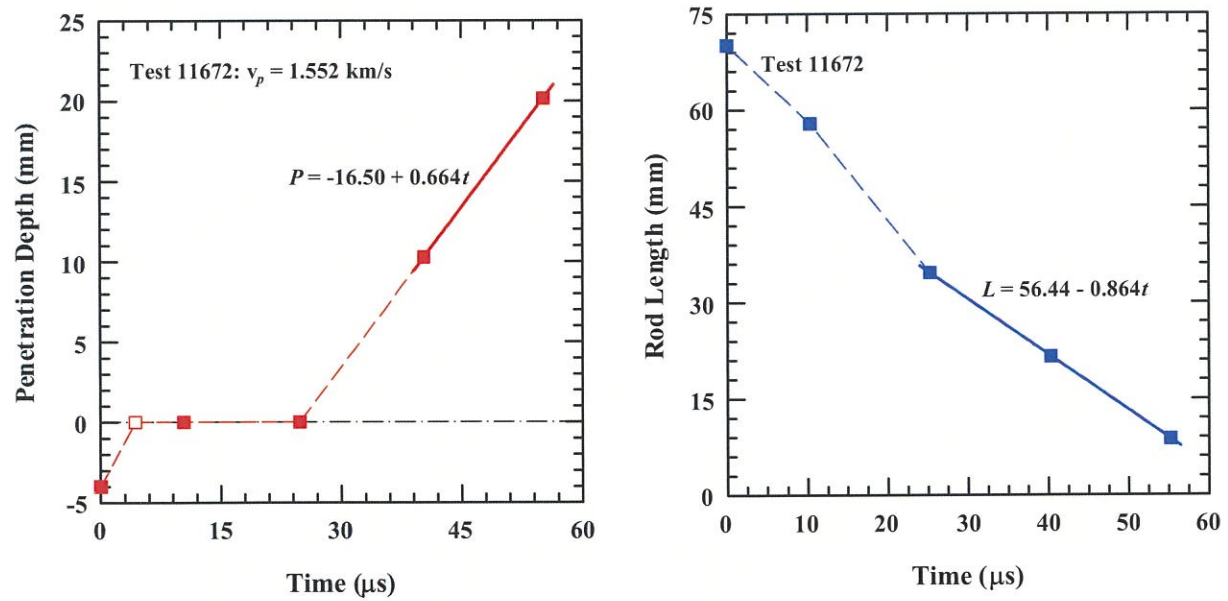


Figure B-20. Penetration vs. time and rod length vs. time for Exp. 11672: $v_p = 1.552$ km/s.

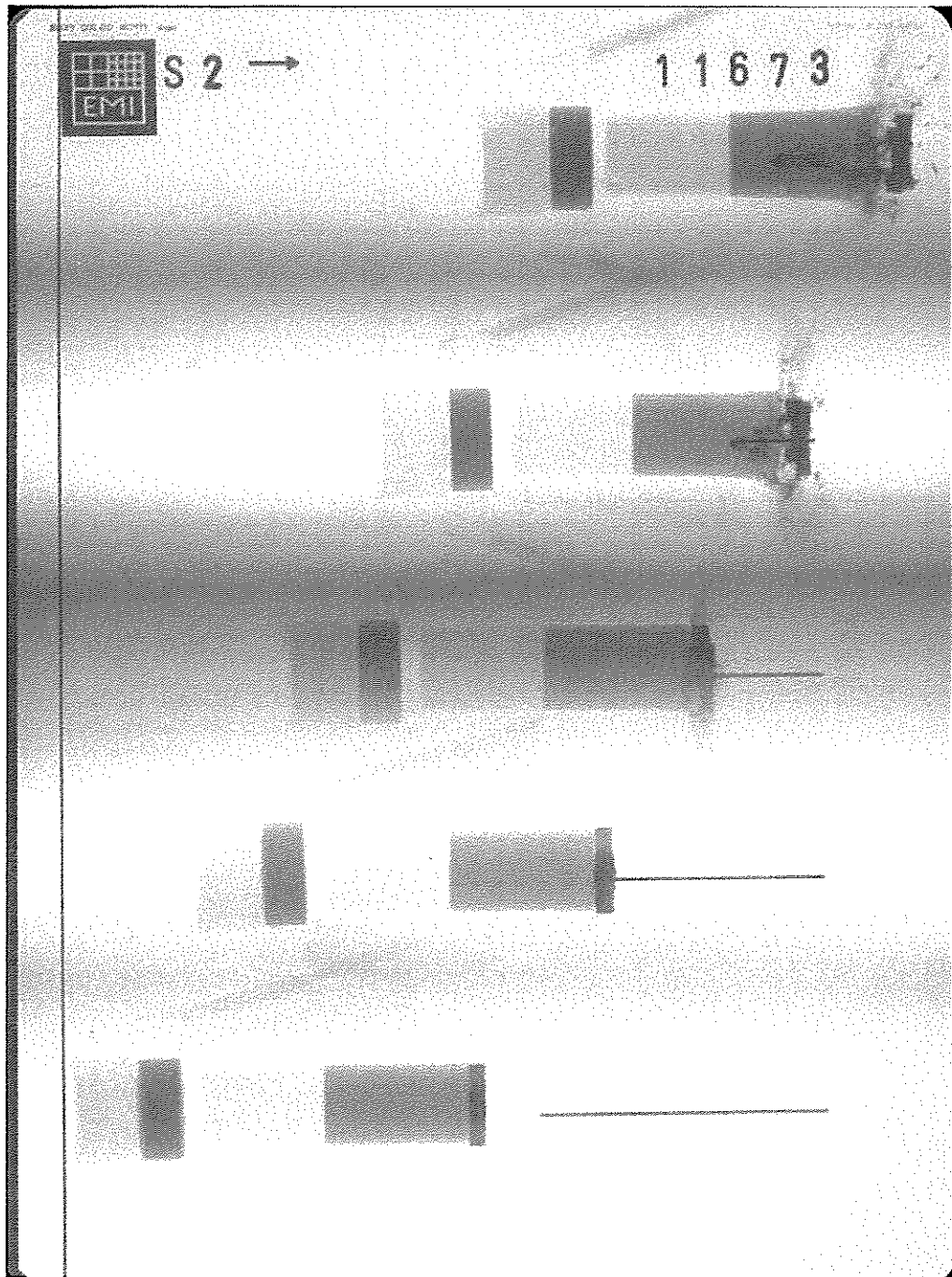


Figure B-21. X-ray picture for Exp. 11673: C4 buffer, $v_p = 1.555$ km/s.

