CAPACITOR DISCHARGE JOINING

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For Mom and Dad and all the kids.

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ABSTRACT

Capacitor Discharge Joining

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Although the capacitor discharge welding process has many applications, it has been limited to studs less than 3/8" in diameter. This limitation comes from an incomplete understanding of the fundamental process and key variables that influence the resulting fusion joint.

The objective of this investigation was to conduct a fundamental study of the capacitor discharge welding process in order to develop a model of the basic weld cycle.

The following parameters were systematically varied to determine their effect on the weld: voltage, capacitance, drop height, drop weight, ignition tip geometry, shielding gases, base plate surface condition, and polarity.

The weld cycle was studied by recording and analyzing the welding current and arcing phenomenon, the impact of the stud on the base plate with an accelerometer, and with high speed videography. Weld mechanical

strength was checked by tensile testing. Fracture surface, cross section, and microstructural examinations were conducted with optical and scanning electron microscopy.

From the work the following generalized conclusions have been made:

1. The optimum voltage for carbon steel is approximately 100 volts.
2. The capacitance is dependent on the cross sectional area of the stud.
3. Wetting agents enhance weld strength and consistency.
4. Similarly, shielding the weld with certain gases improve weld integrity.
5. The drop weight and height influence both the speed and force of impact. It is important to co-ordinate these two parameters to insure proper weld cycle timing.
6. Using the fundamental understanding developed, full strength 1/2" diameter welds, previously unweldable, were successful.

INTRODUCTION

The Capacitor Discharge (CD) welding process is a method of attaching variously configured projections to another piece of metal. Alloys that can be joined include steel, aluminum, titanium, vanadium, zinc, and copper. Typical applications extend into heavy construction, transportation, ship building, cabinetry, cookware, and microelectronic circuitry. The equipment used to make the welds can be portable or stationary production machinery.

The basic welding set-up (Fig. 1) consists of a capacitor bank, a mechanism that holds and directs the stud to be welded, and a controlling circuit that co-ordinates the charging and discharging of the capacitor bank. After placing a stud in the fixture and activating the controller, the capacitor banks are charged and the stud is pushed against the second component. When the stud contacts the second component the stored electrical energy in the capacitor bank is discharged between the two pieces. The molten pool that is produced by the arc solidifies rapidly after the two components contact each other. The weld is completed in approximately 2 milliseconds.

The advantages of CD welding are that it is fast, it requires little operator skill, it is adaptable to many applications and materials, heat input is minimized, and the cooling rates are high enough that sensitive and thin materials can be welded with little chance of base material degradation. The process, however, has been limited to stud diameters less than 3/8 inch in diameter. This limitation existed because not all aspects of the welding process were entirely understood. For example, it was not known what role the ignition tip on the face of the stud played in the weld cycle. Some suggested that it was the source of molten metal that bonded the two components together. Others said it was only there to establish the arc, and that it was vaporized in the first few microseconds of arcing. [1-3] The effects of other parameters, too, are unclear. How does changing the voltage differ from changing the capacitance? What influence does the speed of the stud prior to impact have on the weld strength and why?

This study was undertaken to develop a basic understanding of the CD welding process and use the understanding to improve weld quality and consistency, and to increase the pin size. With the influences of the weld parameters known, it would be easier to model the sequence of events of a CD weld, and with an accurate model, the sequence could be manipulated and improved. To that end, eight process variables were systematically varied. The weld cycle was studied by recording the weld current and the impact of the pin on the base plate. High speed videography movies (12,000 frames per second) were also taken.

EXPERIMENTAL PROCEDURE

MATERIALS

The material that was used for 1/4" welds was 1018 cold rolled steel. The 1/4" pins were manufactured by a commercial manufacturing company. The ignition tip section pins were machined from cold rolled 1018 1/4" round stock.

When working with the larger diameter pins, it was necessary to use a different base plate material. The cold rolled 1018 plate had a tendency to delaminate at tensile strengths less than that of the weld strength. The new base material was A36, with the rolling direction of the base plate parallel to the pin, not perpendicular as was the case with the 1018 base plate.

EQUIPMENT

Welder

The welds were made with an Erico Jones Model PSW-100 Capacitor Discharge Production Stud Welding System. Some additions and modifications were made to the system. They included:

1. The design and fabrication by the Erico Jones Company of a weld head velocity measuring system.
2. The incorporation of a shot filled canister on the drop head as a substitute for the solid weights normally provided. This was done to reduced drop head rebound.

3. The installation of an Endevco accelerometer and associated amplification equipment. This permitted the quantitative and qualitative evaluation of drop head impact. Approximately half way through the project the accelerometer was replaced by another that had a greater range.
4. The installation of a calibrated shunt in the power cable of the welder to provide a welding current signal.
5. The addition of an auxiliary capacitor bank.

Monitoring and Recording

The equipment used to monitor and record the welding process included:

1. For approximately the first half of the project, a Tektronix Differential Probe, Model P6046, and associated amplifier was used to sense the welding current. The probe permitted sensing the voltage developed across the shunt without using two oscilloscope channels. A more accurate current record was possible without the probe, however, and it was removed. The shunt's signal was then fed directly into the oscilloscope.
2. The current signal and the accelerometer's signal were fed into a Sony-Tektronix Digital Storage Oscilloscope. The oscilloscope was capable of recording up to eighteen separate waveforms, which were then transferred to permanent paper copy and floppy diskette.

High Speed Videography

The high speed videography equipment was a Spin Physics 2000 System. It was capable of up to 12,000 partial frames per second with two cameras. When two cameras were used, one recorded the weld event, and the other recorded the line trace on the oscilloscope. This permitted the association of weld events to the recorded electrical signals.

WELDING PROCEDURES

Sample Preparation

Except in the surface conditions section, all parts (pins and base plate) were cleaned in acetone prior to welding. The base plate was surface ground.

Parameters Varied

Eight different welding parameters were evaluated. Table I lists the welding conditions.

Prior to actual testing, Baseline parameters were established. The parameters, obtained from the CD welding industry, were typical for this size weld. The Baseline was used as a basis for comparison for all following work. The specific parameters were:

1. Voltage	125
2. Capacitance	80,000 μF
3. Drop height	2 inches
4. Drop weight	5 pounds, lead shot
5. Polarity	reverse

6. Ignition tip .04" X .04", conical, 4° bevel on pin face

7. Base plate surface ground, acetone cleaned, dry

8. Atmosphere air

b. Voltage. Five different voltages were tested. They were 70, 90, 110, 135, and 150. The voltage was controlled by a rheostat built into the welding machine that charged the capacitor bank to the required voltage.

c. Capacitance. Three capacitances were used, including 40,000 μF, 120,000 μF, and 160,000 μF. The capacitance was varied by physically connecting more or less capacitors to the weld machine buss network. The capacitance values stated throughout this report are taken from the capacitor label. Each capacitor is labelled 8,000 μF. It is common to call this size capacitor a 10,000 μF capacitor. The manufacturing tolerance is the stated value plus 50%, minus 10%. Actual capacitance as measured by a decay time method indicated a typical value for these particular capacitors to be 9,000 μF.

d. Drop Height. Weld head drop heights (initial gaps) of 1/4", 1" and 3" were evaluated. The drop height was controlled by setting a stop on the drop head ram.

e. Drop Weight. Three drop weights 2, 5, and 8 pounds, all in solid form, were used. The Baseline drop weight was 5 pounds, but in lead shot form. The results of the two different forms of the weight were compared, and the testing was continued with the solid form because it produced better results. The weight was attached to the top of the drop head.

f. Base Plate Surface Condition. Five conditions of the base plate surface were analyzed. Three different wetting agents were applied to the surface, and welds were also made through hot rolling mill scale. The wetting agents were 1) distilled water, 2) soapy water, and 3) glycerol. The surface was tested dry after being cleaned with methanol. The liquids were applied to the surface with a brush, forming a continuous film where the weld was to take place. Except for the rolling scale, the base plate had been surface ground prior to the application of the wetting agent.

g. Shielding Gases. Welds were made in five different atmospheres. They included argon, argon plus 2% oxygen, carbon dioxide, helium, and a welding gas called trimix, which is 90% helium, 7.5% argon, and 2.5% carbon dioxide. The atmospheres were maintained around the weld by a plastic shroud that had a hole in the top large enough for the pin to enter and complete the weld. The gas was delivered at a rate of 50 to 150 standard cubic feet per hour, depending on the gas.

h. Polarity. Straight polarity was tested by switching the welder's electrical leads between the grounding clamps and the drop head.

i. Ignition Tips. The ignition tips on the pin faces were varied and evaluated. Two different geometries, conical and cylindrical, with three sizes for each geometry were used. For the conical geometry, ignition tips .030" in diameter at the base and .020" long, .040" X .060", and .040" X .040" were welded. The cylindrical sizes included .040" X .040", .020" X .040", and .060" X .030". All had a 4° bevel on the face of the pin except the conical .040" X .040" tip.

Welding

Ten welds were made for each condition in every section. The studs were welded in a line on the base plate, approximately one inch apart. The welder's air actuated clamping mechanism was used to hold the base plate and to provide the circuit ground. The clamping points were approximately two inches on either side of the weld point. The welding parameters were varied systematically depending on the section being evaluated.

MECHANICAL TESTING

After the welds were made, the base strap was sectioned to obtain the tensile specimens and specimens for microscopic examination. This was done by making a saw cut midway between two studs (Fig 2). The excess base metal was cut off the specimens that were to be mounted, ground and polished.

All tensile specimens were pulled in a Tinius-Olson Super "L" hydraulic tensile machine. A special fixture was machined into which the specimen base plate fit. The pin was gripped by an Instron Wedge Action Grip. The specimens were pulled to failure, the highest load being recorded.

METALLOGRAPHY

The specimens to be microscopically examined were mounted in a carbon impregnated conductive compound. They were ground to the centerline of the pin and polished up to and including .05 micron alumina powder. Each was etched for approximately 10 seconds in 2% Nital etchant.

The sectioned specimens were examined with both a light microscope and a scanning electron microscope (SEM). They were examined for porosity, heat affected zone dimensions, microstructure, and any other distinguishing characteristics. The tensile specimen fracture surfaces were examined in an SEM.

RESULTS

The results of the experimental work are arranged by welding parameter. Each section is compared to the Baseline, and the tensile specimens' strength, fracture location and appearance are discussed. Due to interest in the role of ignition tip on the weld cycle, comments are made regarding the ignition tip's post-weld condition. Because the equipment used to collect the current and acceleration curves was changed mid-way through the project, and because that equipment had an influence on the nature of the curve recorded, the equipment used for each particular section will be mentioned before the curves are described. A summary of the tensile data is listed in Table II.

Baseline

a. Tensile strength

Approximately one-third of the tensile specimens broke in the pin, while the remaining pulled out of the base plate. The strength of those pins that failed in the pin were in the same range as those that failed in the base plate. None of the specimens broke in the weld zone.

b. Fracture surfaces

Not all of the pin face fused to the base plate. Examination of the fracture surfaces showed fractured metal and smooth shiny areas

(Fig. 3). The smooth areas appeared to have been molten at one time during the welding process, but had not bonded to the base plate. About 10% of the pin face had this unbonded appearance. Generally, the unbonded area was around the pin circumference.

It was not possible to see if any of ignition tips had survived the welding cycle.

c. Current and acceleration

The current curves of the Baseline welds were collected without the differential probe, and indicated that there was current flow for about 1.25 milliseconds (Fig. 4). The peak current averaged 90,000 amperes. There was a large positive discontinuity after the current had returned to zero. This positive spike was followed by a period of "negative" current flow.

The acceleration curves, obtained with the high range accelerometer registered an impact force approximately 450 times the force of gravity (450 g's) that occurred about 1.5 milliseconds after the beginning of the current flow. The large impact was followed by damped oscillations.

Voltage

a. Tensile strength

The highest and most consistent tensile strengths were obtained with applied voltages of 90 and 110 (Fig. 5). These welds averaged approximately 4000 to 4200 pounds or 82 to 85 KSI. If the voltage was decreased to 70 the tensile strength dropped rapidly to less than 3000 pounds. Similarly, with an increase to 125 volts or higher, the strength fell to 3800 pounds or lower. The poorest tensile values, 2340 pounds, resulted from 150 volts.

b. Fracture surfaces

In general, there was a direct correlation between the percent of pin face bonding and the tensile strength. The strongest welds (90 to 110 volts) were bonded over at least 90% of the pin face (Figs. 6 & 7). These welds broke either in the pin or in the base metal, but not in the weld zone.

With 70 volts, only 50% bonding occurred (Fig. 8) and failure occurred in the weld zone. Portions of the pin faces still had machining marks on them, indicating complete melting had not taken place during the weld.

At higher voltages the amount of bonding was again 50% or less and fracture occurred in the weld zone (Figs. 9 and 10). And, although the entire surface had at one time been molten, the ignition tips were still discernable in most of 135 and 150 volt welds.

The splatter on the base plate surrounding the pins changed from almost non-existent at 70 volts to wide-spread and violent at the higher voltages.

c. Current and acceleration

All of current and impact data was collected using the differential probe and low range accelerometer (Figs. 11 - 15). Current flows peaked between 80,000 and 500,000 amperes, and lasted between 3 and 3.25 milliseconds.

There was usually one dip in the current curves. At the lower voltages it was to the left of the peak current, but as the voltage was increased the discontinuity shifted to the right until it occurred just as the highest current was reached.

Deceleration values ranged from 170 to 350 g's. Approximately half of the curves were flat bottomed indicating that the amplifier capacity had been exceeded. There was no pattern between the applied voltage and impact forces.

Capacitance

a. Tensile strength

The capacitance that produced the strongest welds was the Baseline of 80,000 μF. When 40,000 μF were used, the strength dropped from 3875 pounds (78.9 KSI) to 3450 pounds (70.2 KSI) (Fig 16). Increasing the capacitance above the Baseline also resulted in lower tensile strengths, with 120,000 μF producing an average of 2670 pounds (54.4 KSI), and 160,000 μF holding 1810 pounds (36.9 KSI).

b. Fracture surfaces

At least 15% of the pin faces failed to bond when the capacitance used was 40,000 μF (Fig. 17). The higher capacitances increased that number to approximately 50% and 60% for 120,000 μF and 160,000 μF respectively (Figs. 18 & 19). This lack of bonding made it possible to see the pin face center and confirm that at least part of the ignition tips survived arcing. At 40,000 μF there was too much base metal attached to the pin to make this observation.

c. Current and acceleration

All of the current and acceleration data were collected using the differential probe and the low range accelerometer (Figs. 20 - 22). The time of current flow increased from 2.2 milliseconds with 40,000 μF to 4 milliseconds with 120,000 μF and higher. The peak amperage also increased with capacitance from 80,000 to 120,000 amperes. For all three capacitances there was one small current downturn about 1 millisecond into the weld. There were the usual larger negative transients at the very beginning and end of the weld.

All three capacitances produced similar impact curves. They all over-drove the amplifier at 300 g's and produced a clipped signal. The start of impact coincided with the small current downturn.

Drop Height

a. Tensile strength

Drop heights (initial gaps) of 1 and 2 inches (2 being the Baseline) produced the strongest welds (Fig. 23). If a 3" drop was used, the strength was 600 pounds (13 KSI) less than the Baseline of 3875 pounds (78.9 KSI). There was a drastic drop in strength when the drop height was 1/4". The decrease was 2300 pounds (47 KSI) below Baseline, for an average strength of 1538 pounds (31.3 KSI). The 1/4" drop welds failed in the weld zone, while the others failed in the base metal.

b. Fracture surfaces

The 1" drop resulted in the most consistently bonded surfaces, with less than 5% of the pin face not fused to the base plate (Fig. 24). Because bonding was so complete, it was not possible to see the ignition tip. There were significant differences between the 3" and 1/4" drops. The 3" drop resulted in a 70% to 80% bonded surface, and there was an extensive network of ridges on the surface that may have been caused by excessive splatter or bouncing of the pin prior to solidification (Fig. 25). At the other extreme, 1/4" drop, there were very few places that had actually contacted the base plate (Fig. 26). The entire surface had been melted, as evidenced by the smooth, flowing appearance, but only local high spots, less than 25% of the face, touched the base plate. The ignition tip, originally a sharp cone, was still visible but much more smooth and rounded.

c. Current and acceleration

All of the current and impact traces were gathered with the differential probe and low range accelerometer (Figs. 27 – 29). The small current anomaly that usually occurred prior to the peak current was nonexistent for the 1/4" drop, to the left of the peak current for the 1" drop, and in its normal position to the right of the peak current for the 3" drop. When present, it again coincided with the impact indication from the accelerometer. The impact force increased from 120 g's at 1/4" drop, to 280 g's with the 1" drop, and finally to a flat bottomed curve at 300 g's for the 3" gap.

Drop Weight

The Baseline used five pounds weight in the form of lead shot. This section first tested a five pound solid steel weight, and based on those results, continued with other solid weights.

a. Tensile strength

All of the solid weights produced welds that were stronger than the Baseline (Fig. 30). There was very little difference in strength for the three weights used, which included two, five, and eight pounds. The highest average strength, 4730 pounds (96.4 KSI), was only 400 pounds stronger than the low of 4330 pounds (88.2 KSI).

b. Fracture surfaces

Like the tensile strengths, the fracture surfaces were similar for all solid weights. Less than 10% of the pin face failed to fuse to the base plate and the lack of fusion did not occur in any one general area (Figs. 31 - 33). All of the tensile tests failed either in the pin or the base plate, not in the weld zone. Because there was so much base plate still attached to the pin, it was not possible to make ignition tip observations.

c. Current and acceleration

The current and impact records were gathered without the differential probe in the circuit and with the high range accelerometer. Peak currents of 200,000 amperes were recorded, with total current flow lasting 1.75 milliseconds. For all weights there was one current anomaly that appeared approximately one millisecond into the weld (Figs. 34 - 36).

The impacts registered 350 to 400 g's, with no discernable correlation between weight and impact force. The curves showed a minor indication at the beginning of the weld, and a double negative peak that closely followed the current anomaly. All of the acceleration traces ended with damped oscillations.

Wetting Agent

a. Tensile strength

Wetting agents on the base plate surface tended to improve the strength and consistency of the welds. Specifically, distilled water and soapy water resulted in improvements, while glycerol reduced weld quality (Fig. 37). When the scale from hot rolling was left on the base plate, the welds were stronger than the Baseline. The surface that was ground, cleaned with methanol, and dried produced the weakest welds of this series. Those welds were 500 pounds (20 KSI) weaker than with Baseline conditions, and the standard deviation tripled. The distilled water produced welds that were 300 pounds and 6 KSI better than the Baseline. More significantly, there was very little scatter in the data with a standard deviation of only 100 pounds. The remaining surface treatments' strengths and consistency were between the distilled water and methanol cleaned values.

b. Fracture surfaces

The amount of unbonded surface on the pin face ranged from 15% with the distilled water treatment, to approximately 45% when glycerol was used (Figs. 38 - 42).

The ignition tips were generally not visible on the fracture face. This was due to the base plate metal remaining on the pin face. When the failure occurred in the base plate, there was evidence of base metal delamination. Only the dry, methanol cleaned condition experienced failures in the weld zone.

c. Current and acceleration

All of the current curves were made using the differential probe and low range accelerometer. And, with the exception of the mill scale condition, the resulting curves were very similar (Figs. 43 - 47). There was current flow for 3 milliseconds, with one small disturbance near the 2 millisecond mark in an otherwise smooth trace. The maximum amperage, averaging 1,200,000 amperes, was reached in approximately .25 milliseconds. When there was mill scale on the base plate, numerous large positive spikes were seen. These spikes usually occurred near the beginning of the weld, resulting in currents greater than 1,200,000 amperes.

The acceleration curves were flat bottomed, with one large impact developing 250 g's, and beginning 1.5 milliseconds after the weld cycle start. The beginning of deceleration preceded the disturbance in the current trace.

Shielding Gas

a. Tensile strength

Results in this section indicate that a shielding gas is beneficial. Of the five gases tested, only helium produced welds that were weaker than the Baseline. The strengths ranged from 4150 pounds (84.5 KSI) when using argon, to 3710 pounds (75.6 KSI) with helium (Fig. 48).

b. Fracture surfaces

Approximately one fourth of the tensile specimens broke in the pin, and the remainder pulled metal out of the base plate. Only two helium shielded welds failed in the weld zone. Fracture surface studies revealed more than 95% of the pin face had fused to the base plate (Fig. 49 - 53), and lack of fusion was observed only near the pin circumference. Areas that had not bonded had been melted during the weld. The ignition tip region of the pin face was not visible.

c. Current and acceleration

Because the current and acceleration curves for all of the gases tested in this section were similar, they will be described only once (Figs. 54 - 58). The current records were made using the differential probe in the sensing circuit. The weld current time averaged 2.75 milliseconds, with the impact in the acceleration curves occurring after 1.25 milliseconds. The acceleration curves were generally not flat bottomed, but "V" shaped, with a maximum of 260 g's recorded. The current reached a peak value of 600,000 amperes after .25 milliseconds, started to decrease slightly, and then increased again at the point of impact.