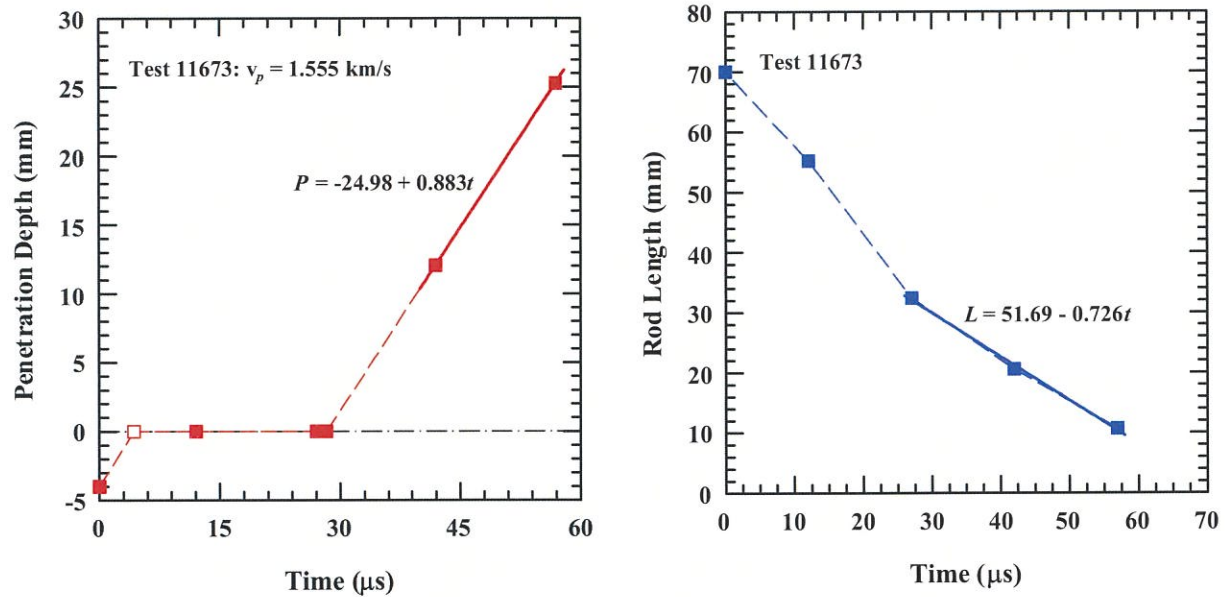


Figure B-22. Penetration vs. time and rod length vs. time for Exp. 11673: $v_p = 1.555 \text{ km/s}$.

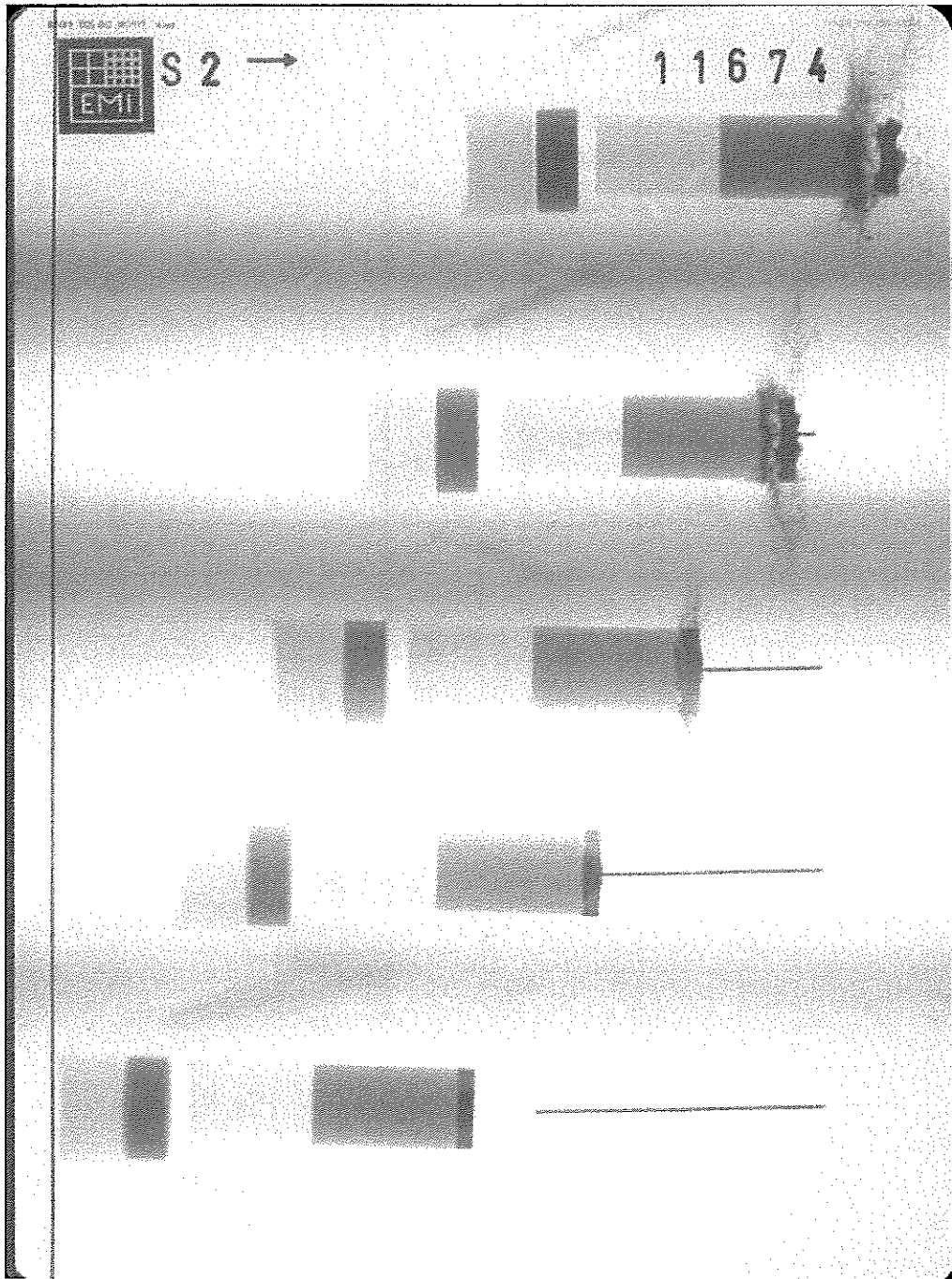


Figure B-23. X-ray picture for Exp. 11674: C4 buffer, $v_p = 1.549$ km/s.