Straight Polarity

a. Tensile strength

Switching the polarity from reverse (Baseline) to straight, increased the tensile strength 400 pounds, or 8 KSI. The standard deviation increased from 8.1 (Baseline) to 11.4 KSI.

b. Fracture surfaces

The welds failed in the base plate during the tensile tests. The fracture surface was all base plate material, with less than 5% unfused area (Fig. 59). The ignition tip region of the pin face was obscured.

c. Current and acceleration

The current curves for this section were obtained without using the differential probe in the circuit (Fig. 60). They were similar to the Baseline reverse polarity curves, and the weld time averaged 1.3 milliseconds. The maximum current recorded was 90,000 amperes, and this was reached in .2 milliseconds. There was one discontinuity in the current curve, and it appeared just as the current was returning to zero at the end of the weld cycle.

The acceleration trace showed one large impact 1.75 milliseconds after the start of current flow, and it reached a peak value of 450 g's. The impact indication was followed by a rapidly decaying sine wave.

Ignition Tips

Each ignition tip geometry will be discussed individually because several tip dimensions were changed making it difficult to directly compare the results.

a. .04" X .06", Conical

This section's ignition tip had the same diameter, .040", and the same geometry, conical, as the Baseline, but its length was increased from .040" to .060". The length change resulted in a higher average tensile strength by 200 pounds, or 4 KSI. The welds generally failed in the base plate.

Most of the fracture surface consisted of material pulled from the base plate, though 15% of the surface showed unbonded areas (Fig. 61). The pin face regions not bonded to the base plate had been molten however, and were not located in one general area. There was the normal weld splatter on the base plate, but there was more than the usual amount on the side of the pin.

Two of the pin faces had little enough bonding in the ignition tip region to see that part of the ignition tip had survived the arcing.

The current curve was made with the differential probe (Fig. 62). There were two notable features on the current curve. One was .5 milliseconds into the weld where the steep slope of the initial current temporarily moderated, then increased again until the peak current of 900,000 amperes was reached. The second occurred 2 milliseconds into the weld where the negative current slope became less negative, and then continued to zero. This second discontinuity corresponded to the major bump in the acceleration curve.

The acceleration curve had only one indication, that being a "V" shaped negative spike, placed about 2.25 milliseconds after the start of current flow. The entire weld cycle was 3.5 milliseconds long.

b. .030" X .020", Conical

When the length of the ignition tip was half that of the Baseline, there was a drastic drop in tensile strength. This section averaged 2200 pounds, or 45 KSI less. All of these welds failed in the weld zone, and, although the entire pin face had been molten, the amount of unbonded area was greater than 85% (Fig. 63). All of the ignition tips remained on the pin face after the weld.

The current curve was obtained using the differential probe in the circuit (Fig. 64). There was one anomaly on the curve, and that was a positive spike that occurred at the peak current, about 1 millisecond after the start of current flow. Including this spike, the maximum current reached was 1,800,000 amperes. The entire weld cycle lasted 2.7 milliseconds.

The acceleration curve consisted of one negative transient, 1 millisecond into the weld, that was "V" shaped and corresponded to the spike in the current record.

c. .040" X .040", Conical, no pin face bevel

To test the effect of the pin face bevel, this section, with the same size ignition tip as the Baseline, but without any bevel, was tested. It was weaker than the Baseline by 1400 pounds or 28 KSI and all of the tensile tests failed in the weld zone. Approximately half of the pin face did not bond to the base plate (Fig. 65). Usually the center portion of the pin, where the ignition tip was located, was the only area of fusion. The weld splatter on the base plate around the pin had a more violent appearance than usual. Because there was so little fusion, it was possible to observe some of the ignition tips on the fracture face.

The current curves were recorded without the differential probe (Fig. 66). The greatest amperage was 100,000 amps, reached less than .25 milliseconds into the weld, with a total time of current being 1.2 milliseconds. There was a change in slope as the current was decaying back to zero, and this was .75 milliseconds into the weld.

The acceleration trace displayed minor disturbances corresponding to the beginning of the current, and a double negative excursion following the return of the current to zero. The large negative excursion registered 400 g's, and was placed 1.5 milliseconds into the weld cycle.

d. .020" X .040", Cylindrical

When the diameter of the ignition tip was halved and the geometry switched from conical to cylindrical, the strength of the weld decreased by 900 pounds, about 18 KSI.

The welds failed partially in the base plate, and partially in the weld zone. The fracture surfaces revealed lack of fusion over 50% of the pin face, with the unbonded areas randomly located (Fig. 67). Although it was possible to see the center of the pin where the ignition tip had been, there were no ignition tips remaining.

The current traces were obtained without the differential probe (Fig. 68). The current increased to a maximum of 220,000 amperes in .3 milliseconds, and then decayed to zero in another 1.75 milliseconds. About 1 millisecond after the peak current there was a small positive increase before zero was reached.

Due to instrumentation problems, there was no useful acceleration information obtained.

e. .040" X .040", Cylindrical

This size ignition tip was tested to compare the difference between the cylindrical and conical geometries with the same diameter and lengths. The cylindrical produced welds that failed at strengths 1550 pounds (31 KSI) less than the Baseline, which was conical.

The tensile tests failed in the weld zone. Although it appeared that the entire pin face had at one time been molten, 25% had not bonded to the base plate (Fig. 69). That 25% area was always located on the face circumference.

It was possible to see several ignition tips on the fracture surfaces. It appeared as though enough of the ignition tip had survived the arcing to prevent the mating of pin and the base plate.

The differential probe was not used for the recording of the current curves (Fig. 70). Those current records indicated that a maximum current of 275,000 amperes was reached in .3 milliseconds, and that there was current flow for 1.4 milliseconds. The curves were relatively smooth, with a change in slope midway between the peak current and the end of the weld. A second anomaly occurred after the current had returned to zero.

The acceleration traces consisted of minor indications that started when the current started, and a larger negative spike 1.75 milliseconds after the start of the weld. It registered a force of 350 g, and followed the second anomaly in the current curve.

f. .060" X .030", Cylindrical

This final ignition tip had a shorter length but larger diameter tip. The tips were massive enough that they deformed on impact and passed all the weld energy without establishing an arc. Only two of the specimens actually welded to the base plate (Fig. 71).

The current trace, recorded without the differential probe, increased to a peak current of 300,000 amperes in .25 milliseconds and decayed smoothly to zero in another 1 millisecond (Fig. 72). There were no discontinuities in the traces. The accelerometer output recorded one minor disturbance that corresponded to the beginning of the current flow, followed closely by a larger 200 g impact. The trace then was similar to a decaying sine wave.

Larger Diameter Studs

One of the original project objectives was the ability to weld larger than 1/4" diameter studs. Instead of a parametric study, however, a factorial study was necessary to consider the combined effects of each parameter on the others.

First 3/8" welds were attempted. The cross sectional area was calculated and compared to that of the 1/4". Since there was increase in area from .05 in^2 to .11 in^2, the power, assuming a linear ratio, had to be increased by a factor of 2.25. Although both voltage and capacitance were considered as possible alternatives to obtain the power increase, the previous work indicated that a voltage increase may not be able to deliver the correct energy without detrimental effects. It was found that the larger studs could tolerate slightly higher voltages than the smaller studs, up to approximately 110 volts, but then the strength dropped. The capacitance proved to be the better parameter to provide the extra power, and it was increased by a factor of 2, close to that of the cross sectional area increase.

The next parameter considered was the drop height. It was known that a minimum drop height caused less molten metal expulsion so the optimum 1" stud drop height was used with the 3/8" pins. As the drop was varied to either side of the 1" mark, mechanical properties again fell. The 1" drop, then, was best for all diameter studs.

With drop height and power requirements set, the next task was to match the ignition tip to the new values. The current curves were extremely useful in this determination. With the curves it was a relatively simple process to match the point of pin face impact to the exhaustion of the stored electrical energy by altering the length of the ignition tips (Fig. 73 and 74). The best strength was obtained with a .060" long ignition tip.

Finally, the drop weight had to be matched to the larger studs. The 1/4" pin relationships indicated that the weight had to be increased to approximately 11 pounds. This was found to be surprisingly accurate, with the best 3/8" diameter welds being made with 12.5 pounds. With all of the parameters optimized, 8966 pound (81.2 ksi) tensile strength welds were made.

After the 3/8" studs were successfully welded, 1/2" diameters were attempted using basically the same procedure as the 1/4" to 3/8" upgrade. The linear area/capacitance relationship was found to hold, so the capacitance was increased to 320,000μF, with voltage, again, remaining at 110 volts. The ignition tip length also required a linear increase from the 3/8" value to .085". The optimum drop height remained 1" as expected, and the best drop weight also changed very little. Essentially, the only parameters that needed a proportionate increase to provide full strength 1/2" welds were the capacitance and ignition tip length. The best 1/2" stud tensile strength averaged 14900 pounds (75.9 ksi).

One problem encountered with the larger studs that had not been seen at the smaller diameters was the tendency to form hot cracks formed in the metal during solidification. As the metal cools and solidifies, it shrinks. If there is not enough liquid metal to feed the voids vacated by the contracting metal, the voids remain. The problem was unique to the larger studs because, for the same pin face bevel angle, the vertical distance difference from the pin center to the edge was greater than the smaller diameters. The problem was solved by changing the bevel on the pin face from 4° to 2° for the larger studs.

High Speed Videography

Although the videography did not constitute a separate experimental section, it was used on several occasions and the resulting high speed movies did support many of the facts presented. For example, calculations indicate that an electric potential in the range used for CD welding can jump a gap of less than one thousandth of an inch [4], and the arcing that would take place for the amount of time it would take the pin to transverse this distance is insignificant. The movies visually proved that no arcing occurred until the ignition tip had touched the base plate. In addition, video sequences demonstrated arcing is directly proportional to the length of the ignition tip. (Figs. 75 and 76). The arcing of a .060" long ignition tip consists of three times as many frames as a .020" tip. In the case of the mill scale covered base plate, the current records showed that the current was unstable and underwent several rapid transients. The videos confirmed that these transients were the result of the arc moving randomly around the pin face instead of gradually developing from the ignition tip to the outer circumference. In these and other situations, the videos were an independent information source.

DISCUSSION

Instrumentation

Evaluation of the current sensing differential probe revealed that a more accurate current record could be obtained without the probe. The current values indicated by the differential probe were excessive and inconsistent. Due to the extreme current transients, it was difficult to confirm exactly which signals were real and which were equipment artifacts. For example, the large negative spike that occurred at the beginning of current flow is in question. One opinion is that it is a reaction to a real, positive spike just before the negative one. [5] An effort was made to confirm the presence of that positive spike, but no conclusive evidence was obtained. Another opinion states that the negative spike is a recording equipment artifact, and that it does not exist in the welding circuit. [6] In light of these uncertainties, the current values obtained with the differential probe should be viewed with caution.

The higher range accelerometer also provided a more accurate record than the first one. The lower range accelerometer developed a signal that was greater than the amplifier was designed for. This produced the clipped or "flat bottomed" acceleration curves in the first half of the project. The higher capacity accelerometer developed signals that were within the range of the amplifier, and that were also in the ranges expected, given the welding set up.

The digital storage oscilloscope provided an adequate method of recording the desired signals. A system for transferring the curves from the oscilloscope to floppy disc was developed and used to retain the weld records. This provided a back-up to the paper copies taken from the oscilloscope.

The current and acceleration curves were useful in determining the optimum parameters for the larger diameter studs. For example, the current trace made it possible to determine how long the ignition tip needed to be to deliver the stored electrical energy. Because the capacitance had been increased from the 1/4" studs, the exact ignition tip length was not known.

The high speed motion analysis was extremely useful in confirming many aspects of the weld cycle. The video tape format has the disadvantage of less resolution compared to photographic film, but does have the important advantage of immediate playback.

Baseline

The average strength of the Baseline was 78.9 KSI. Either the pin itself failed, or material was pulled from the base plate. The weld, then, was a full strength weld that was stronger than the base materials. These welds were good to use as a comparison for the work following.

Voltage

Of the six voltages tested on 1/4" pins, 90 volts produced the strongest welds. The larger diameter studs used slightly higher (100 - 110) voltages. The high speed videography indicated that arcing associated with lower voltages developed more slowly across the pin face than that of higher voltages. In addition, the splatter surrounding the stud after the weld had a more violent, thrown appearance in the higher voltage welds. On the other extreme, 70 volt welds displayed pin face areas that had not been contacted by arcing and still had machining marks on them.

Based on these observations, the voltage appears to be critical in determining the activity of the weld. It is possible to use too little voltage, as evidenced by the cold welds resulting from 70 volts. However, it is just as important to avoid generating excessive amounts of violence by using too much voltage. This excessive activity would support the idea that the molten metal developed during arcing "glues" the components together. If too little electrical energy is used, the entire pin face will not be molten, and the weld cannot be complete across the entire face. On the other hand, if too much pressure is developed by the arcing, the melted metal can be expelled before contact and solidification. Some research has shown that a significant amount of pressure is developed in the region of the arc. [7] Though the type of welding investigated was not CD, it did indicate that an arc does develop a positive pressure. If the relationship published could be transferred to CD technology, calculations indicate forces of 10,000 pounds are possible in the arcing region. And, although the relationship between CD and the investigated constant arc process may not be directly related, it is likely that the arc force phenomenon is still significant for CD welding.

Concluding, for steel welds, from 1/4" to 1/2" in diameter, the optimum voltage appears to be 90 to 110 volts.

Capacitance

Of the four capacitances tested, 80,000 μF (Baseline), produced the strongest welds. When the capacitance was decreased to 40,000 μF, the welds were cold. That is, there were portions of the pin face that had not been melted because there was not enough electrical energy. When the capacitance was increased above 80,000 μF, the result was similar to the high voltage condition - more metal was expelled from the weld zone, and incomplete bonding occurred.

Larger diameter studs required additional capacitance in direct proportion to the stud's cross-sectional area. The 3/8" diameter stud, with a cross section 2.25 times that of the 1/4", required 160,000 μF. And full strength 1/2" welds, with 4 times more cross-sectional area than the 1/4", needed 4 times the capacitance, 320,000 μF. This leads to a capacitance/area relationship of 8,000 μF/.0049 square inches of weld surface area, or

$$C\ (\mu F) = \frac{(8000\ \mu F)}{(.0049\ in^2)}\ X\ (\text{pin face area})$$

This linear capacitance-area relationship is useful in determining the amount of capacitance required for steel welds. It eliminates one variable from the list of CD weld parameters. Because it is necessary to have a method of determining the amount of electrical energy for a weld, it is beneficial to have the capacitance determined by the size of the stud, and the voltage pre-determined by the activity needed.

Drop Weight

Four weights were tested: 5 pounds of lead shot, 2, 5, and 8 pounds of solid steel. The solid 5 pounds produced the strongest welds. All of the solid weight welds were stronger that the lead shot welds. Initially the lead shot weight had been incorporated onto the welder to help reduce weld head rebound because accelerometer signals indicated that the shot did reduce the bouncing effect. Welds made with solid weights do have many more reverberations following the initial impact of the pin on the plate. For the conditions tested, however, it is probable that the cooling rate of the weld was so rapid that the welds had solidified before the components could be pulled apart by the head bouncing.

The weight on top of welder influences the impact force. There is a resistance to joining in the form of arc pressure separating the components, and the weight is used to overcome that resistance. It was, however, possible to use too much weight. If more weight than necessary was used, more of the molten metal was expelled from the weld zone, and resulted in less fusion.

As expected, larger diameter studs required greater amounts of weight due to greater forces between the stud and the base plate. Three-eighths inch studs and one-half inch studs required 12.5 pounds of solid weight to produce full strength welds. It was, however, possible to use too much weight for these larger welds also. Twenty pound weights produced weaker 1/2" diameter welds than did the 12.5 pounds.

Other welding conditions may require more elaborate weight set-ups. If, for example, a material with lower cooling rates is being welded, it may be necessary to incorporate a type of shock absorbing system under the base plate. This would keep the components together until solidification was complete. Such a compliance system would need to be matched with the drop weight to insure component mating for the required time without reducing necessary impact forces.

Concluding, the drop weight influences the forces on impact. Five pounds of solid weight is necessary for 1/4" welds, and approximately 12.5 pounds is necessary for 3/8" and 1/2" diameter studs. There did not appear to be a predictable relationship between the weld size and drop head weight.

Drop Height

A one inch drop height produced the strongest welds when compared to the other drop heights of 3", 2" and 1/4". With a drop of 1/4", almost no fusion took place. Although the entire pin face had been melted, the pin did not contact the base plate except in one or two small spots. This implies, that for this drop weight, a 1/4" drop height does not generate sufficient force to overcome the arc resistive forces. It would also indicate that either a definite speed or momentum is necessary to join the components, even though they are in the liquid state.

At drop height of 3 inches, there was evidence of pin bouncing before solidification could occur. The fracture face had ridges on the surface that looked like the components had been pulled apart before solidification had been complete. A comparison might be pulling two glued surfaces apart before the glue has set. In addition, there was more molten metal expelled from the fusion zone by the impact associated with the 3" drop.

The drop height influences two aspects of the pin/base impact. The first is the speed. Because the welder chuck free falls, the higher the drop, the greater the speed just prior to contact. The higher speeds will increase the momentum and promote the tendency to throw the liquid metal from the fusion zone. The speed also affects the timing of the weld cycle. For a given ignition tip length, the arcing time can be increased or decreased by reducing or increasing the drop height, and therefore the speed of the pin, just prior to impact. All of the events of the weld cycle must be coordinated and occur in the proper sequence for the proper length of time. For example, the time available for arcing must be long enough to deliver most of the electrical energy available, but not so long that excessive metal is expelled from the weld zone or that solidification has begun prior to the components contacting each other. To insure that all of these events occur as required, not only must the correct electrical energy and the proper length ignition tip be available, but these must also be matched to the correct pin speed. This is where the drop height is so important. The amount of electrical energy (capacitance) can be determined by the size of the stud being welded. Then the ignition tip and the drop height can be set so that there will be enough, but not too much, time to deliver that energy. It is also desirable to minimize the impact forces, so the drop height should be kept as low as possible without compromising the quality of the weld. The drop <u>weight</u>, then, can be used to overcome the forces resisting the joining. Changing the drop height changes the impact forces and the speed, and therefore timing, of the weld. If the drop height is minimized, one more variable that influences the impact forces is also minimized, and more consistent control can be obtain with the drop weight.

Shielding Gases

The six shielding gases are listed below in the order of decreasing weld strength.

1. Argon
2. CO_2
3. Argon + 2% Oxygen
4. Trimix ($HeArO_2$)
5. Air (Baseline)
6. Helium

In general, shielding gases are used to either protect molten metal from undesirable reactions with the atmosphere, or to promote a desirable reaction in the weld zone.

Only one gas, helium, produced welds that were weaker than those made in air. This indicates that shielding a CD weld is beneficial. Although the tensile strength increases were only a couple thousand pounds, the weld's consistency, based on the standard deviation, was doubled. A statistical confidence test concerning the variance among different types of gases indicated that there was significant difference between some, but not all, of the tested gases. [8]

Wetting Agent

The six surface conditions tested, including the Baseline, are listed below in order of decreasing weld strength.

1. Surface ground, distilled water
2. Surface ground, soapy water
3. Mill scale on hot rolled plate
4. Surface ground, dry, acetone cleaned (Baseline)
5. Surface ground, glycerol
6. Surface ground, dry, methanol cleaned

Two dry conditions were tested, one cleaned with acetone, which was the Baseline, and one cleaned with methanol. Both dry conditions were tested because when a surface is cleaned with acetone, a thin film of residue remains on the surface. The methanol leaves no foreign material. The fact that the completely clean surface (the one treated with methanol) produced the weakest welds in the entire section indicates that almost any wetting agent is beneficial.

High speed videography showed that the arcing on a wetted surface was more uniform. The arc developed more rapidly and did not wander across the pin face. The wetting agents, then, promote a more stable arc, and the electrical energy was delivered more efficiently.

One unexpected result was the relatively good weld strengths obtained with the plate that had not been surface ground and cleaned. The plate had been hot rolled and the mill scale was left on the surface.

It was expected, and the high speed videography supported it, that the scale would interfere with the arcing process. High speed movies of a weld on scale showed the arc wandering randomly around the pin face. For the conditions tested, however, the scale produced no significant drop in weld strength.