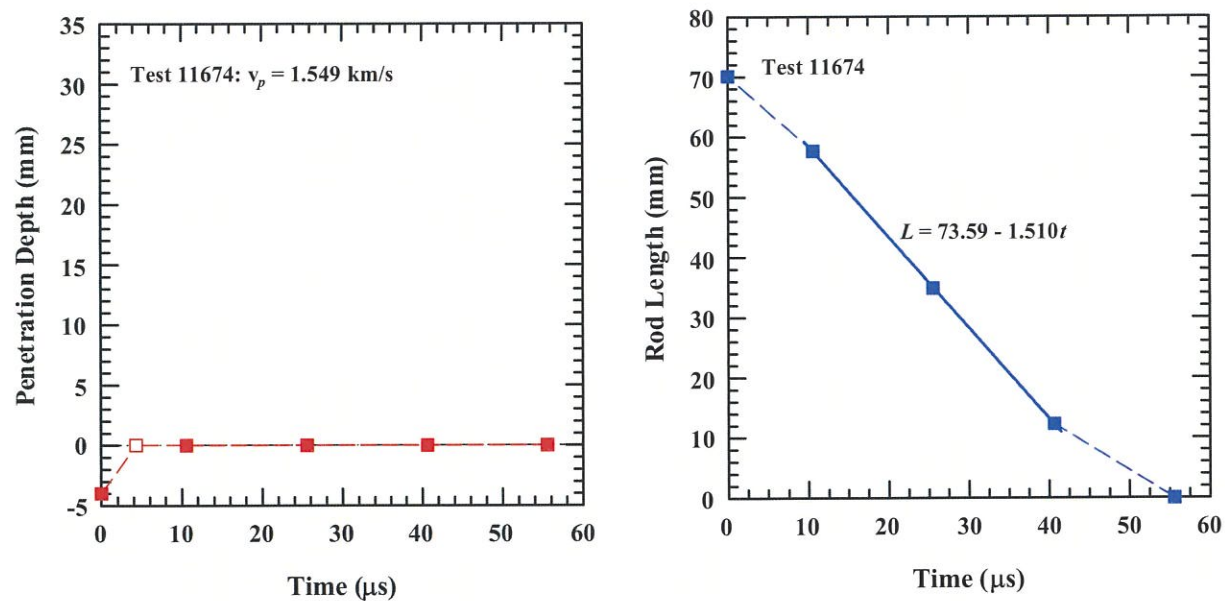


Figure B-24. Penetration vs. time and rod length vs. time for Exp. 11674: $v_p = 1.549$ km/s.

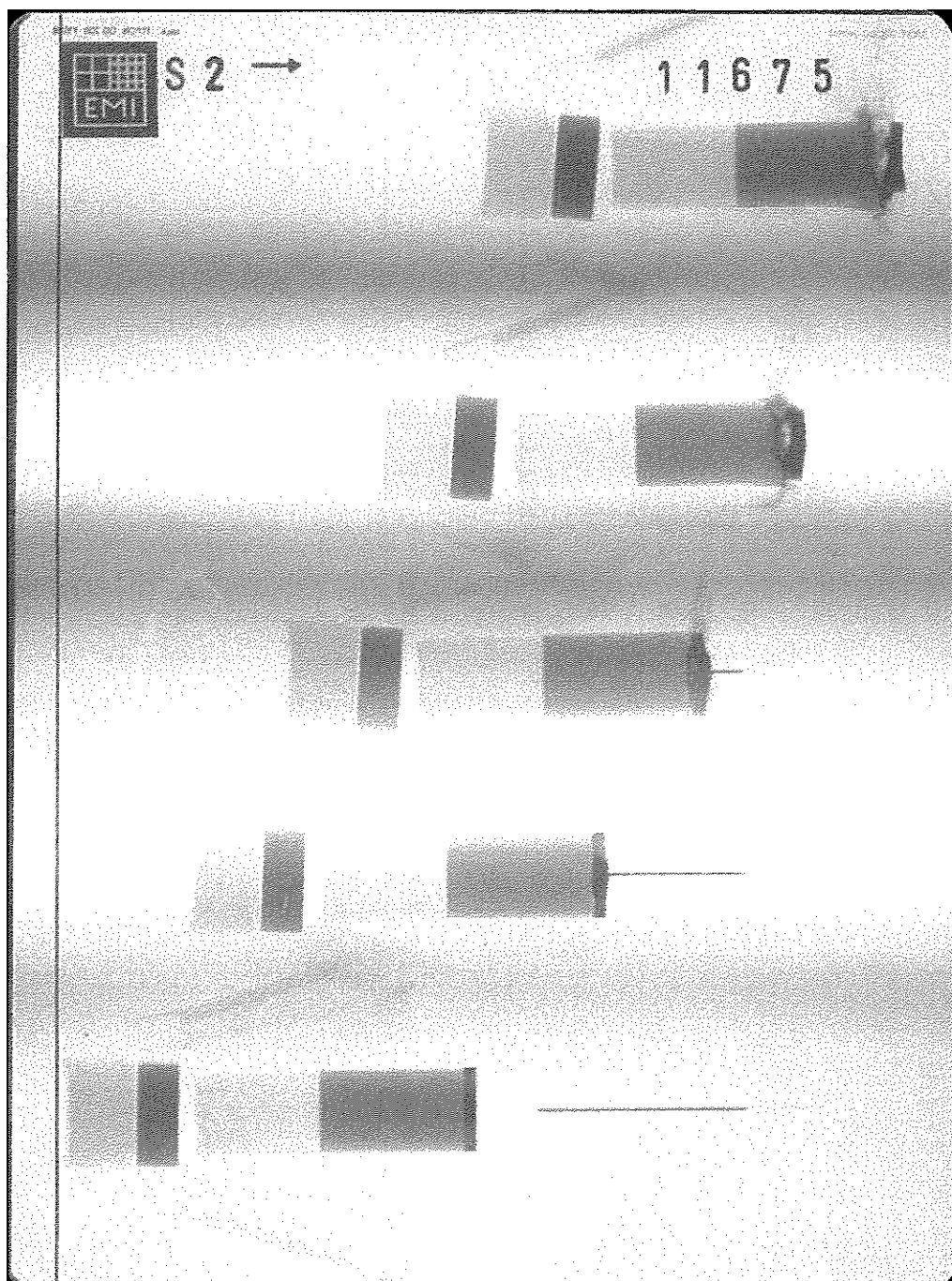


Figure B-25. X-ray picture for Exp. 11675: C3 buffer, $v_p = 1.571$ km/s.

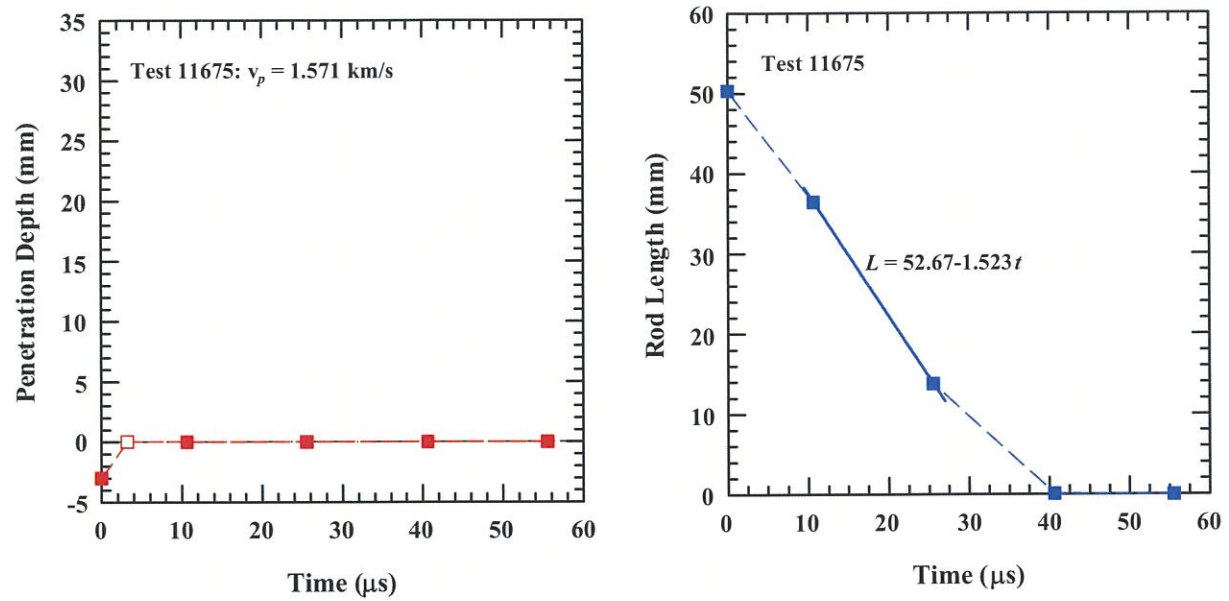


Figure B-26. Penetration vs. time and rod length vs. time for Exp. 11675: $v_p = 1.571$ km/s.

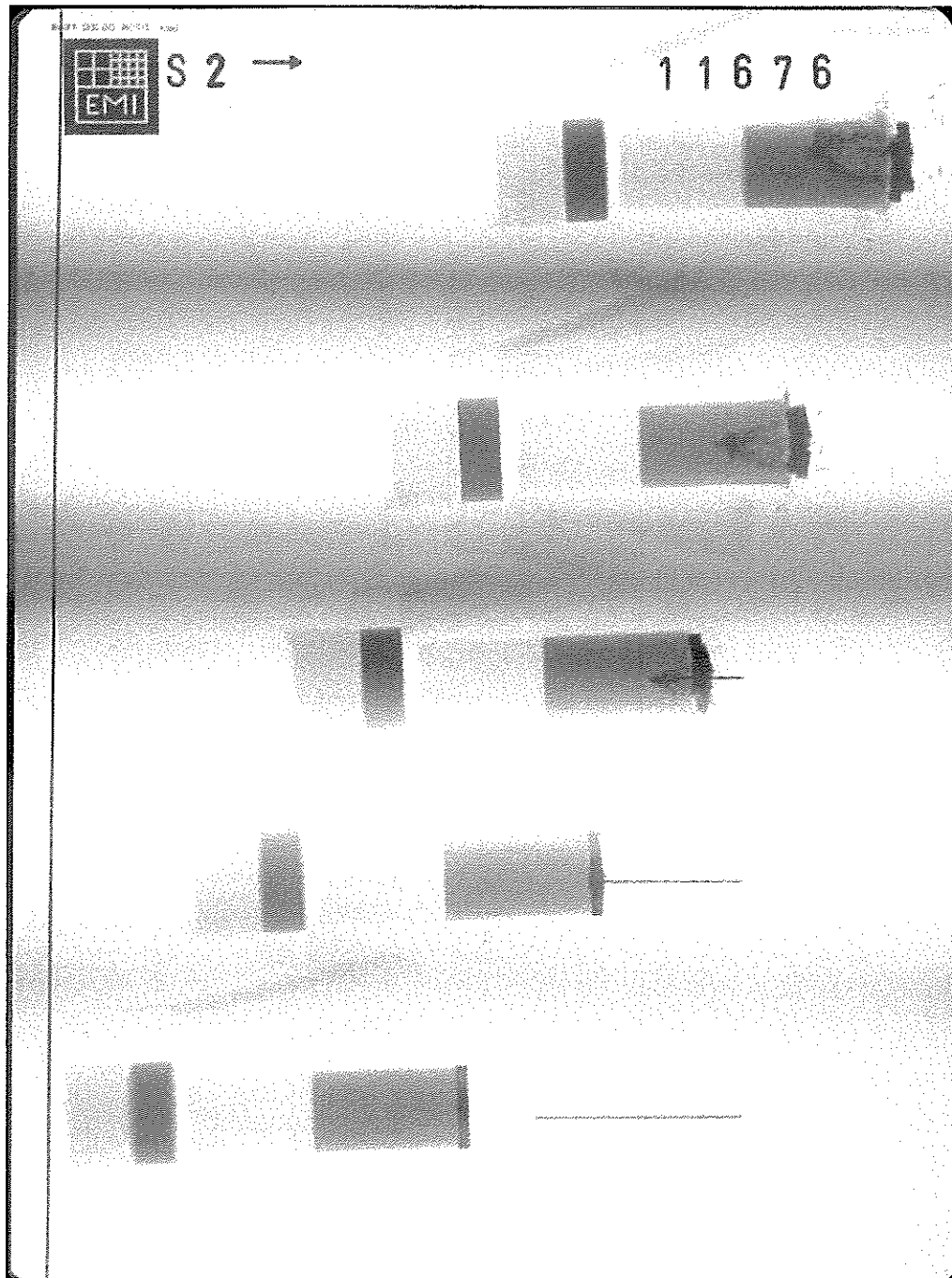


Figure B-27. X-ray picture for Exp. 11676: C3 buffer, $v_p = 1.598$ km/s.