Two explanations for this may be possible. The first may be that the scale, or components of the scale, act to improve the weld strength. The other more likely explanation is that the welding parameters used for these welds may be the optimum to weld through a scale surface. For example, the voltage section indicated that 90 volts was the optimum voltage for the Baseline surface condition, clean and dry. It may be that the higher voltage, 125, is better suited for a scale surface.

Comparing the welds made with wetting agents to those shielded by gases, the tensile strengths were approximately equal. Both produced welds that were stronger and more consistent than the Baseline. Either could be used to improve the weld quality and reliability.

Straight Polarity

When the polarity of the 1/4" weld was changed from reverse to straight, the strength of the welds increased. The change was from an average of 3875 pounds using reverse, to 4275 pounds with straight. Although there was no provision for measuring the stud length melted during the weld cycle, it was possible to measure the depth of penetration into the base plate. This was done by magnifying the cross section of the weld and measuring the weld depth relative to the original plate surface. Both conditions, however, averaged melt depths between .008" and .010".

Because the melt depth was similar, the general weld zone appearance was used to estimate preferential melting. Usually more of the original shape of the pin face (ignition tip and bevel) remained after a weld done with reverse polarity. In addition, the pin's edges of the straight polarity welds were more rounded. These conditions indicate that reverse polarity preferentially melts the base plate, while the straight polarity concentrates more heat on the pin side of the weld. High speed videography revealed no differences between the two set-ups.

Due to the preferential melting, polarity could be switched to suit each particular application. If, for example, distortion of the base plate was critical, straight polarity could be used to concentrate the melting to the pin side of the weld.

Ignition Tip

Several objectives were sought in the ignition tip testing. They included the influence on the weld quality by the length, mass, and geometry of the ignition tip, and to find some limits of those dimensions. To these ends, seven ignition tip geometries were tested.

It was found that, in general, the most important parameter of the ignition tip is the length because the tip length controls the arcing time. An ignition tip length of .020" produced very short arcing times. The corresponding weld strength was very poor, and all of these welds failed in the weld zone. Examination of the fracture surfaces revealed areas of the pin face that still had machining marks remaining, indicating that portions of the pin face had never been melted. High speed videography showed that no arcing occurred until the ignition tip had touched the base plate. The current and acceleration curves supported this. They showed the time between the beginning of current until the impact on the base plate was directly related to the ignition tip length. Additionally, the high speed movie of a .060" long ignition tip indicated arcing three times longer than the .020" tip.

The mass of the tip had no direct relationship to weld strength. Though it is possible to have an ignition tip that is too massive or not massive enough, those limits were not as restrictive as the length. For steel, conical tips performed better than cylindrical. For this geometry, the proper length tip was within the mass limits.

The specific dimensional limits included the following:

a. For 1/4" diameter steel studs, the best welds were made with tips that were .040" X .060", conical.

b. If the tip length decreased below .040" or increased above .060", the strength dropped.

c. For 3/8" studs, the best length was .060".

d. For 1/2" studs, the best length was between .085" and .090".

e. The best ratio of tip length to diameter is 3:2. That is, if the length of the ignition tip required is .080", the diameter at the base should be .053".

To test the effect of the bevel on the pin face, some tips were made that were the same as the Baseline, except there was no bevel. These welds were significantly weaker than the Baseline welds, indicating the bevel was beneficial. This may be due to an increased tendency to throw more molten metal from the weld zone by the flat pin face.

The 3/8" and 1/2" welds, however, suffered a lack of fusion around the outer circumference of the weld if the 4^{o} bevel was used. This is because larger diameter pins, with the same 4^{o} bevel, have a greater vertical distance between the center and the edge of the pin face. Better large diameter welds were made with a 2^{o} bevel.

The larger diameter studs were also more susceptible to hot cracking. Hot cracking is a condition that occurs when there is not enough liquid metal to feed the areas that are shrinking due to solidification. The problem is prominent in poorly designed castings where feeding is insufficient and shrinkage is significant, and in more massive welds, also where there is a relatively large amount of metal solidifying. The problem was not encountered with the 1/4" welds due to the small weld zone size and molten metal volume. With larger studs there is more metal to solidify and hot cracking became a problem. If there was no bevel, the arcing, which was more concentrated in the center of the pin, produced a concave pin surface. This exaggerated the hot cracking problem by forming a cavity isolated from any means of filling shrinkage voids. A two degree bevel on the pin face was a compromise that minimized both the shrinkage and the vertical center to outer diameter mis-match problems.

Basic Weld Cycle

Using the information obtained from all sections, the following CD weld cycle model was developed.

The first event in the cycle is the beginning of arcing that occurs when the ignition tip touches the base plate. The peak currents obtained are primarily a function of the welder configuration. The time of arcing is determined by the length of the ignition tip, the amount of energy stored in the capacitor bank, and the pin speed on impact. The optimum arcing time is such that the stored electrical energy is exhausted precisely at the point of pin/base plate impact.

A properly sized ignition tip does not totally disintegrate during the arcing. After the start of arcing and prior to pin face/base plate contact, the leading portion of the ignition tip is melted. The base of the ignition tip, however, should survive the entire arcing process. This probably helps maintain the arc and also may act as a cushion prior to the pin face impact. The arc starts at the ignition tip and travels outward across the pin face. With properly adjusted parameters, the arc contacts and melts the entire pin face and a matching spot on the base plate.

During the final stages of arcing, with both sides fully molten, the pin face should contact the base plate. With proper speed and weight, the two molten pools will contact with a minimum amount of expulsion. Solidification is very rapid, in the order of 10^6 ^{o}C/sec or faster, and should be fast enough to preclude any separation due to rebound.

Summary of Conclusions

1. The most important aspect of obtaining a sound CD weld is controlling the amount of molten metal present in the weld zone.

2. An optimum voltage exists that provides enough energy to melt the required amount of metal, and that does not expel an excessive amount of that metal from the weld.

3. Capacitance is the parameter that is best varied to accommodate the different stud sizes. Too little capacitance will result in a cold weld, and too much capacitance will expel excessive metal from the weld zone. This leads to the capacitance/area relationship of 8,000 μF/.0049 square inches of weld surface area.

4. Drop height controls the speed and forces on impact. It is preferable to use the minimum drop height to minimize the impact and expulsion without compromising the weld strength. The drop height must be matched to the ignition tip length and the amount of electrical energy to be delivered.

5. The drop weight should be used to counteract forces that resist the mating of the pin and the plate. Too little weight will preclude the components contacting fully, and too much will unnecessarily throw metal from the weld joint.

6. It is beneficial to use a shielding gas. For the conditions tested, argon and carbon dioxide produced the strongest, most consistent welds.

7. It is beneficial to use a wetting agent. The wetting agents appear to improve the weld by improving the arc stability. Of the liquids tested, distilled water and soapy water produced the strongest,

most consistent welds.

8. Polarity controls which side of weld, the stud or the plate, is hotter. Depending on the requirements, the polarity can be switched to optimize the final weld.

9. The ignition tip controls the start of arcing and the timing of the weld cycle. It is one of the most crucial parameters in obtaining a full strength weld. The ignition tip (or portion thereof) can and should survive the arcing cycle. If it is completely obliterated, a less than optimum weld will result.

10. Arcing begins when the ignition tip touches the base plate, and in a good weld, covers the entire pin face.

TABLE I

WELDING PARAMETERS

1. Baseline

Volts	125
Capacitance	80,000 μF
Drop Height	2 inches
Drop Weight	5 pounds, lead shot
Atmosphere	Air
Ignition Tip	.040" X .040", conical
Base Surface Condition	Surface ground, acetone cleaned
Polarity	Reverse

2. Volts

Volts	70, 90, 110, 135, 150
Capacitance	80,000 μF
Drop Height	2 inches
Drop Weight	5 pounds, lead shot
Atmosphere	Air
Ignition Tip	.040" X .040", conical
Base Surface Condition	Surface ground, acetone cleaned
Polarity	Reverse

TABLE I (Continued)

WELDING PARAMETERS

3. Capacitance

Volts	125
Capacitance	40,000, 120,000, 160,000 μF
Drop Height	2 inches
Drop Weight	5 pounds, lead shot
Atmosphere	Air
Ignition Tip	.040" X .040", conical
Base Surface Condition	Surface ground, acetone cleaned
Polarity	Reverse

4. Drop Height

Volts	125
Capacitance	80,000 μF
Drop Height	1/4, 1, 3 inches
Drop Weight	5 pounds, lead shot
Atmosphere	Air
Ignition Tip	.040" X .040", conical
Base Surface Condition	Surface ground, acetone cleaned
Polarity	Reverse

TABLE I (Continued)

WELDING PARAMETERS

5. Ignition Tip

Volts	125
Capacitance	80,000 μF
Drop Height	2 inches
Drop Weight	5 pounds, lead shot
Atmosphere	Air
Ignition Tip	.040" X .060", conical
	.030" X .020", conical
	.040" X .040", conical, no bevel
	.020" X .040", cylindrical
	.040" X .040", cylindrical
	.060" X .030", cylindrical
Base Surface Condition	Surface ground, acetone cleaned
Polarity	Reverse

TABLE I (Continued)

WELDING PARAMETERS

6. Drop Weight

Volts	125
Capacitance	80,000 μF
Drop Height	2 inches
Drop Weight	2 pounds, solid
	5 pounds, solid
	8 pounds, solid
Atmosphere	Air
Ignition Tip	.040" X .040", conical
Base Surface Condition	Surface ground, acetone cleaned
Polarity	Reverse

TABLE I (Continued)

WELDING PARAMETERS

7. Wetting Agent

Volts	125
Capacitance	80,000 μF
Drop Height	2 inches
Drop Weight	5 pounds, lead shot
Atmosphere	Air
Ignition Tip	.040" X .040", conical
Base Surface Condition	Surface ground and coated with
	Distilled water
	Soapy water
	Glycerol
	Methanol cleaned
	Hot rolling scale
Polarity	Reverse

TABLE I (Continued)

WELDING PARAMETERS

8. Shielding Gas

Volts	125
Capacitance	80,000 μF
Drop Height	2 inches
Drop Weight	5 pounds, lead shot
Atmosphere	Argon, Argon + 2% Oxygen, CO_2, Helium, Trimix (He, Ar, CO_2)
Ignition Tip	.040" X .040", conical
Base Surface Condition	Surface ground, acetone cleaned
Polarity	Reverse

9. Polarity

Volts	125
Capacitance	80,000 μF
Drop Height	2 inches
Drop Weight	5 pounds, lead shot
Atmosphere	Air
Ignition Tip	.040" X .040", conical
Base Surface Condition	Surface ground, acetone cleaned
Polarity	Straight

TABLE I (Continued)

WELDING PARAMETERS

10. 3/8 Inch Studs

Volts	90
Capacitance	160,000 μF
Drop Height	1 inches
Drop Weight	12.5 pounds, solid
Atmosphere	Air
Ignition Tip	.040" X .060", conical, 2° bevel
Base Surface Condition	Surface ground, acetone cleaned, distilled water
Polarity	Straight

11. 1/2 Inch Studs

Volts	115
Capacitance	320,000 μF
Drop Height	3/4 inch
Drop Weight	12.5 pounds, solid
Atmosphere	Air
Ignition Tip	.057" X .085", conical, 2° bevel
Base Surface Condition	Surface ground, acetone cleaned, distilled water
Polarity	Straight

TABLE II

SUMMARY OF TENSILE STRENGTHS

Section	Average		Standard Deviation	
	Breaking Load (lbs)	Breaking Strength (ksi)	Load (lbs)	Strength (ksi)
Baseline	3875	78.9	397	8.1
Voltage				
70	2953	60.2	404	8.2
90	4150	84.5	111	2.3
110	4030	82.2	230	4.7
135	3210	65.4	669	13.6
150	2340	47.7	852	17.3
Capacitance				
40,000 μF	3450	70.2	526	10.7
120,000 μF	2670	54.4	687	14.0
160,000 μF	1810	36.9	480	9.9
Drop Height				
1/4"	1538	31.3	575	11.7
1"	4020	81.9	207	4.2
3"	3230	65.8	480	9.8
Drop Weight				
2#, solid	4481	91.3	560	11.4
5#, solid	4731	96.4	328	6.7
8#, solid	4328	88.2	614	13.7
Ignition Tip				
Conical				
.04" X .06"	4084	83.2	518	10.6
.03" X .02"	1653	33.7	805	16.4
.04" X .04", no bevel	2475	50.4	585	11.9
Cylindrical				
.02" X .04"	3009	61.9	488	9.9
.04" X .04"	2334	47.5	897	18.3
.06" X .03"	203	4.1	555	11.3

TABLE II. (continued)

SUMMARY OF TENSILE STRENGTHS

Section	Average: Breaking Load (lbs)	Average: Breaking Strength (ksi)	Standard Deviation: Load (lbs)	Standard Deviation: Strength (ksi)
Baseline	3875	78.9	397	8.1
Wetting Agents				
H_2O	4172	85.0	99	2.0
Soapy H_2O	4092	83.4	277	5.6
Mill Scale (Hot rolled)	4044	82.4	312	6.4
Glycerol	3525	71.8	707	14.4
Methanol Cleaned	3369	68.6	988	20.1
Shielding Gases				
Argon	4150	84.5	304	6.2
CO_2	4075	83.0	183	3.7
Argon + 2% O_2	4069	82.9	565	11.5
Trimix	3931	80.1	210	4.3
Helium	3712	75.6	663	13.5
Straight Polarity	4257	86.7	562	11.4
3/8" Studs	8966	81.2	376	3.4
1/2" Studs	14900	75.9	1789	9.1

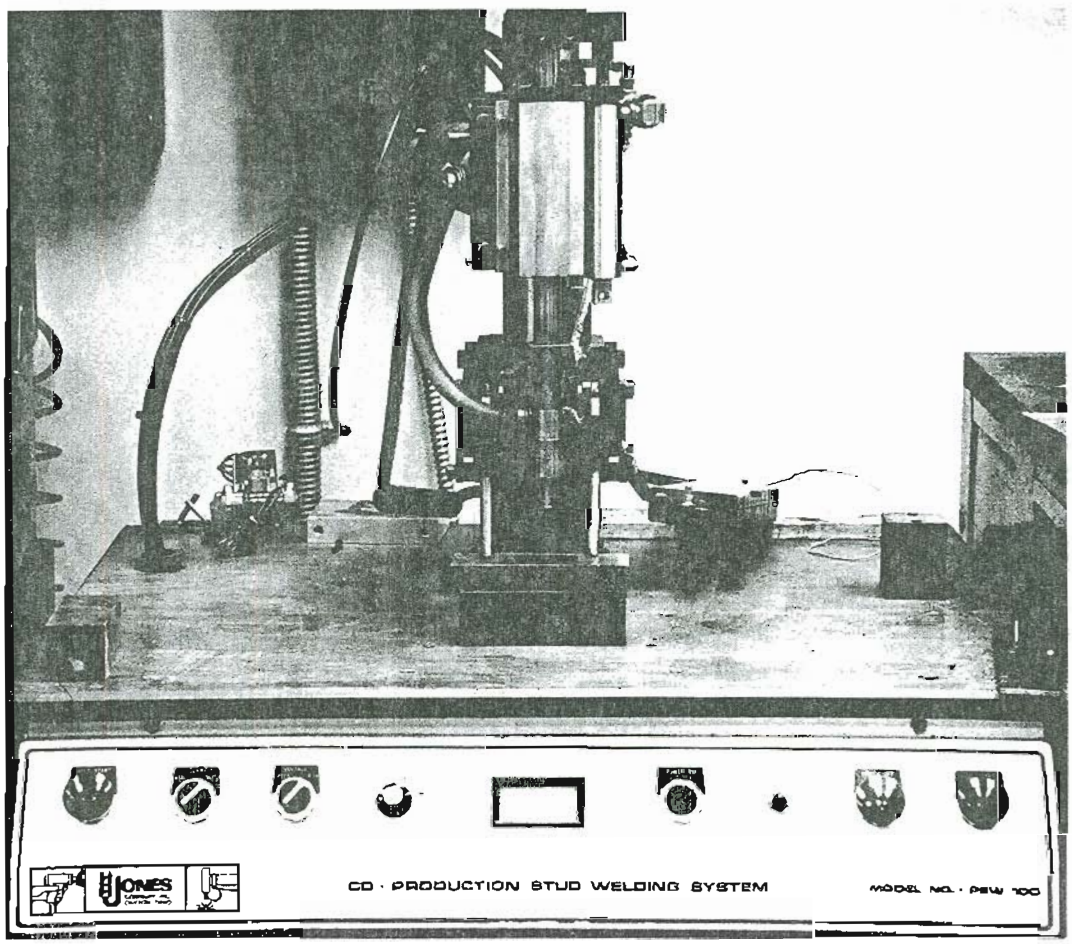

Figure 1. Capacitor discharge welding equipment: a) Capacitor bank (inside cabinet), b) stud chuck, c) drop weight, d) ground clamps, e) control panel.

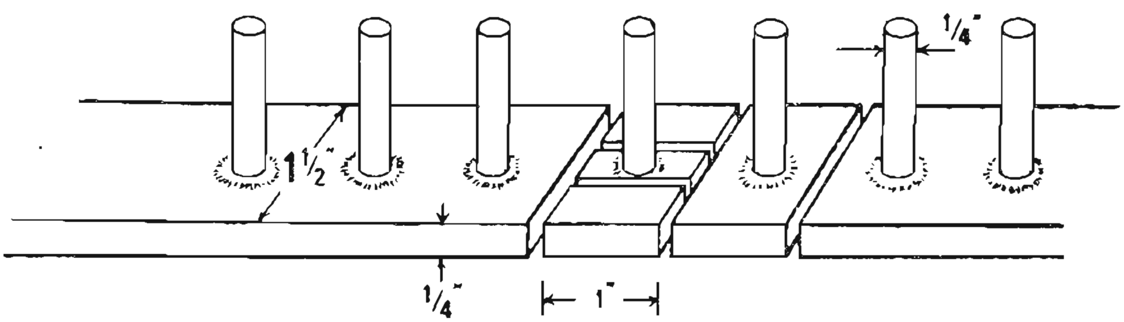

Figure 2.
Tensile specimen sectioning.

Figure 3.
Fracture surface,
Baseline Section. 12X.

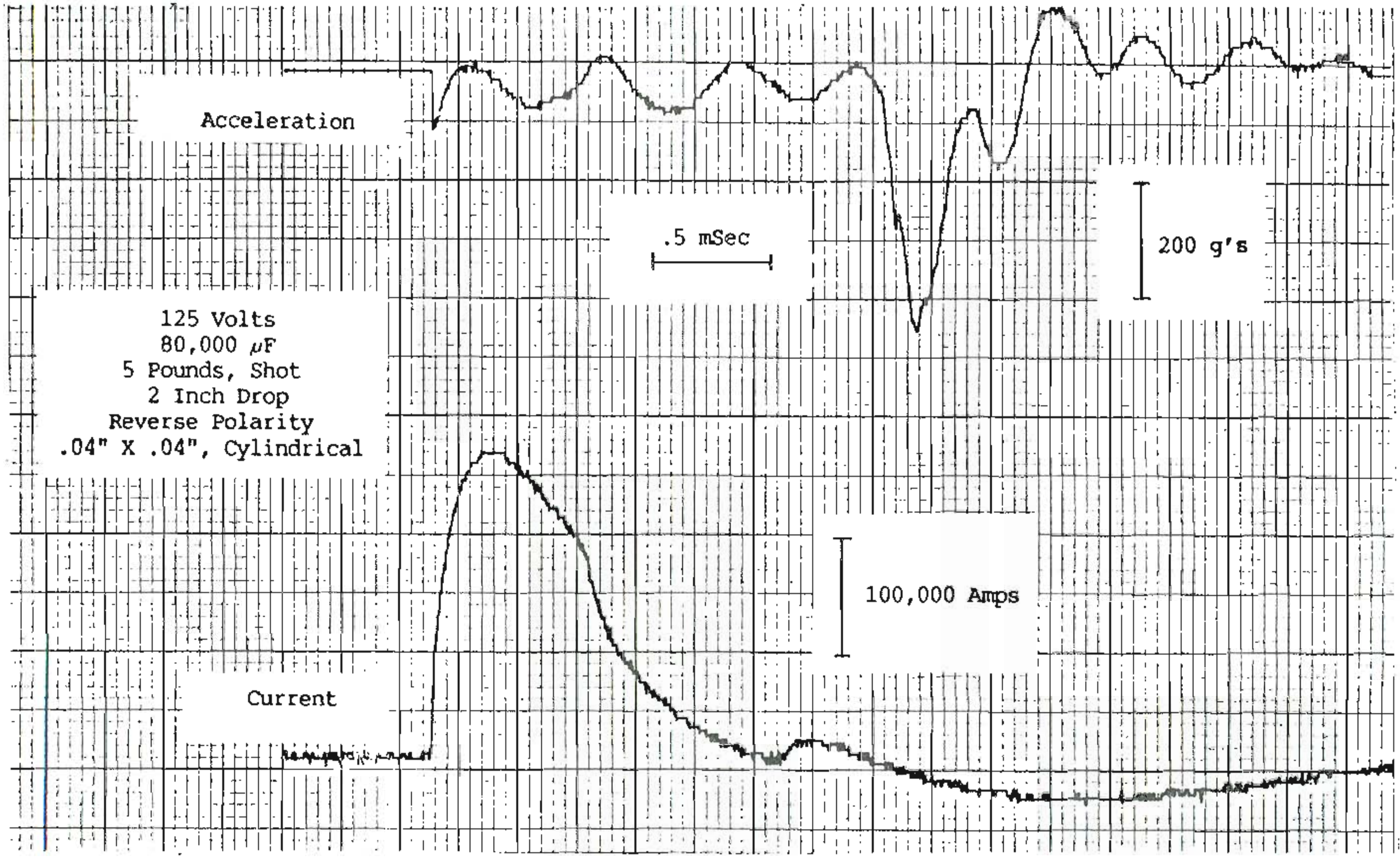

Figure 4. Current and acceleration curves, Baseline.