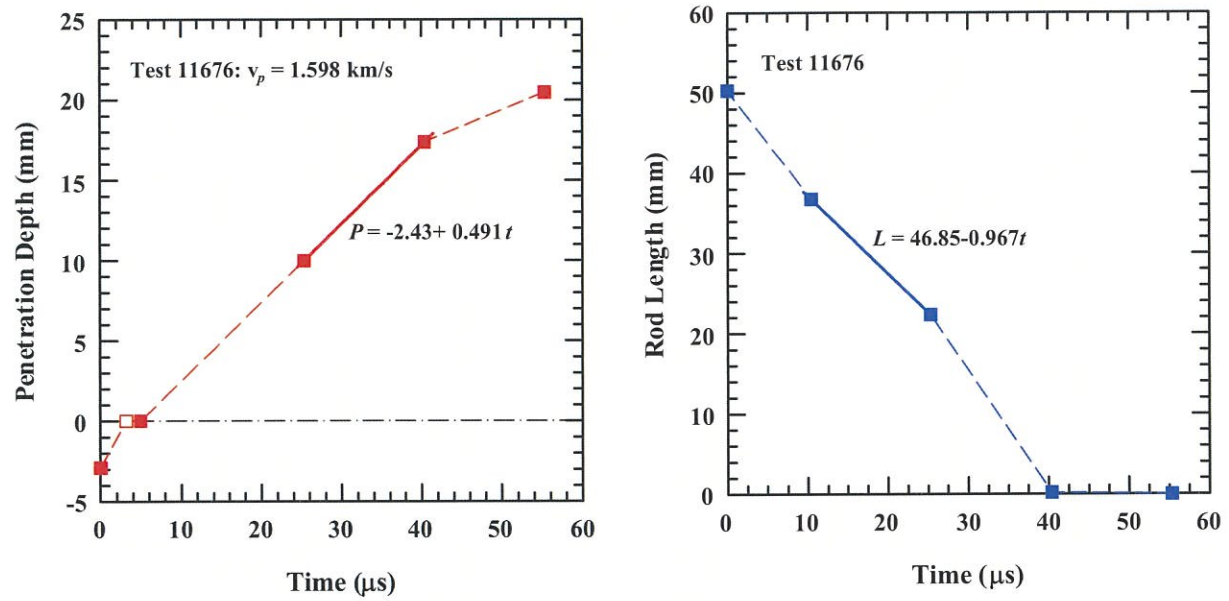


Figure B-28. Penetration vs. time and rod length vs. time for Exp. 11676: $v_p = 1.598$ km/s.

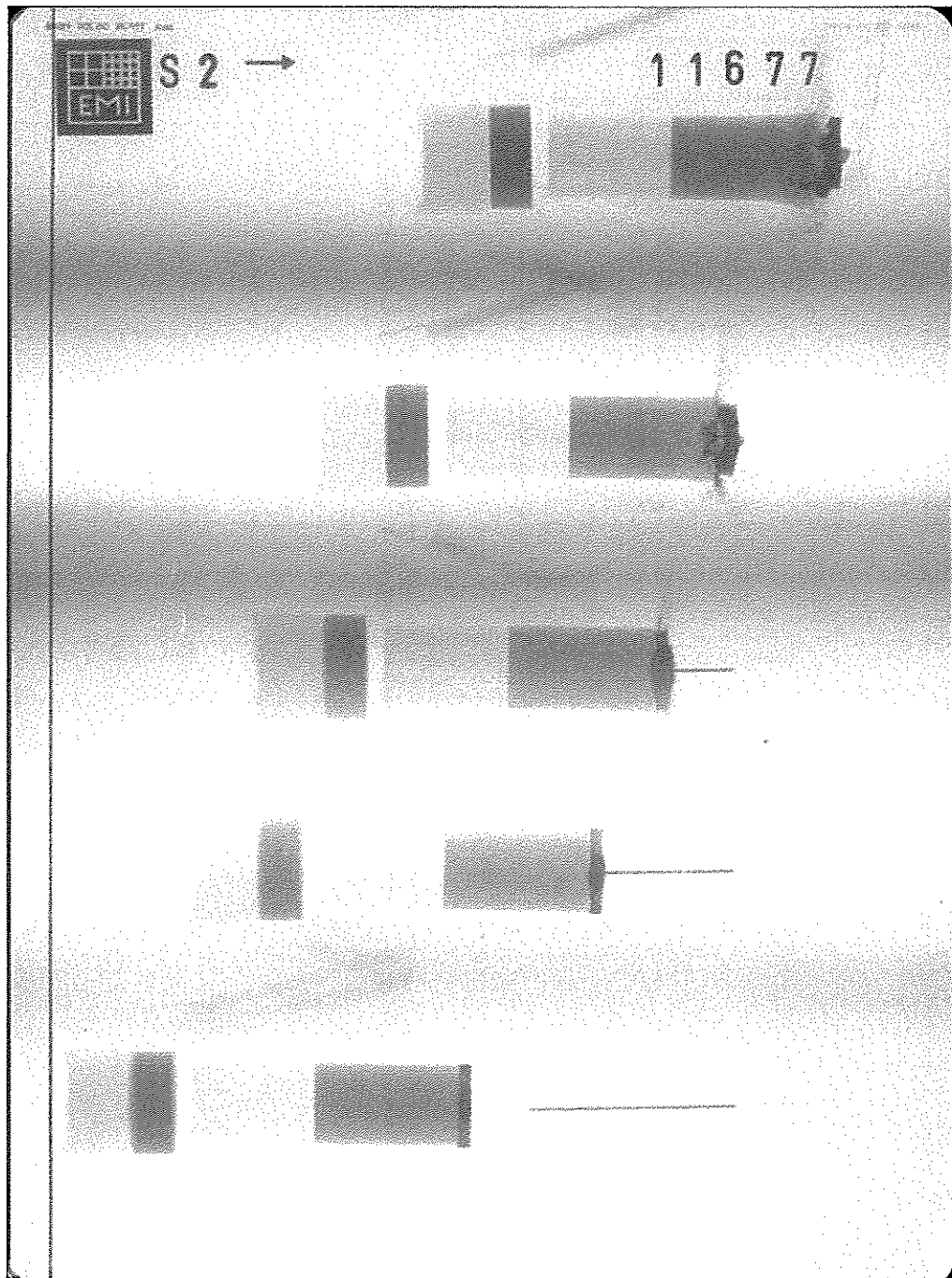


Figure B-29. X-ray picture for Exp. 11677: C3 buffer, $v_p = 1.600$ km/s.