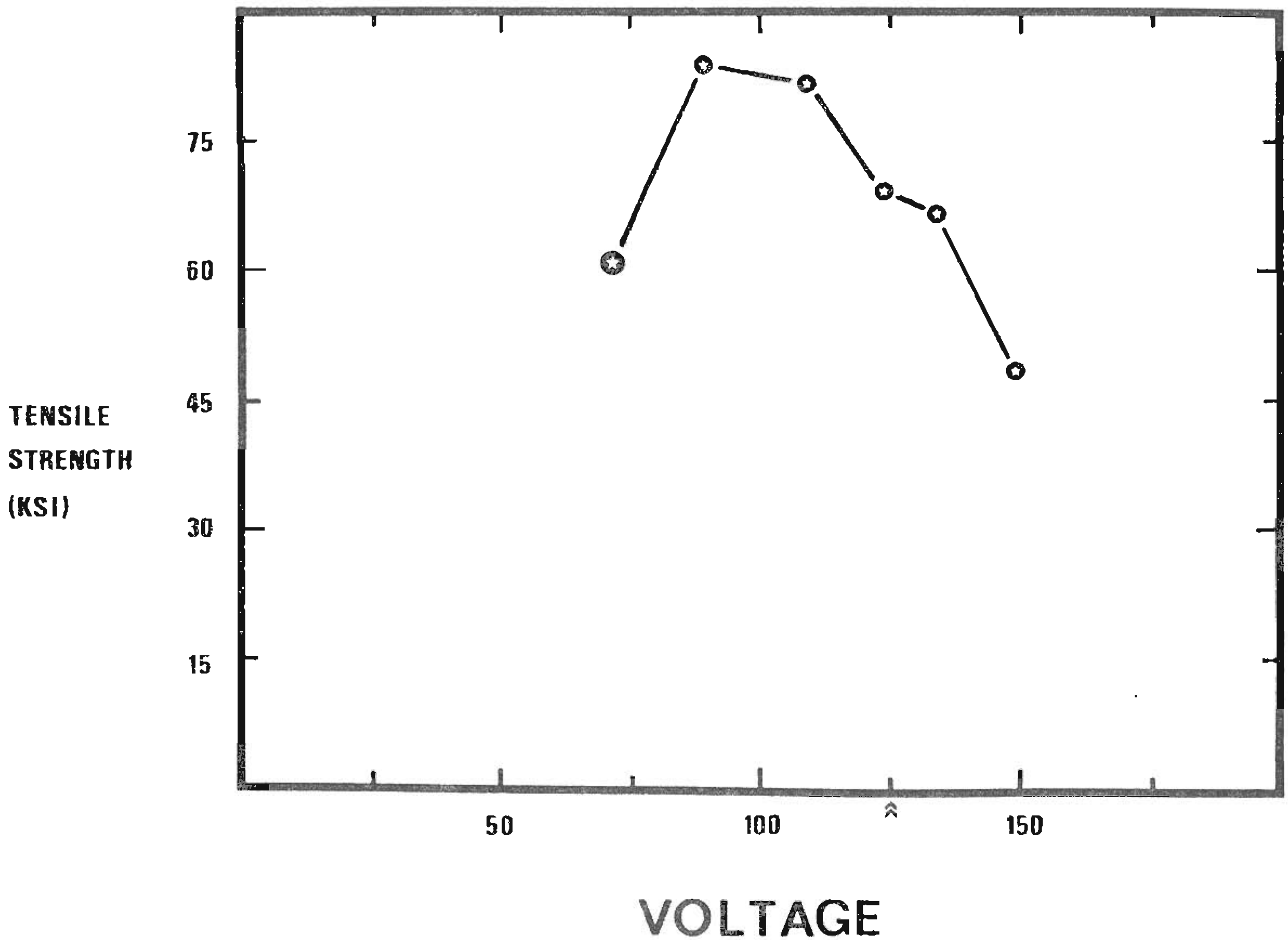

Figure 5. Tensile strength vs. applied voltage.

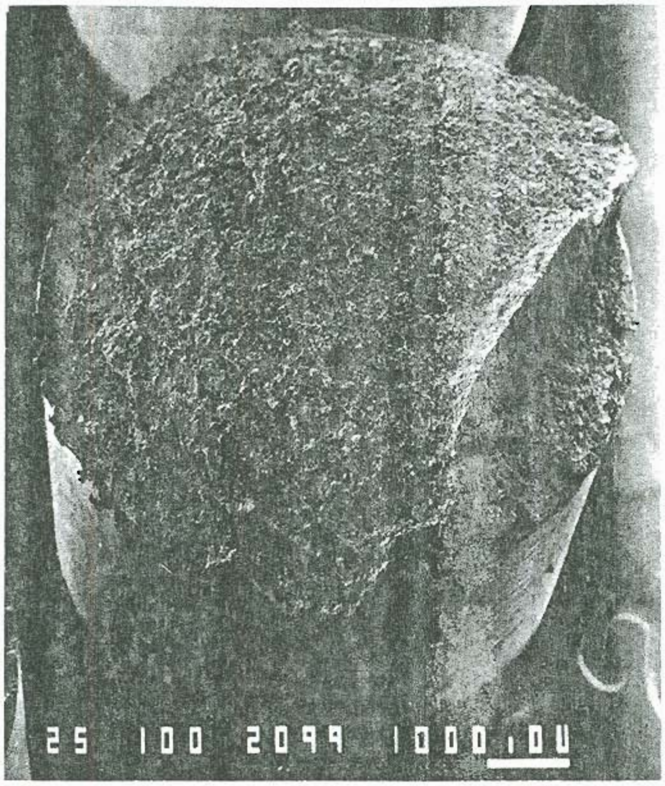

Figure 6.
Fracture surface,
90 volts. 12X.

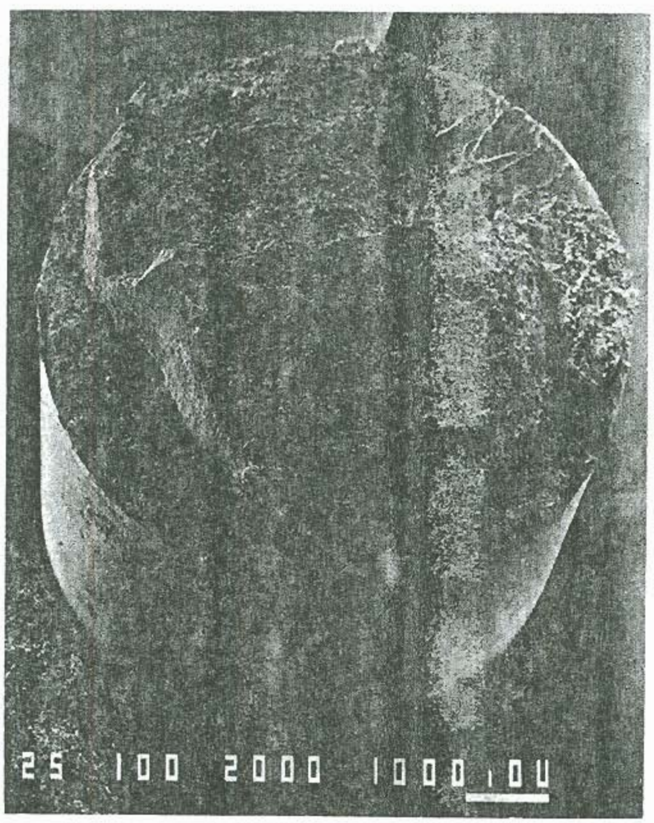

Figure 7.
Fracture surface,
110 volts. 12x.

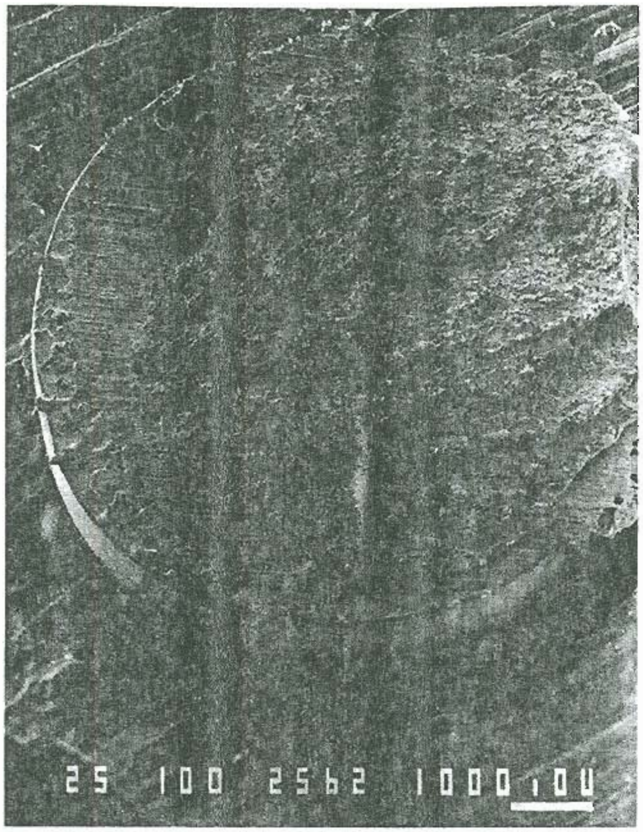

Figure 8.
Fracture surface,
70 volts. 12X.

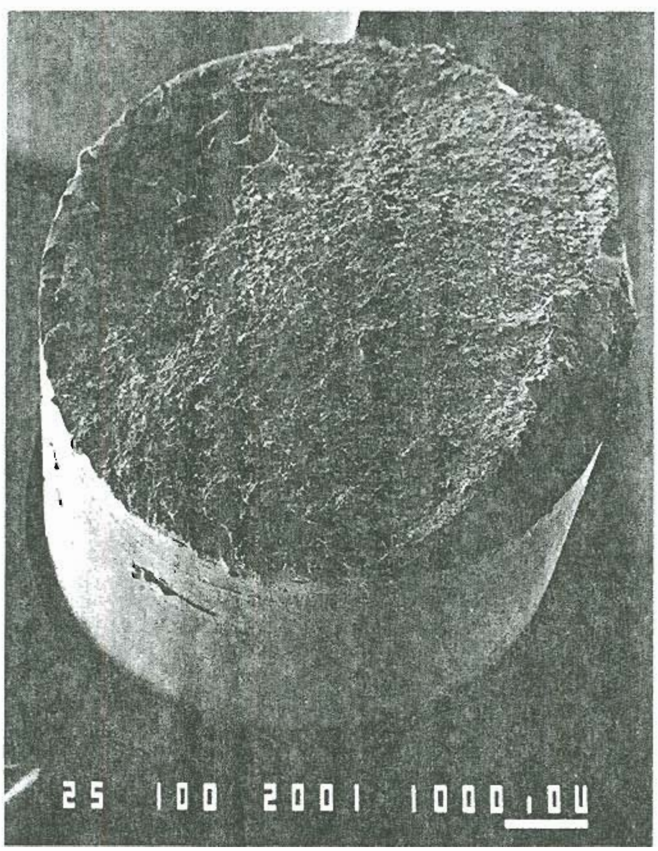

Figure 9.
Fracture surface,
135 volts. 12X.

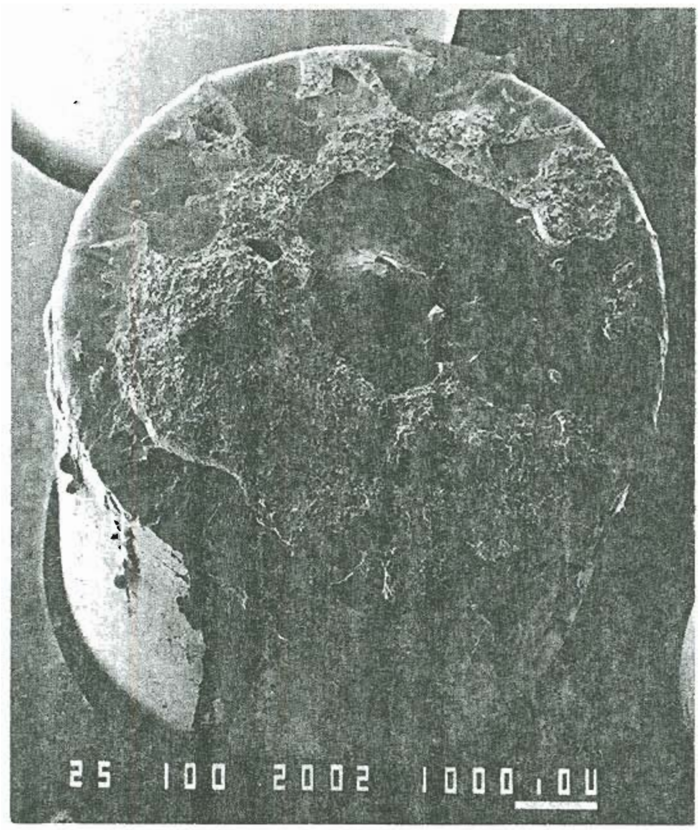

Figure 10.
Fracture surface,
150 volts. 12X.

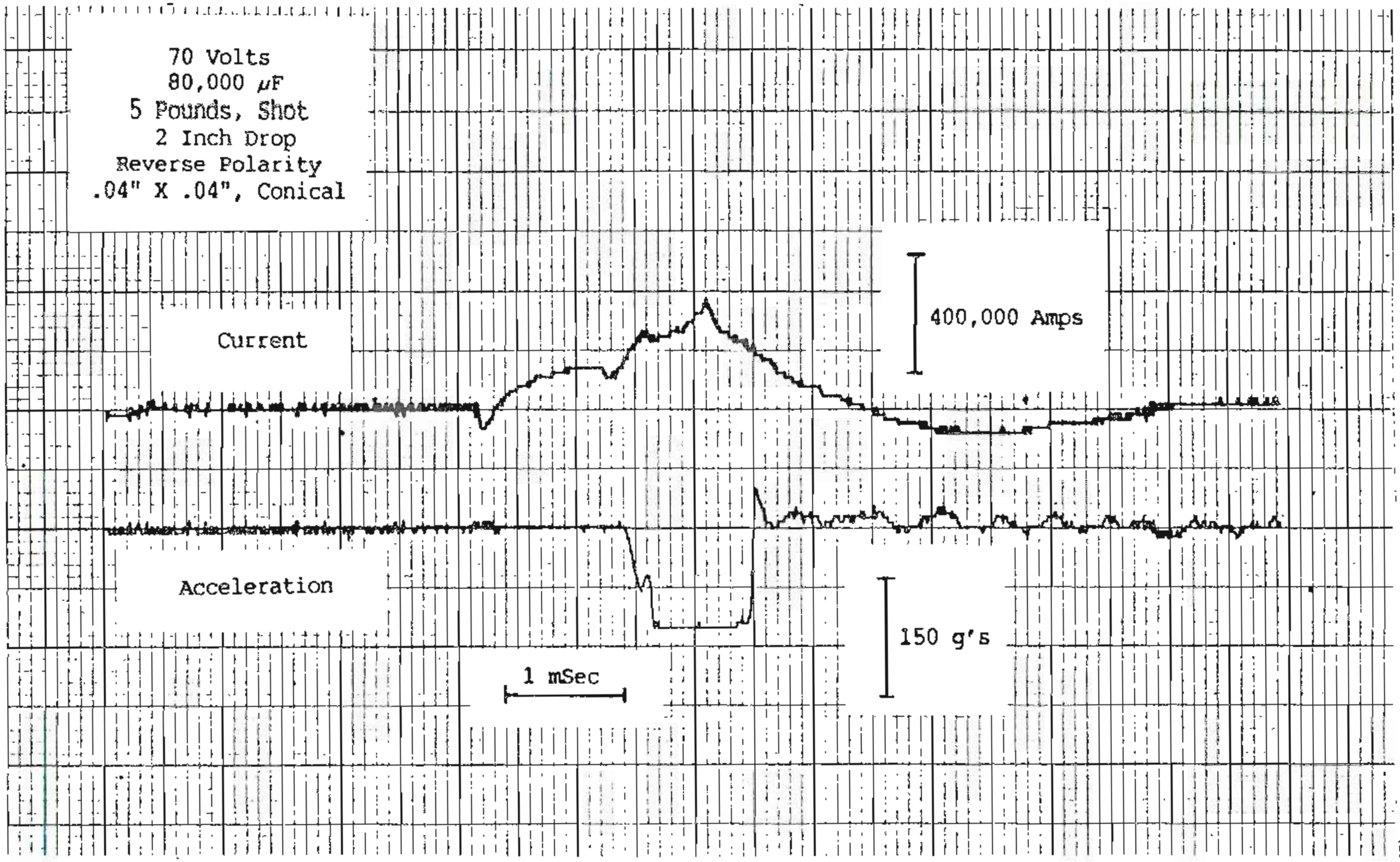

Figure 11. Current and acceleration curves, 70 volts.

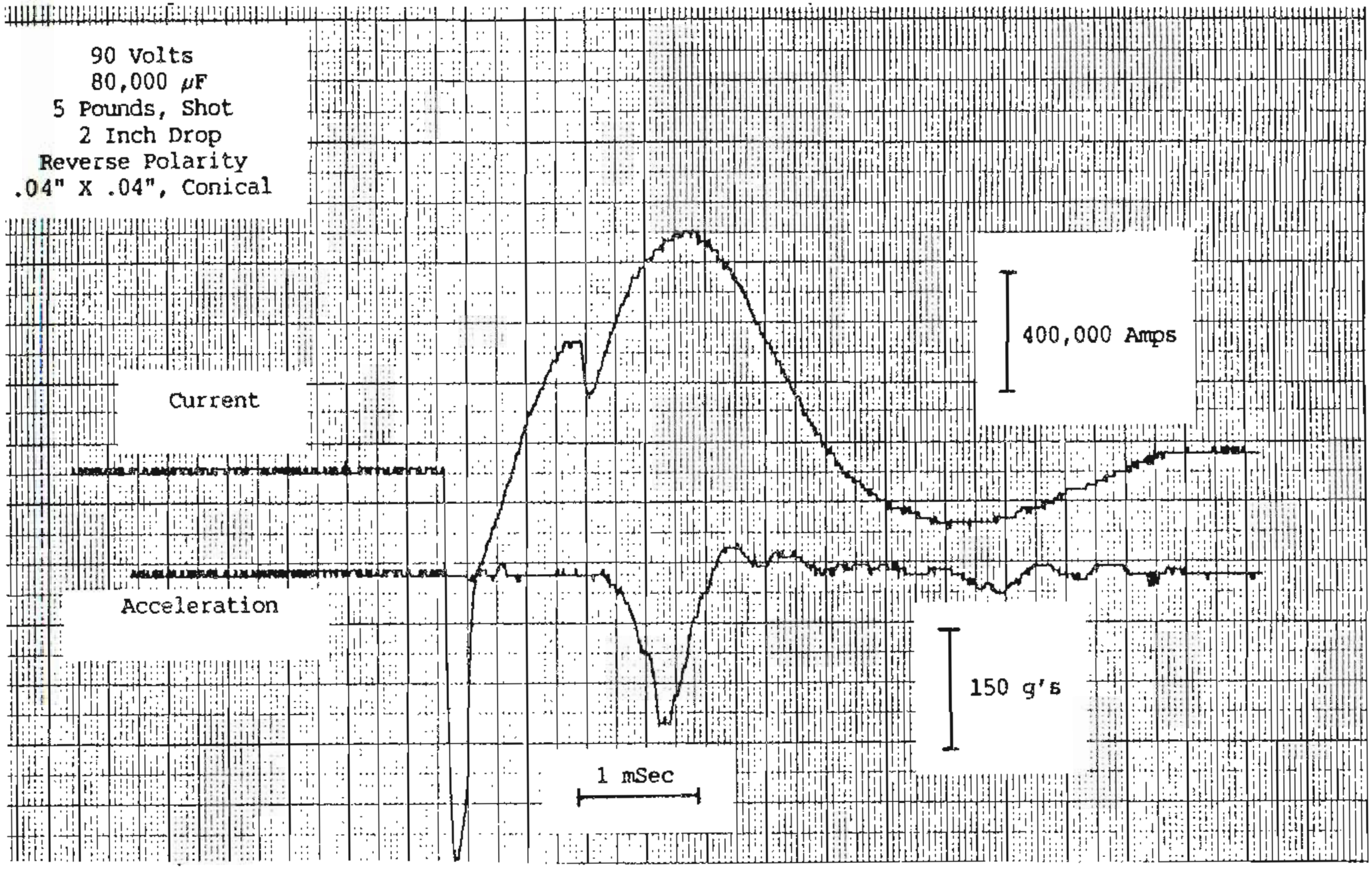

Figure 12. Current and acceleration curves, 90 volts.