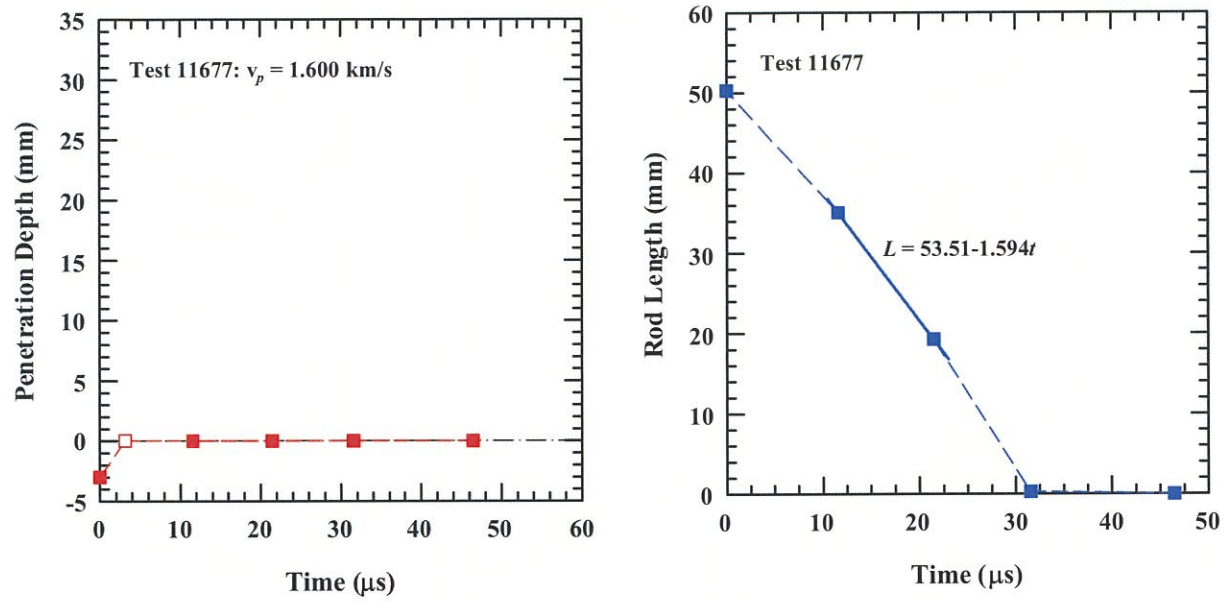


Figure B-30. Penetration vs. time and rod length vs. time for Exp. 11677: $v_p = 1.600$ km/s.



Figure B-31. X-ray picture for Exp. 11678: B2 buffer, $v_p = 1.564$ km/s.

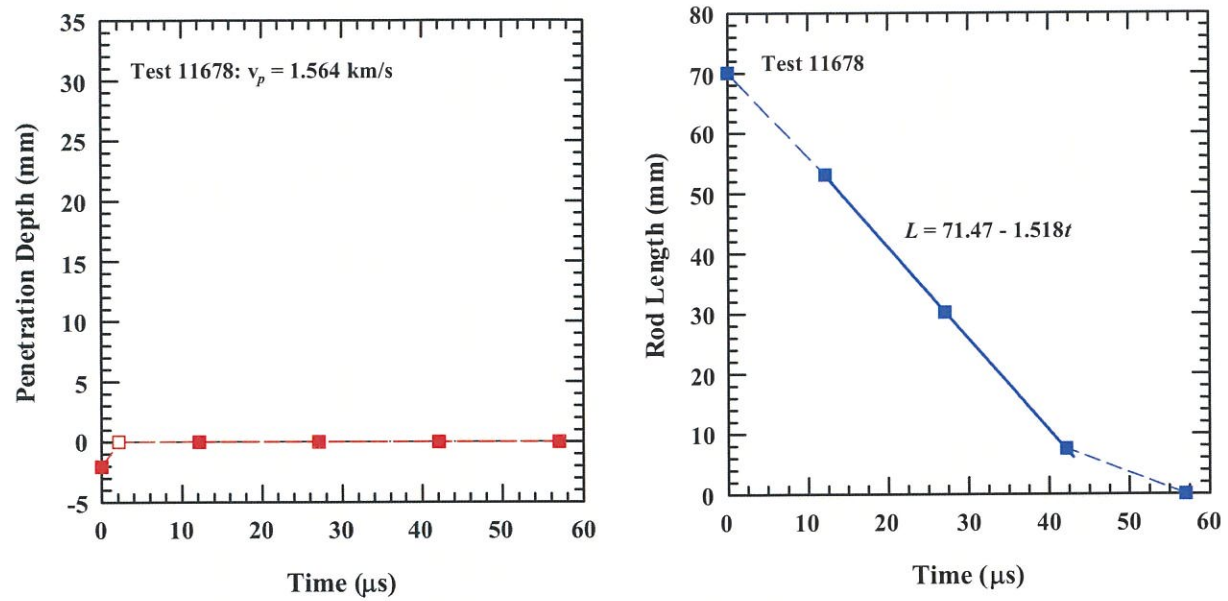


Figure B-32. Penetration vs. time and rod length vs. time for Exp. 11678: $v_p = 1.564$ km/s.