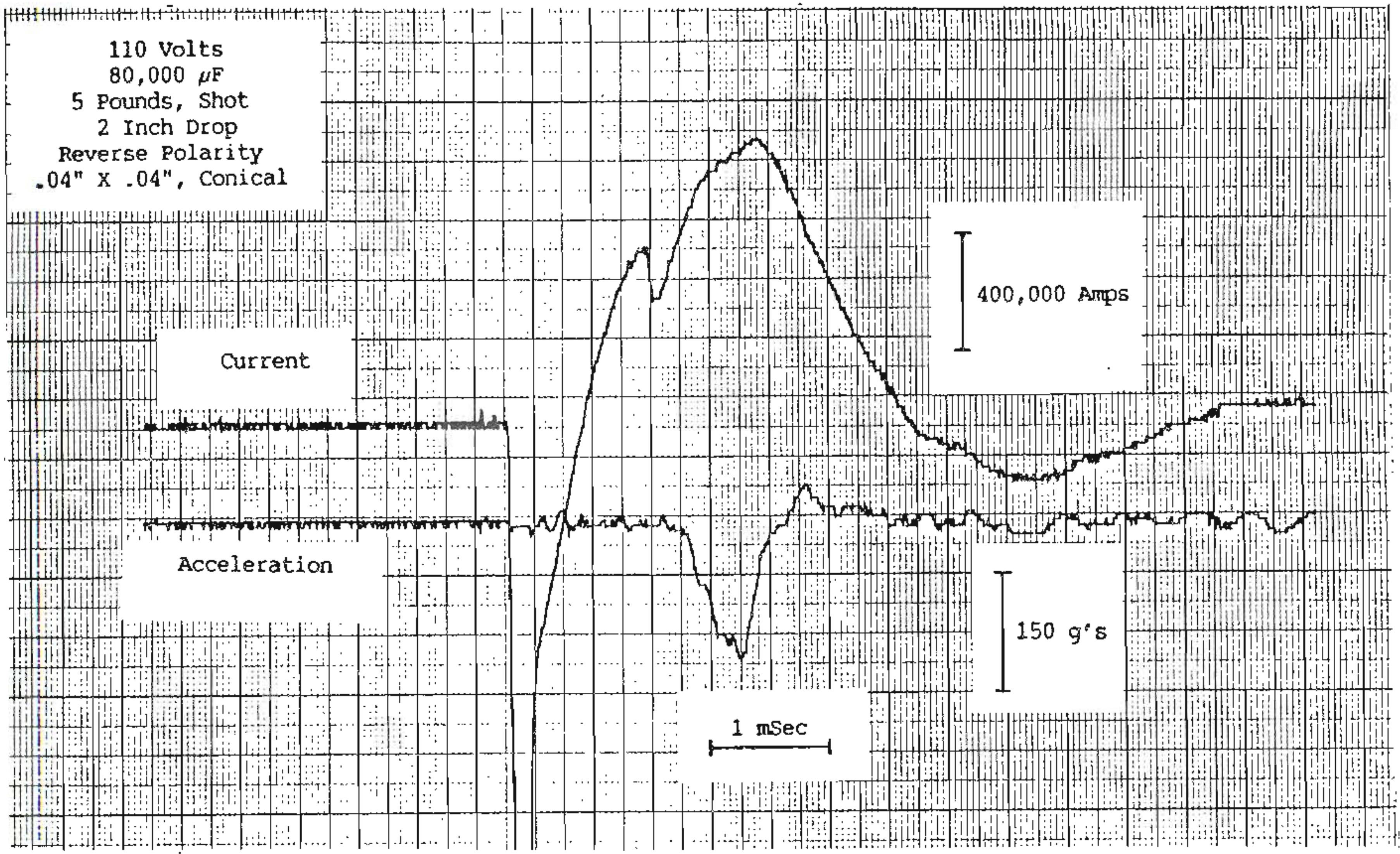

Figure 13. Current and acceleration curves, 110 volts.

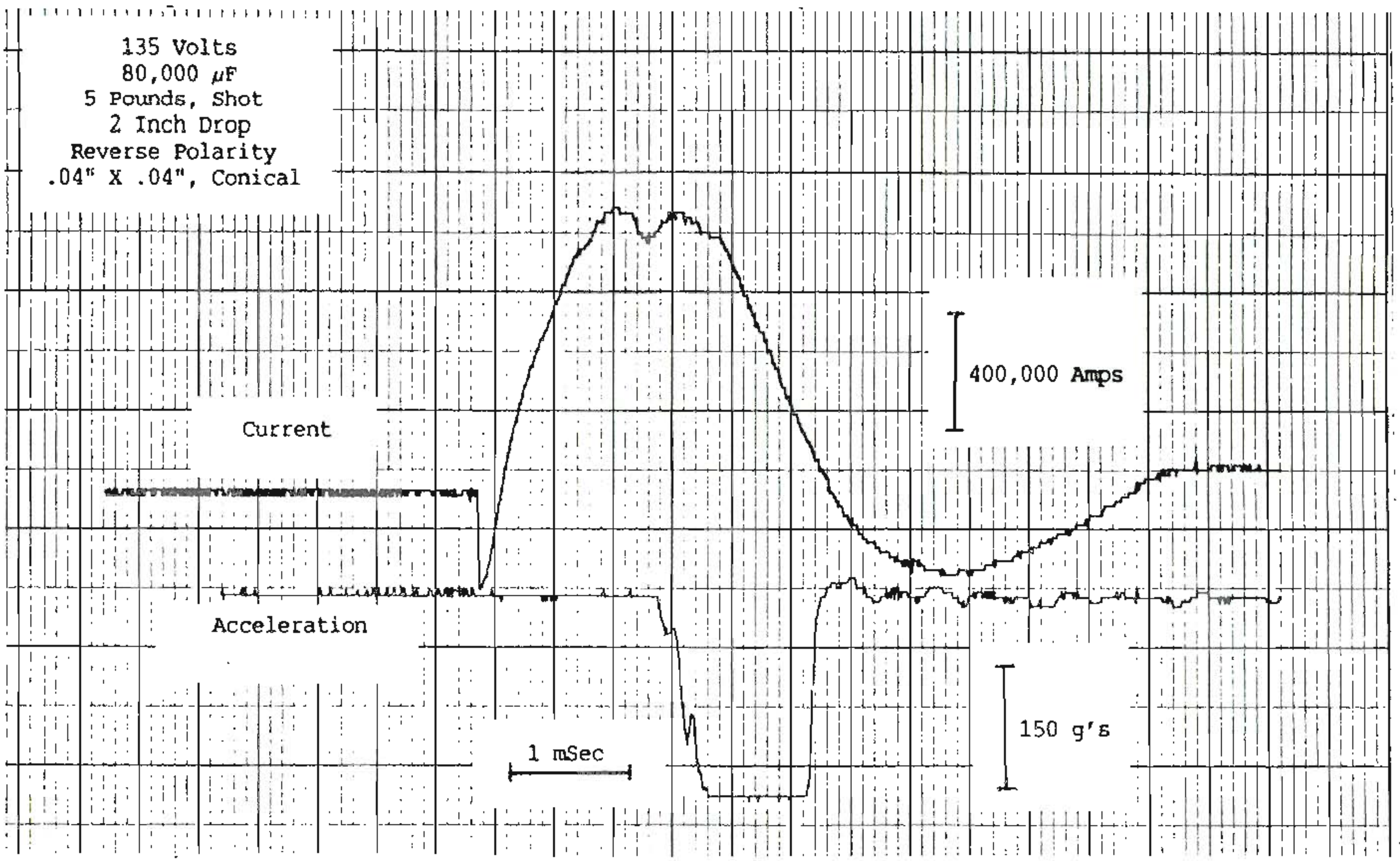

Figure 14. Current and acceleration curves, 135 volts.

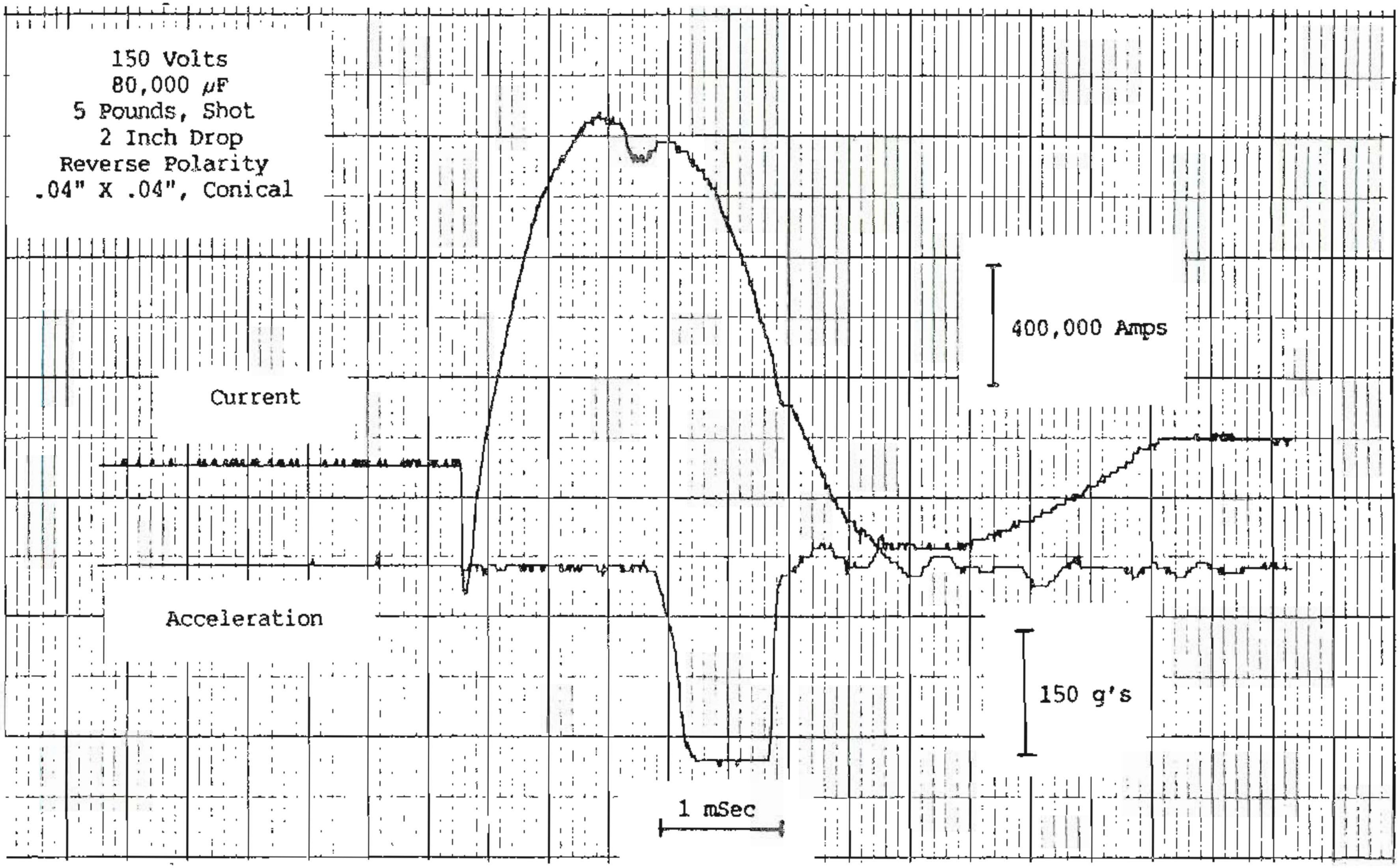

Figure 15. Current and acceleration curves, 150 volts.

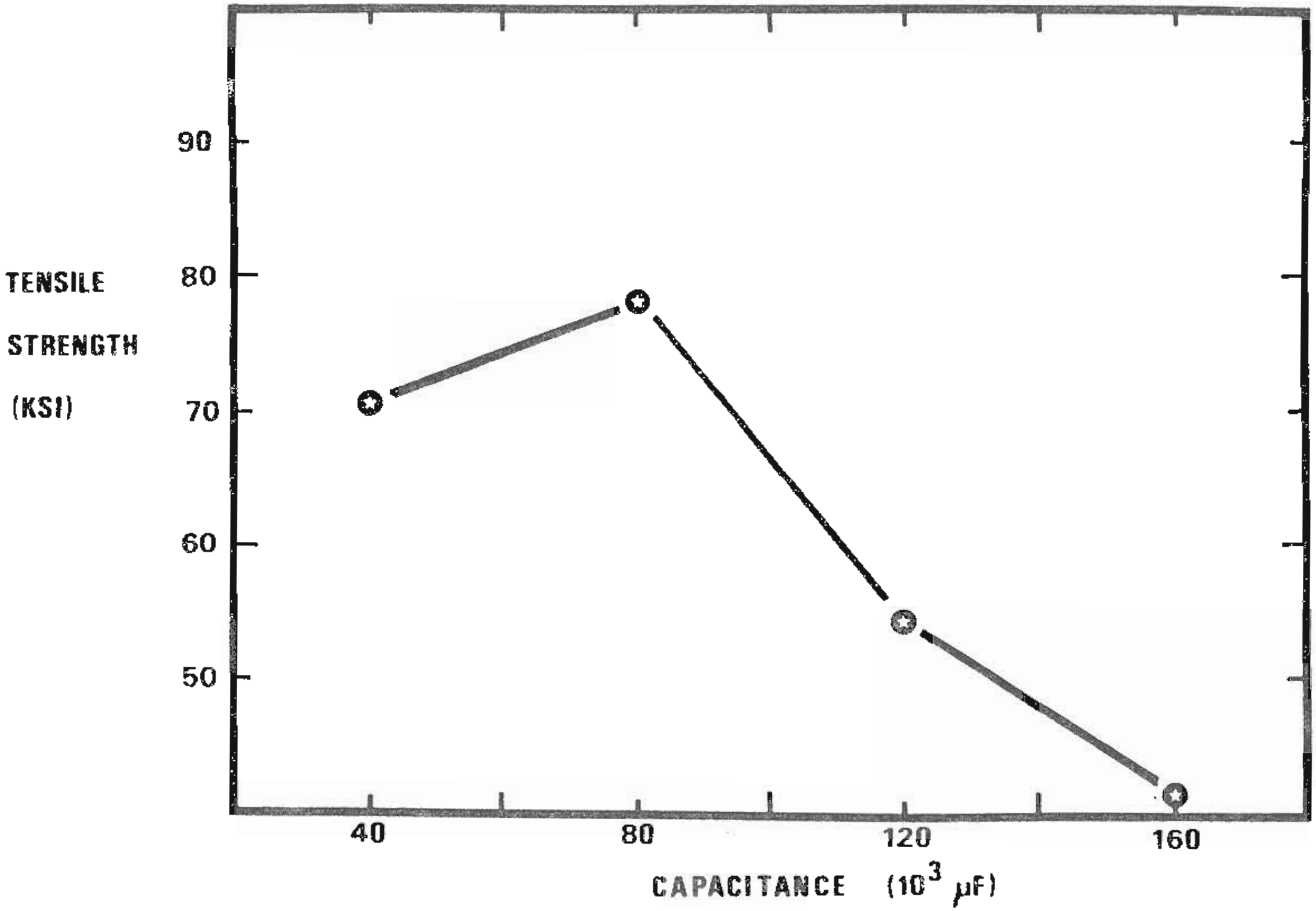

Figure 16. Tensile strength vs. capacitance.

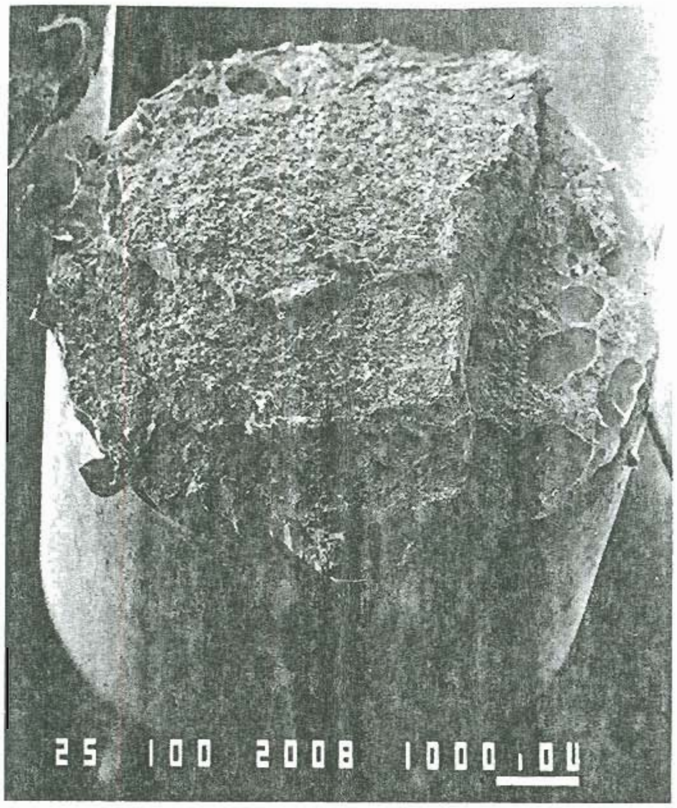

Figure 17.
Fracture surface,
40,000 μF. 12X.

Figure 18.
Fracture surface,
120,000 μF. 12X.

Figure 19.
Fracture surface,
160,000 μF. 12X.

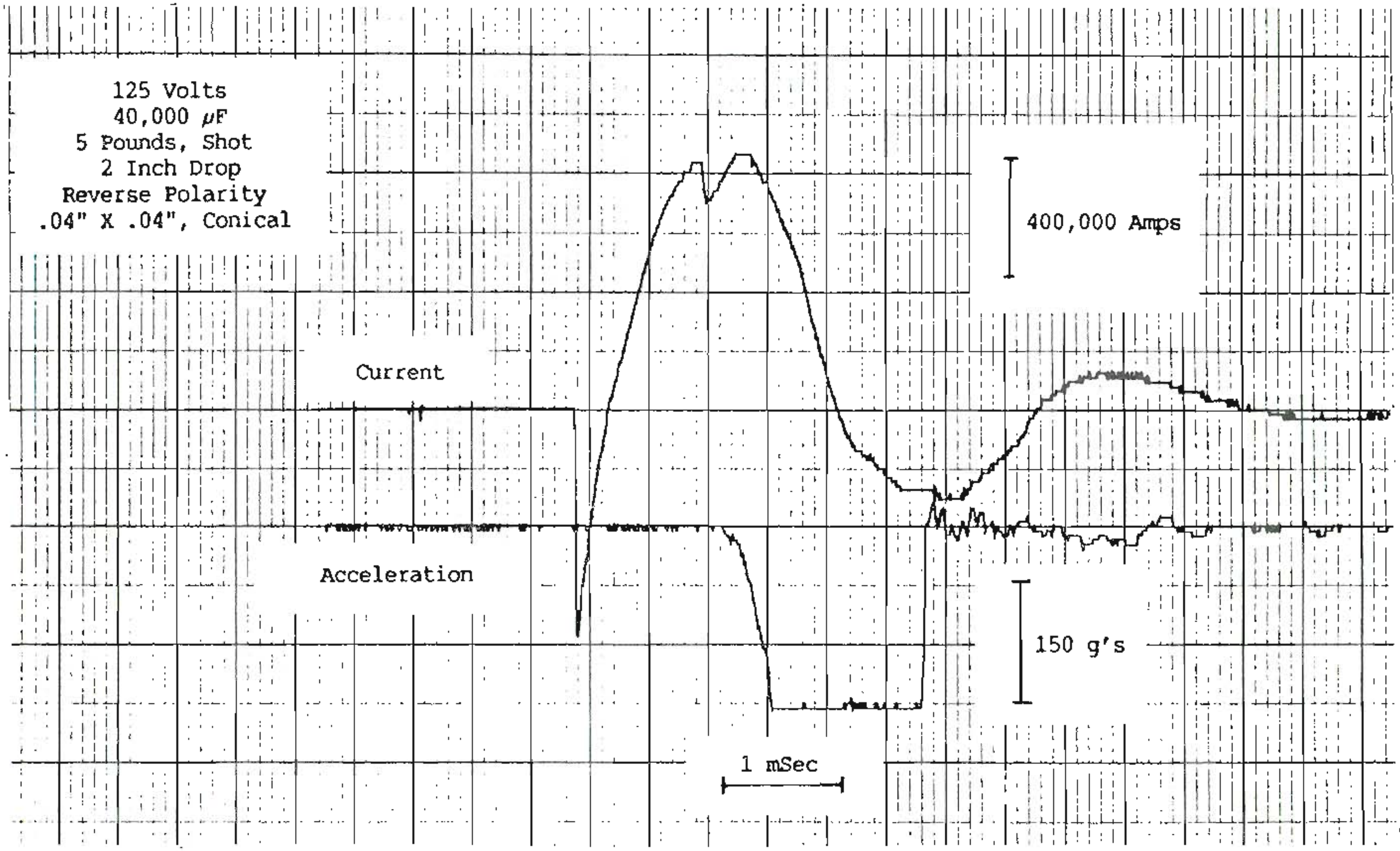

Figure 20. Current and acceleration curves, 40,000 μF.