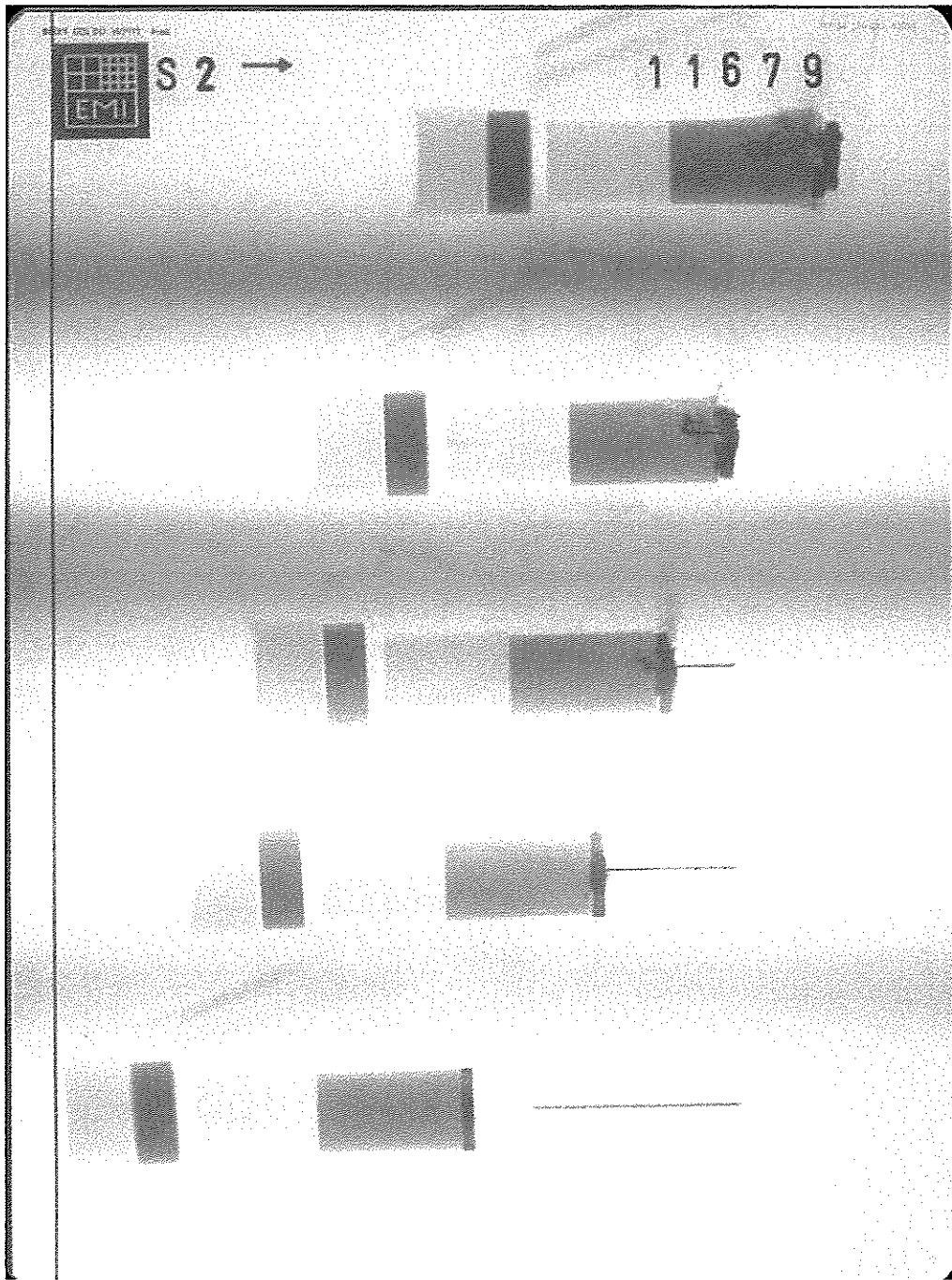


Figure B-33. X-ray picture for Exp. 11679: C3 buffer, $v_p = 1.607$ km/s.

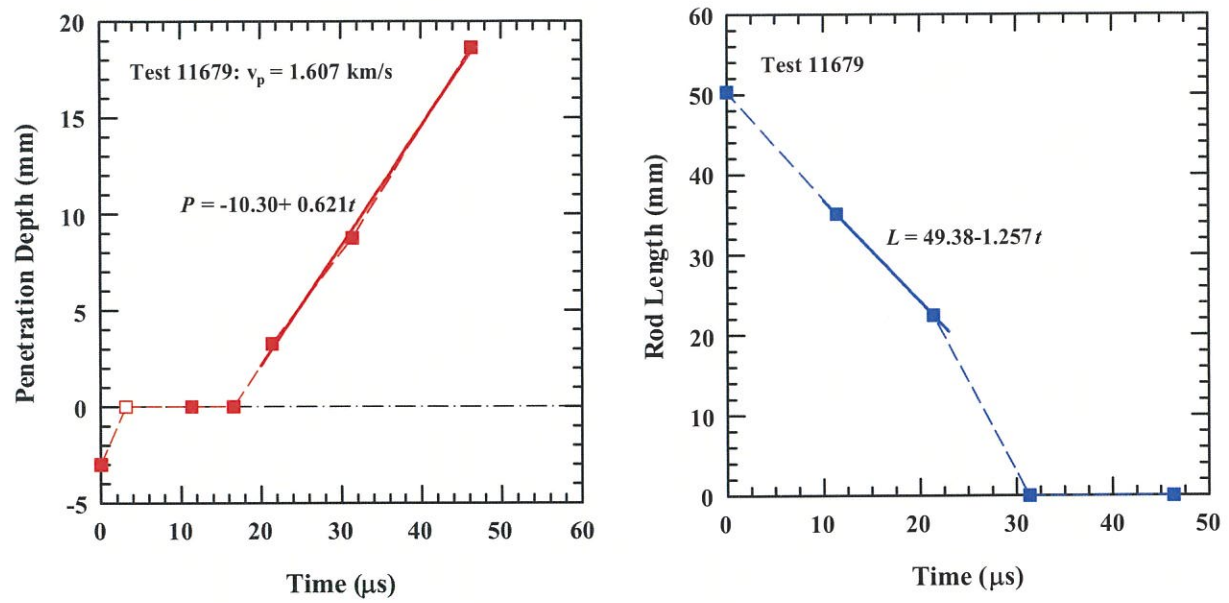


Figure B-34. Penetration vs. time and rod length vs. time for Exp. 11679: $v_p = 1.607$ km/s.