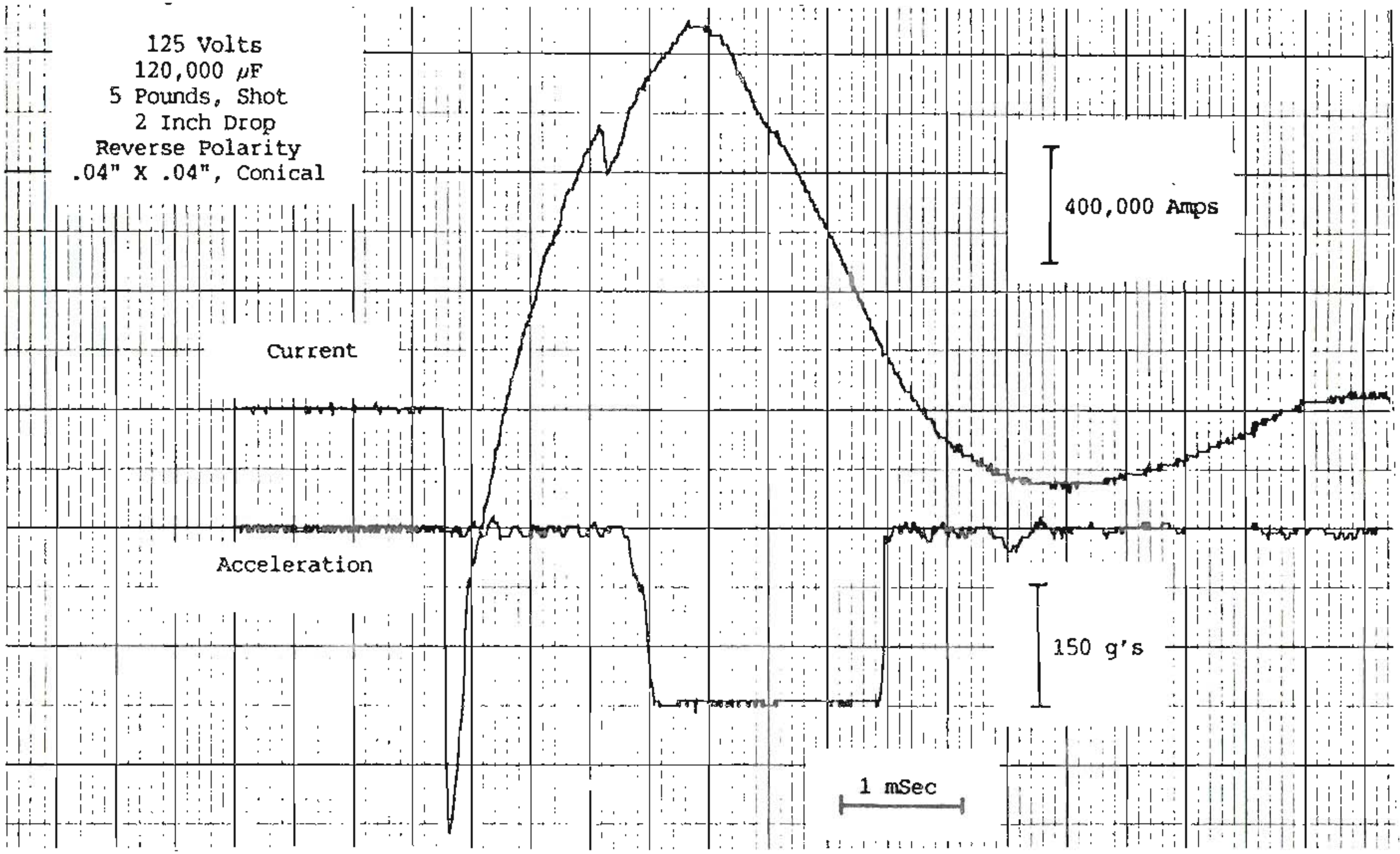

Figure 21. Current and acceleration curves, 120,000 μF.

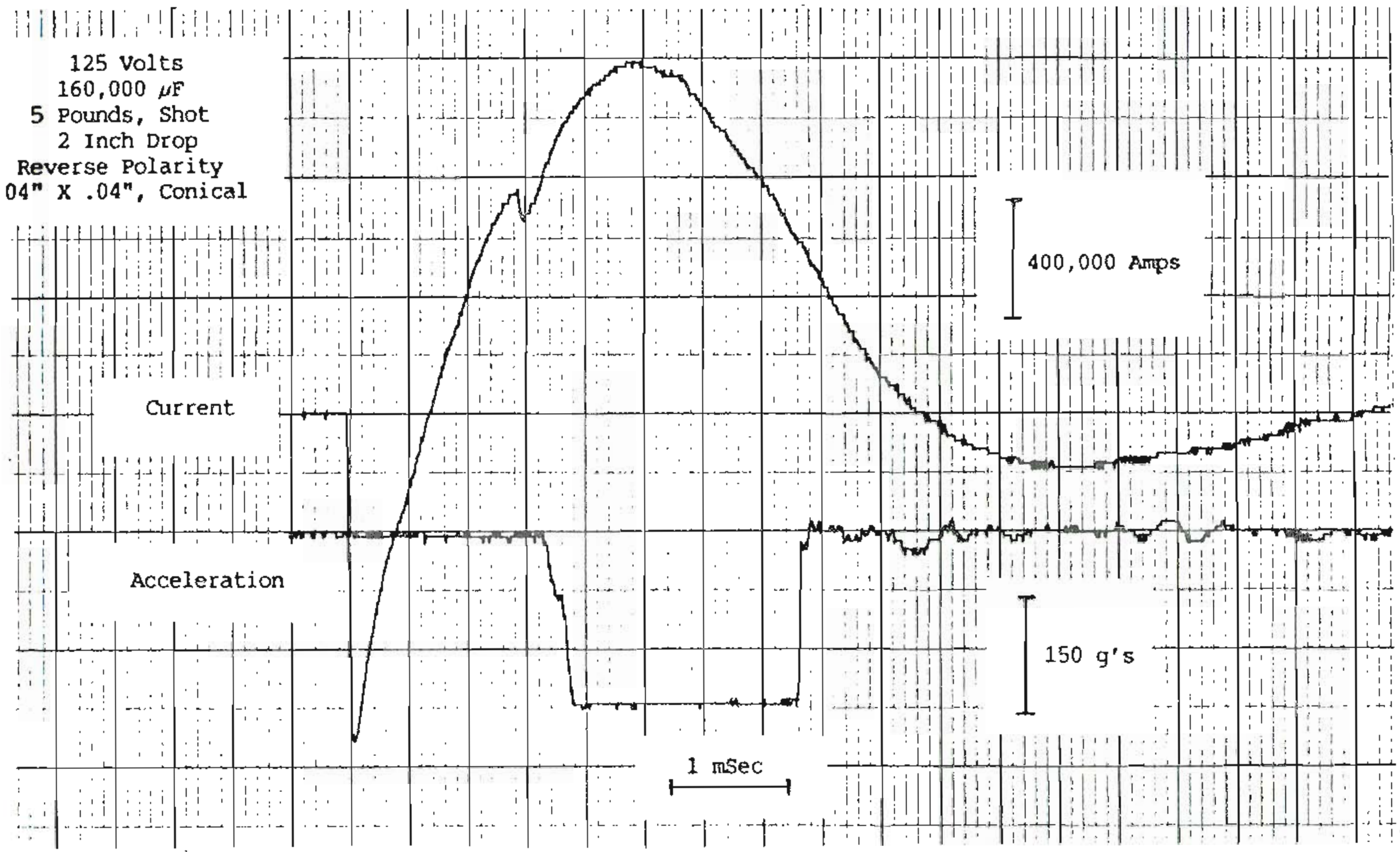

Figure 22. Current and acceleration curves, 160,000 μF.

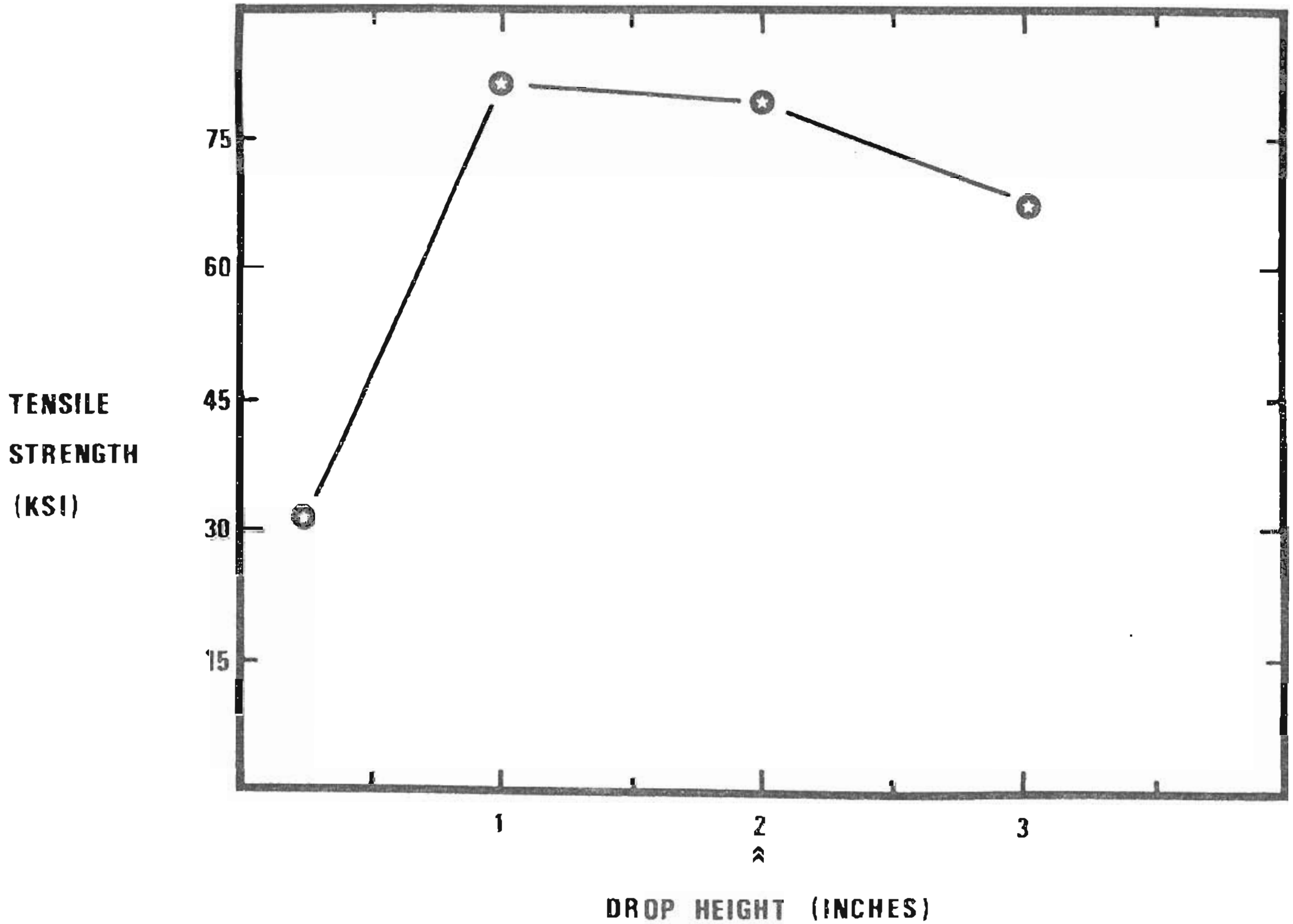

Figure 23. Drop height vs. tensile strength.

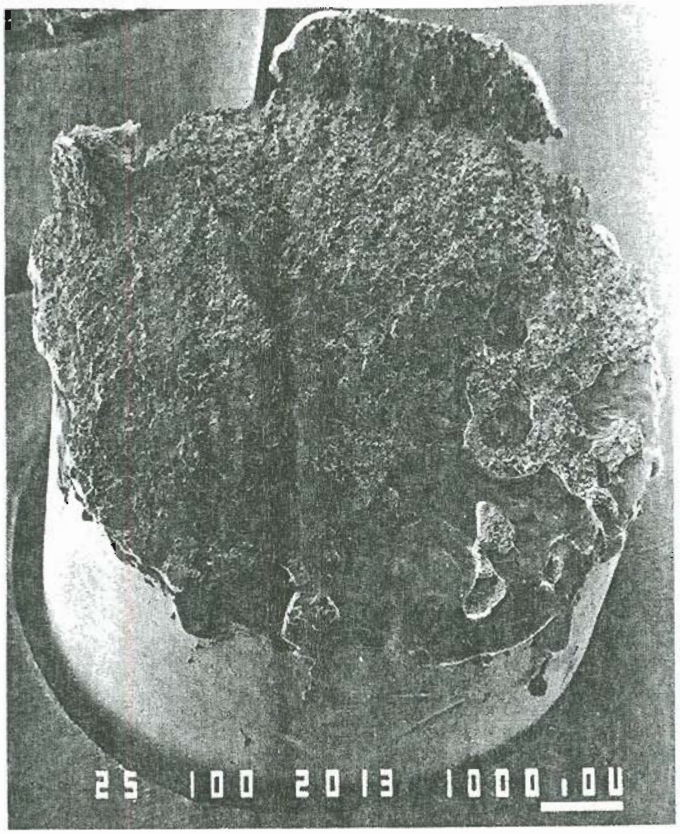

Figure 24.
Fracture surface,
1" drop height.
12X.

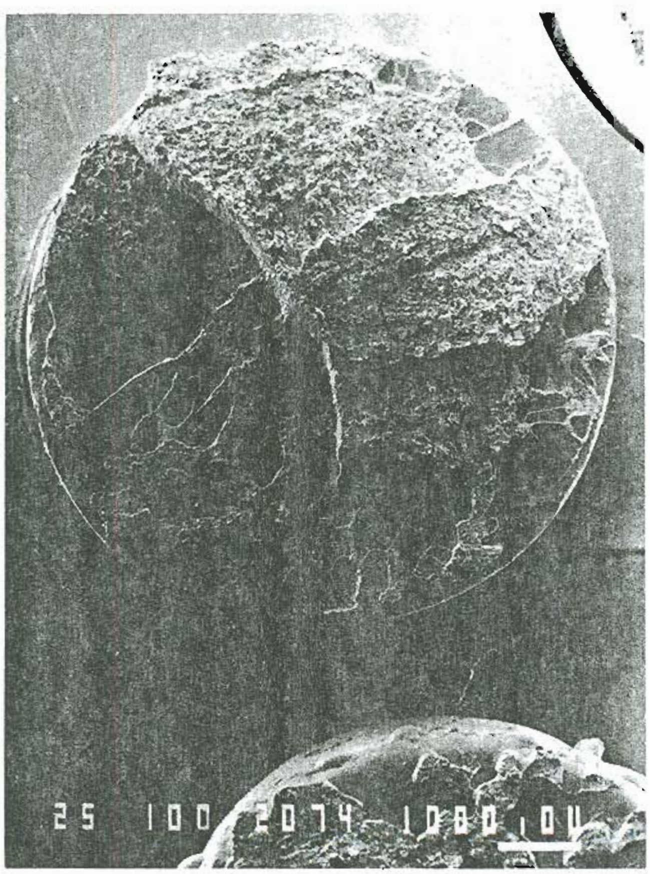

Figure 25.
Fracture surface,
3" drop height.
12X.

Figure 26.
Fracture surface,
1/4" drop height.
12X.

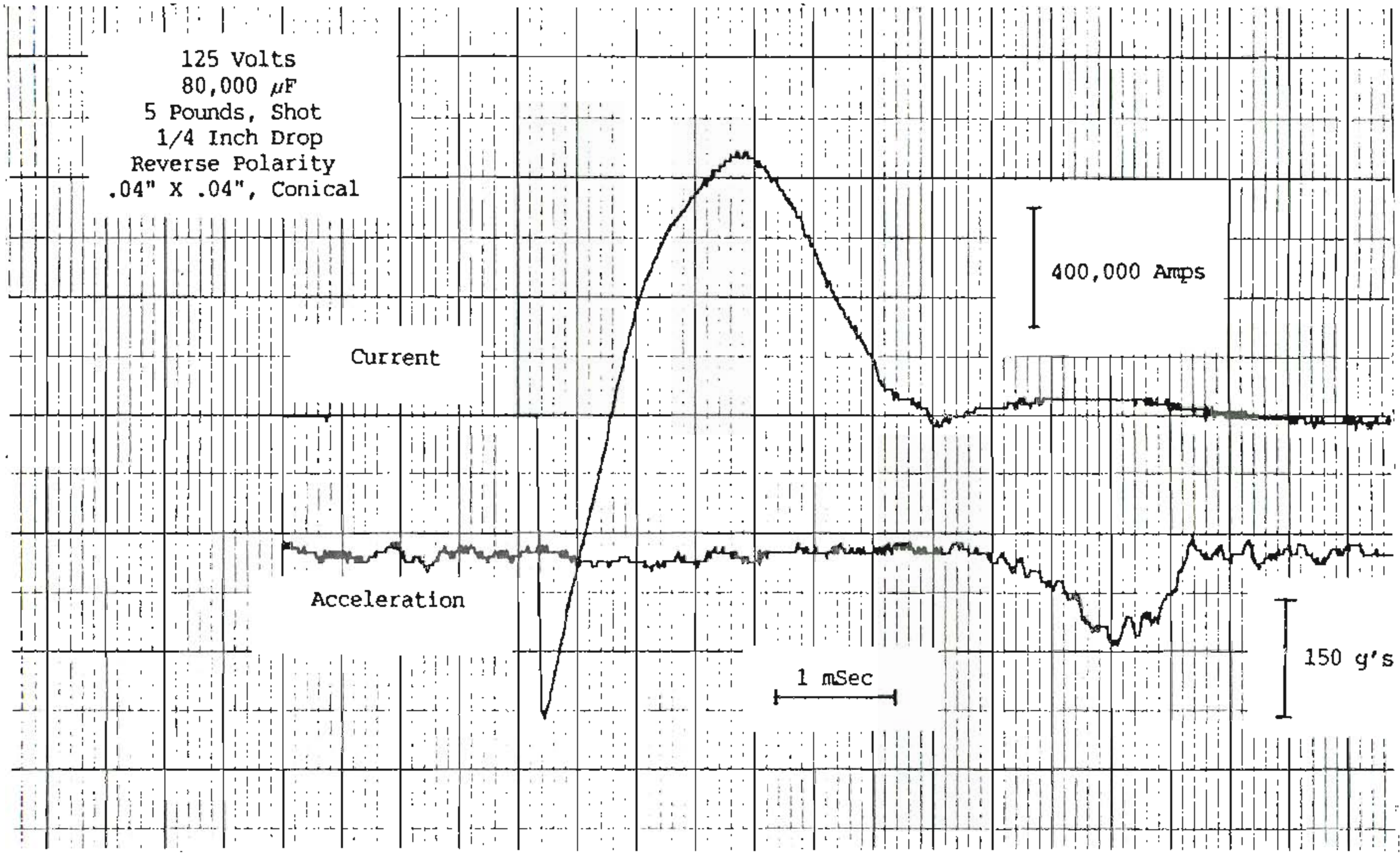

Figure 27. Current and acceleration curves, 1/4" drop.

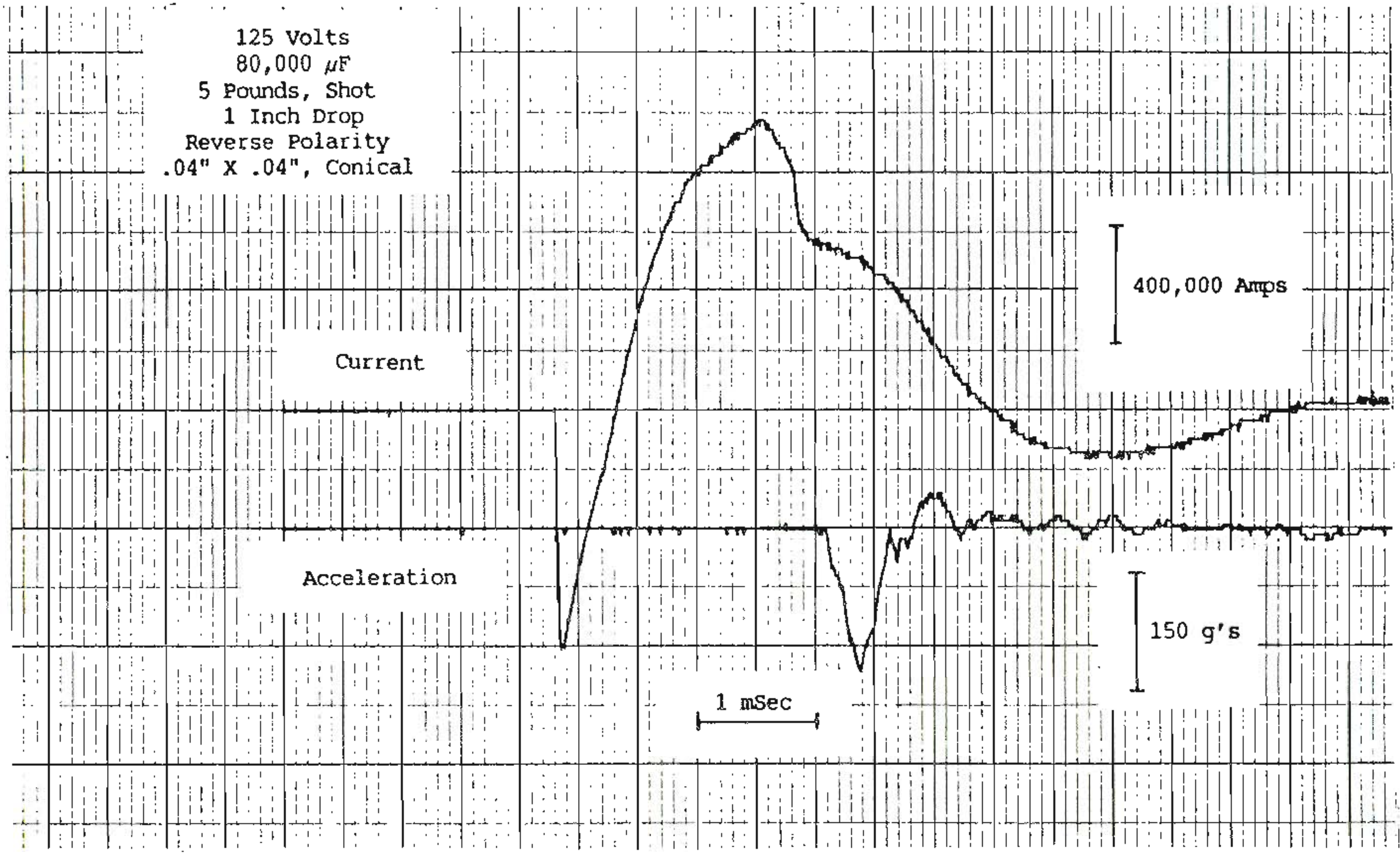

Figure 28. Current and acceleration curves, 1" drop.

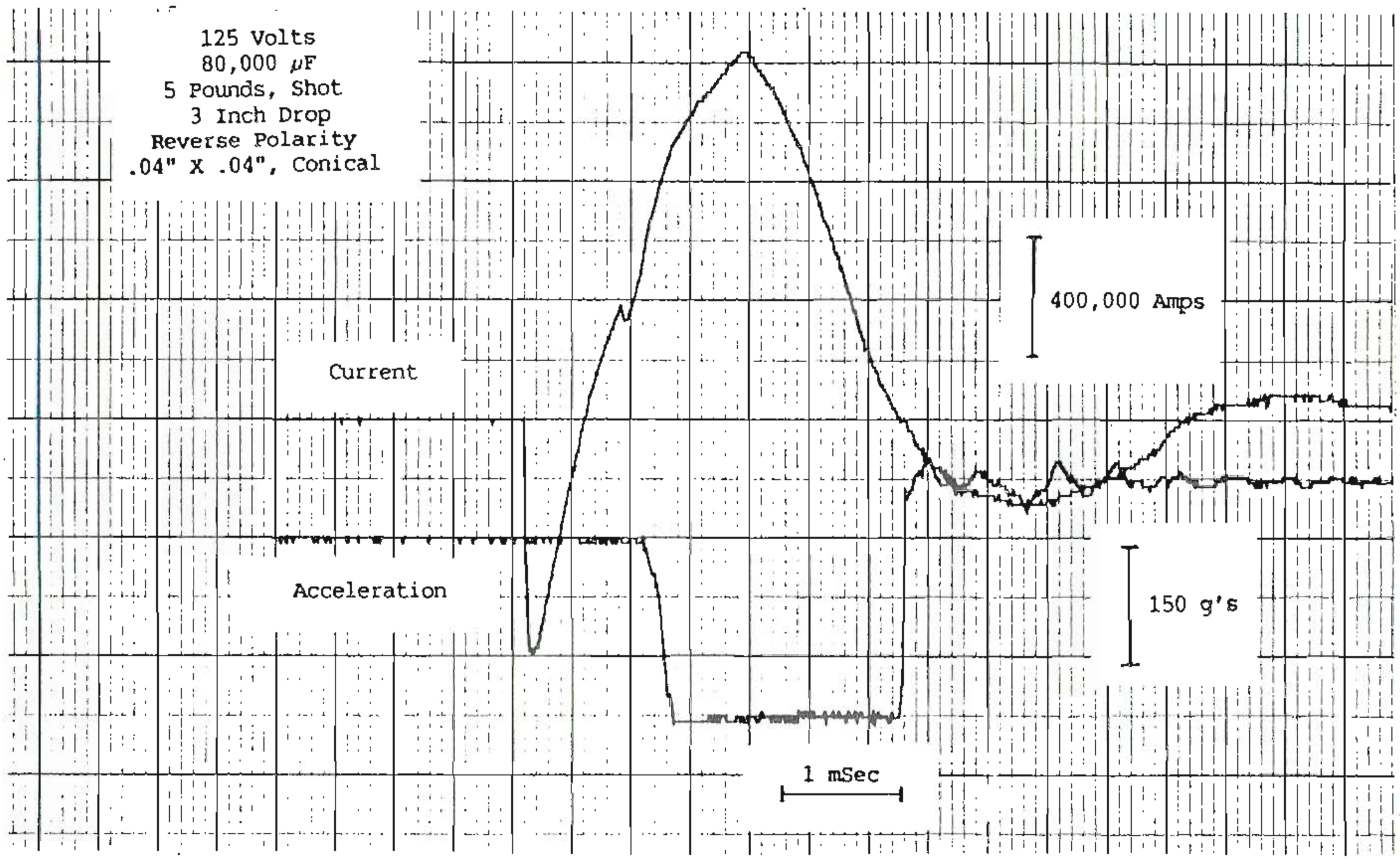

Figure 29. Current and acceleration curves, 3" drop.

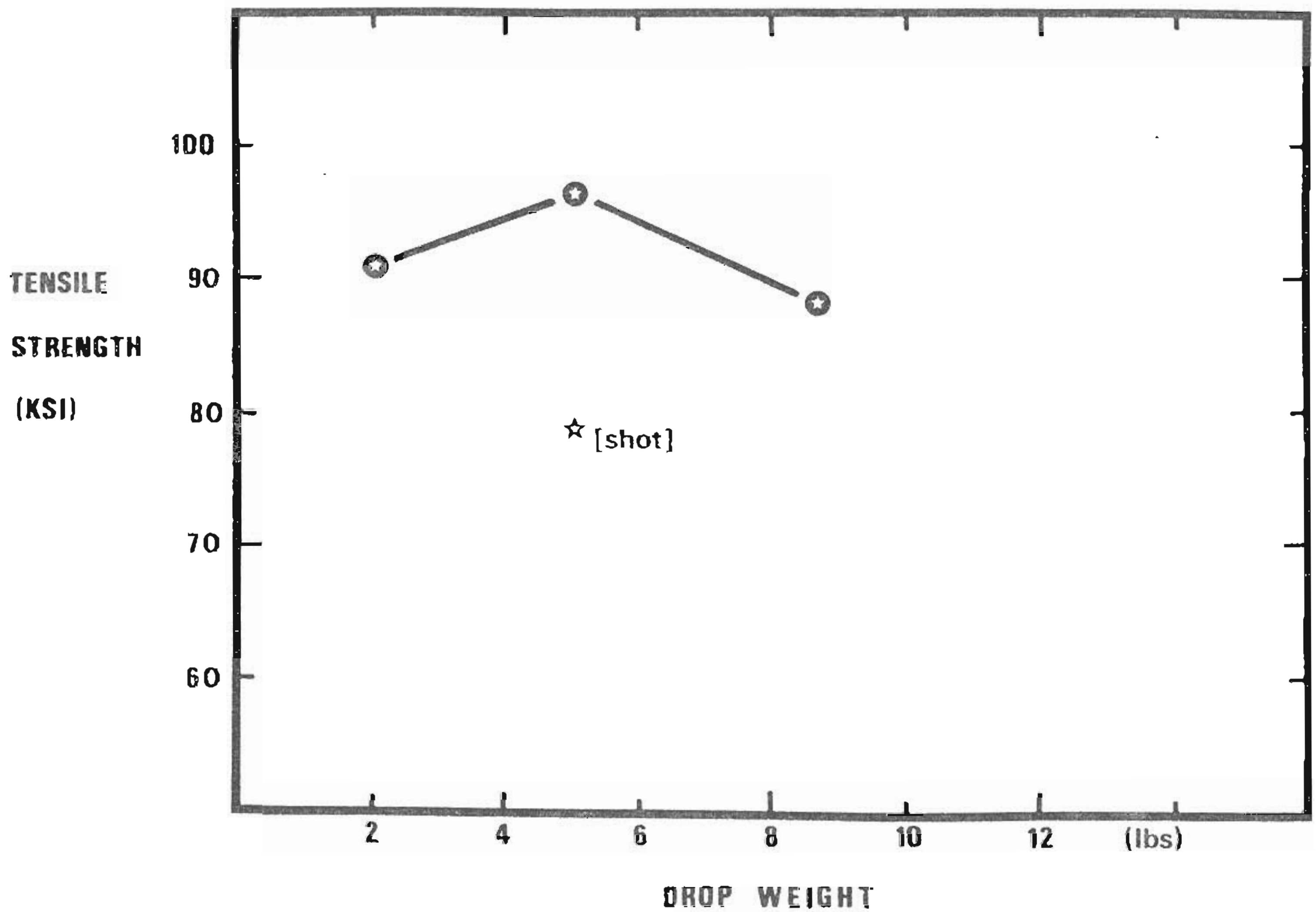

Figure 30. Tensile strength vs. drop weight.

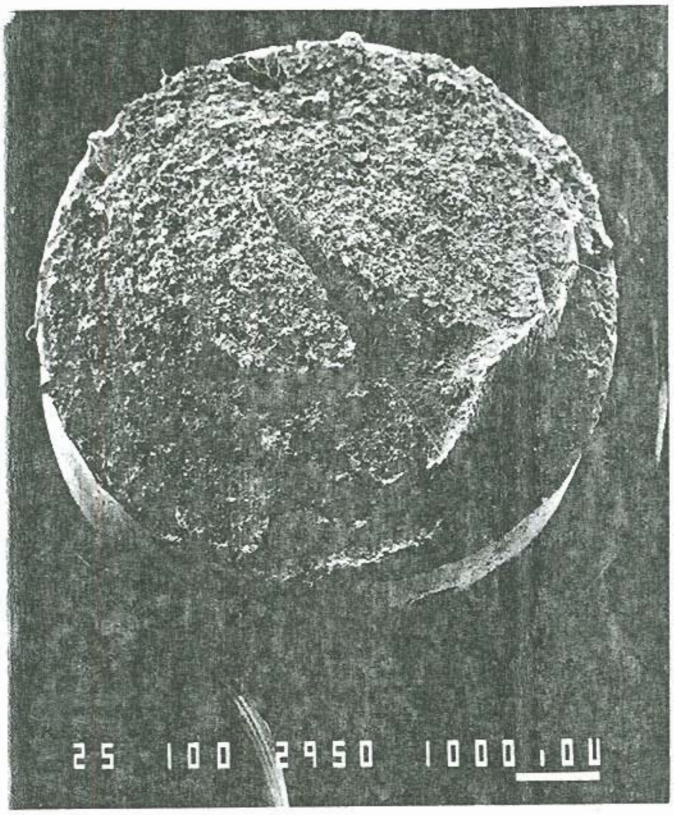

Figure 31.
Fracture surface,
five pound weight.
12x.

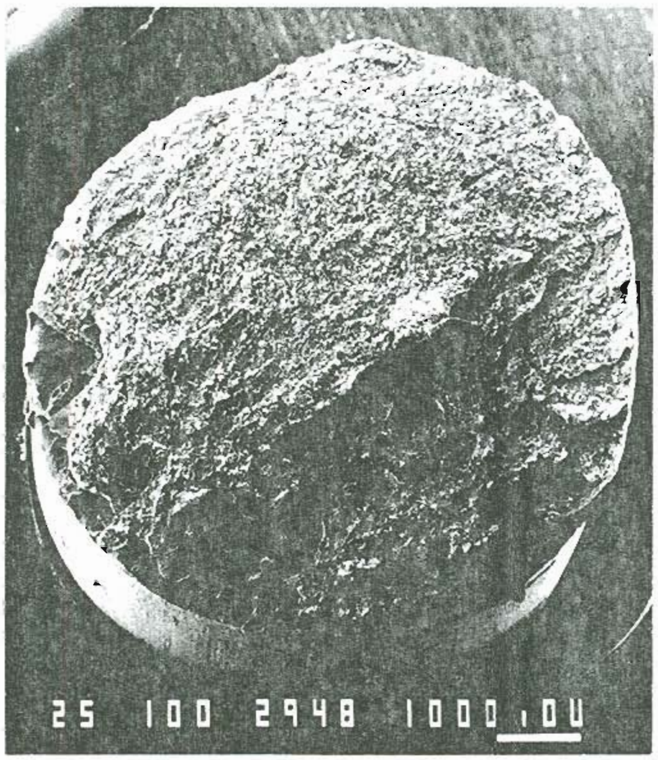

Figure 32.
Fracture surface,
two pound weight.
12X.

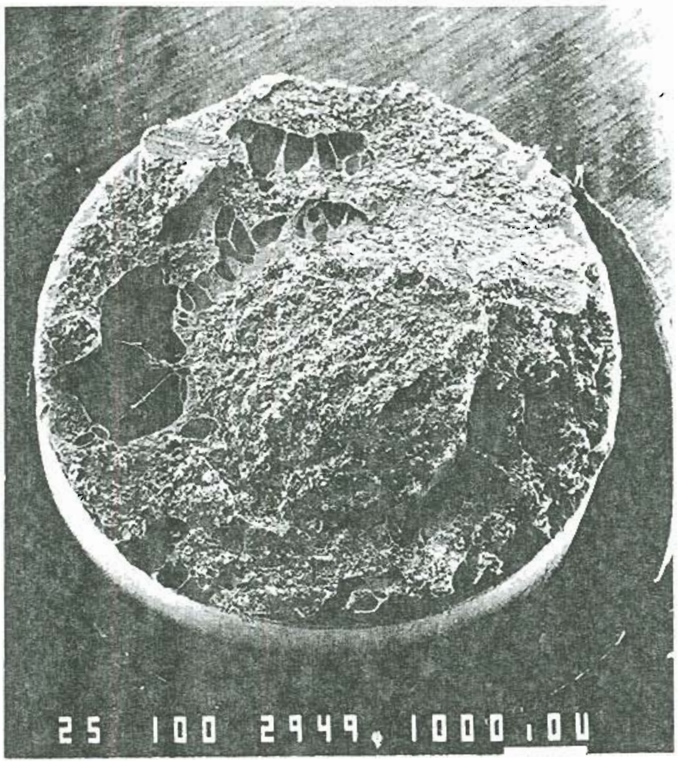

Figure 33.
Fracture surface,
eight pound weight.
12X.

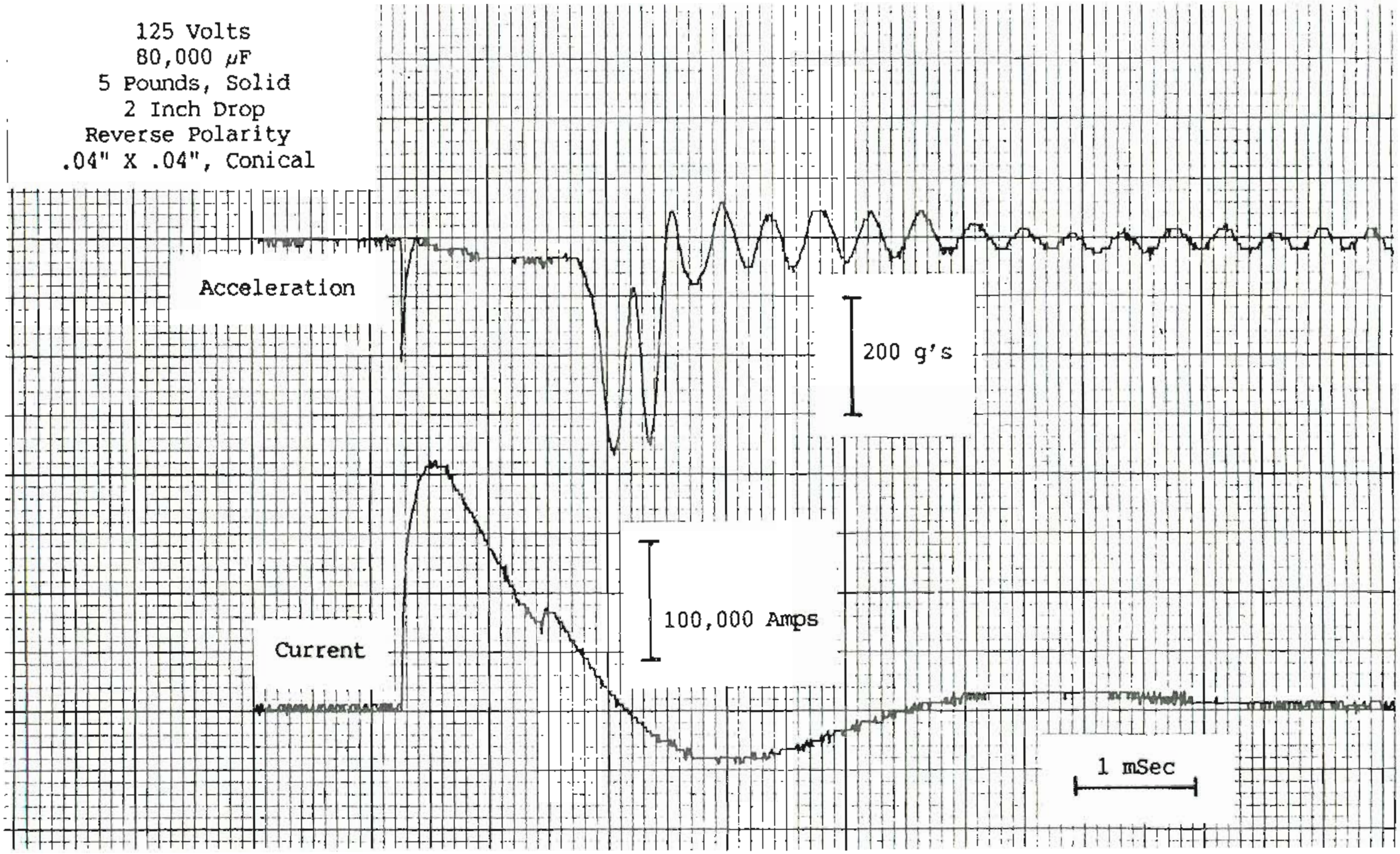

Figure 34. Current and acceleration curves, 5 pounds of solid drop weight.