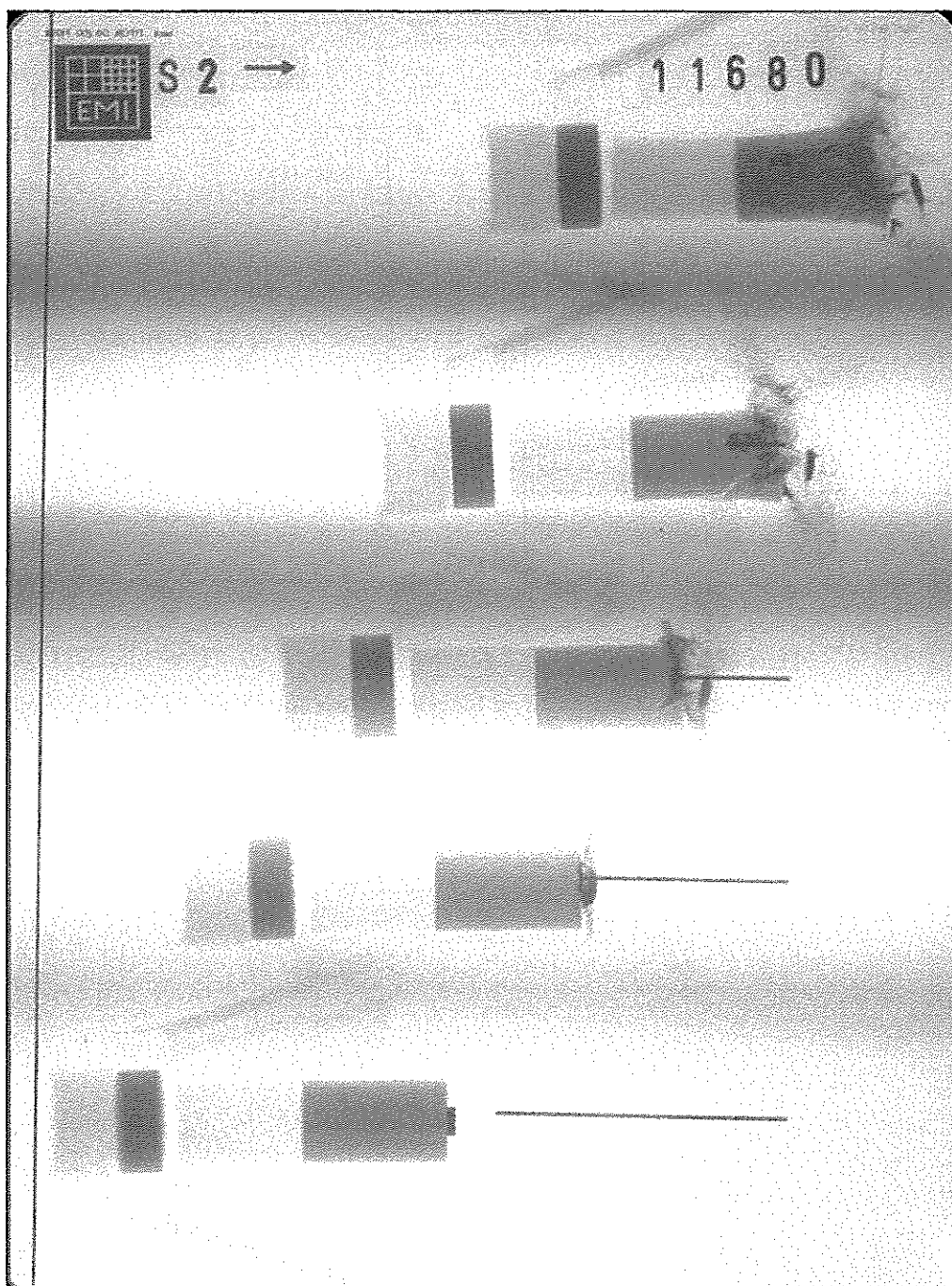


Figure B-35. X-ray picture for Exp. 11680: B2 buffer, $v_p = 1.585$ km/s.

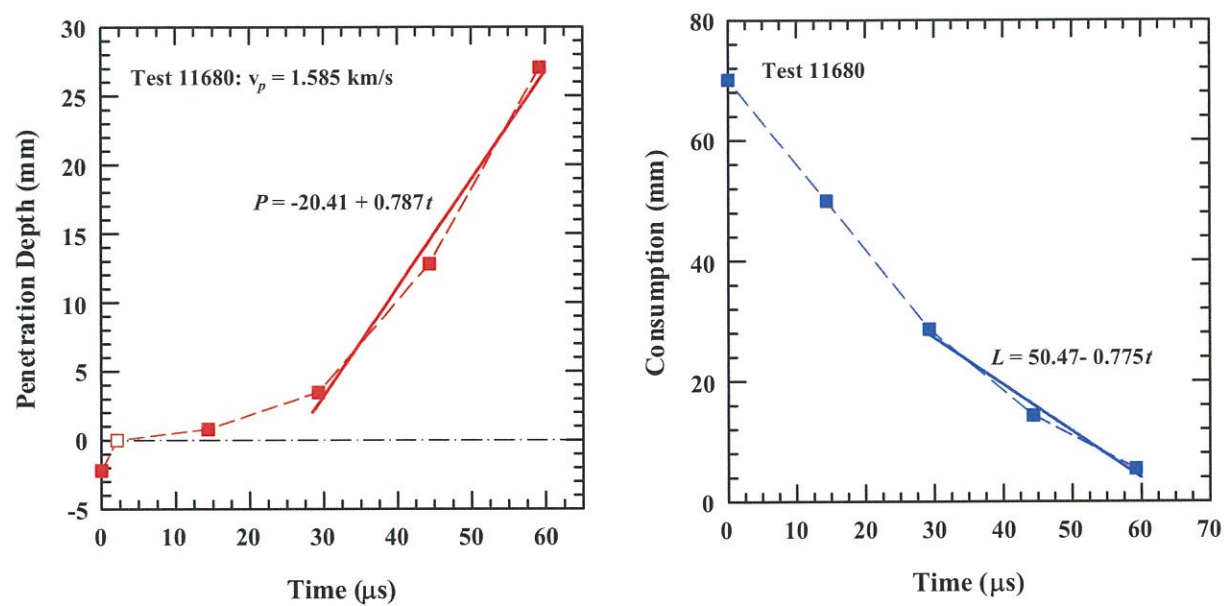


Figure B-36. Penetration vs. time and rod length vs. time for Exp. 11680: $v_p = 1.585$ km/s.

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