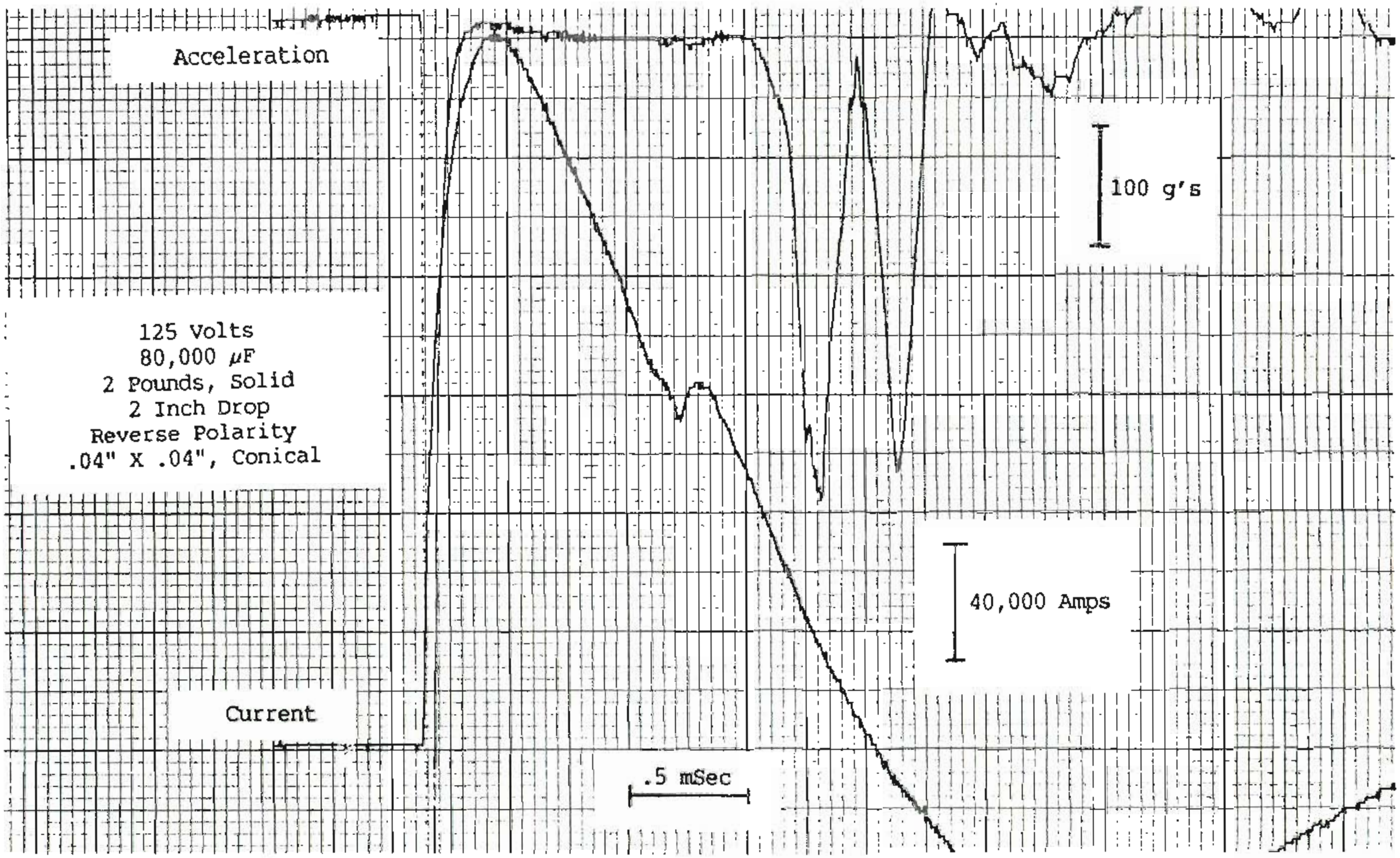

Figure 35. Current and acceleration curves, 2 pounds of solid drop weight.

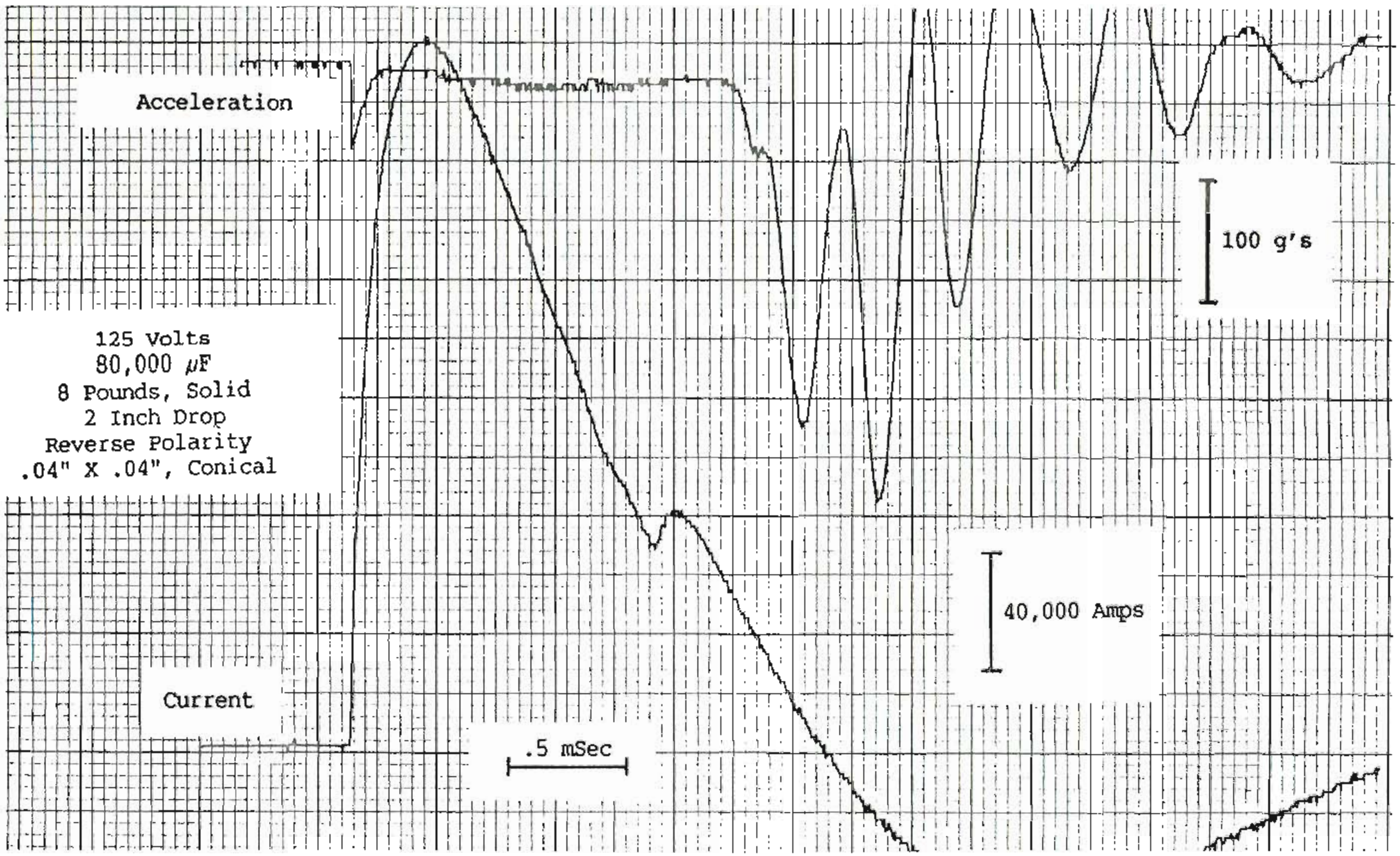

Figure 36. Current and acceleration curves, 8 pounds of solid drop weight.

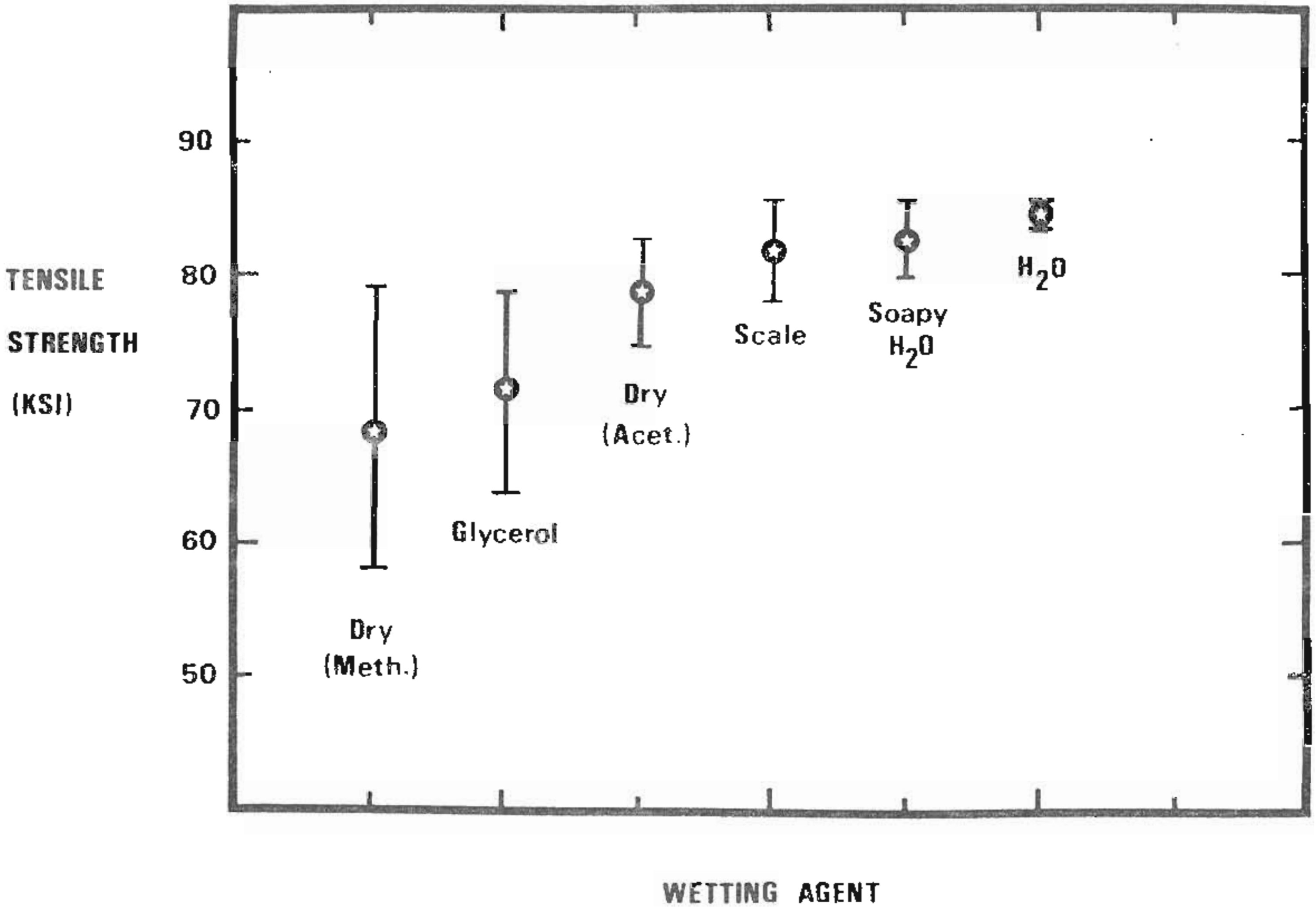

Figure 37. Tensile strength vs. surface condition.

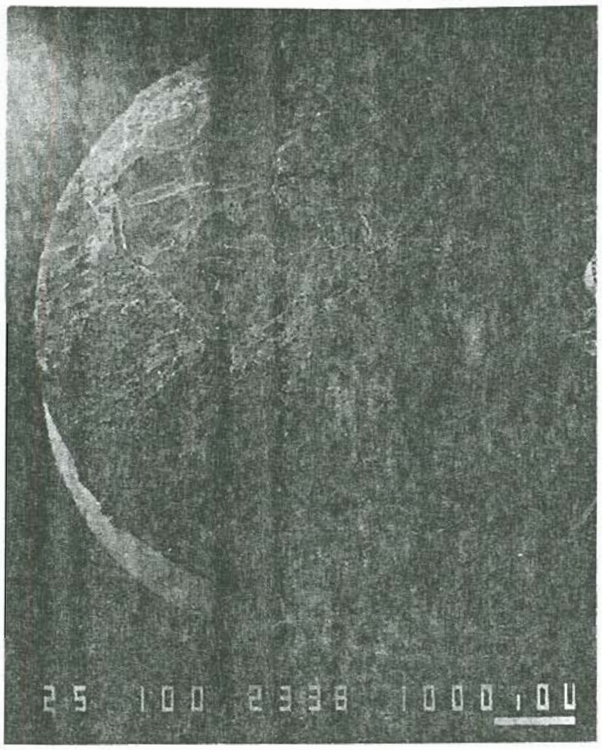

Figure 38.
Fracture surface,
distilled water
wetting agent.
12X.

Figure 39.
Fracture surface,
soapy water wetting
agent. 12X.

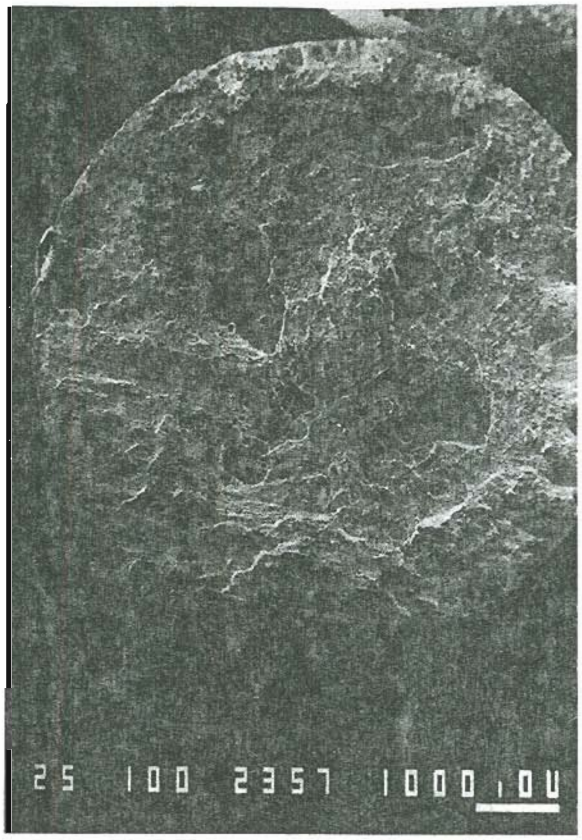

Figure 40.
Fracture surface,
hot rolled plate
mill scale. 12X.

Figure 41.
Fracture surface,
methanol cleaned
plate. 12X.

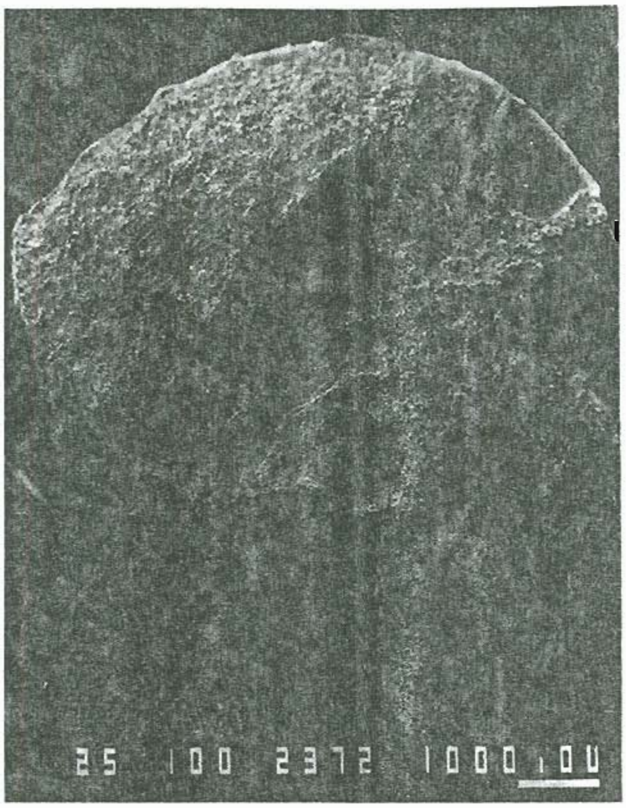

Figure 42.
Fracture surface,
glycerol wetting
agent. 12X.

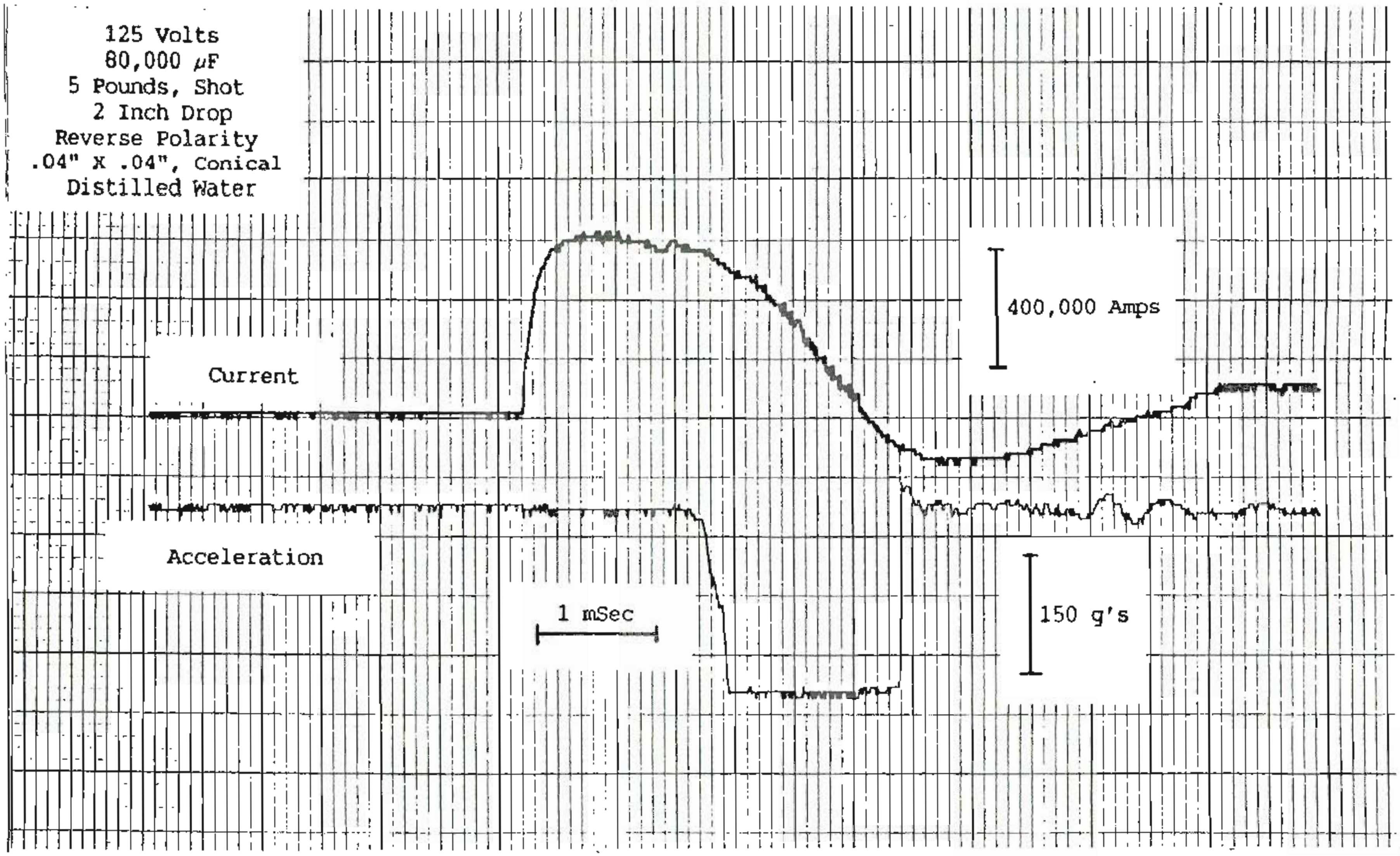

Figure 43. Current and acceleration curves, distilled water wetting agent.

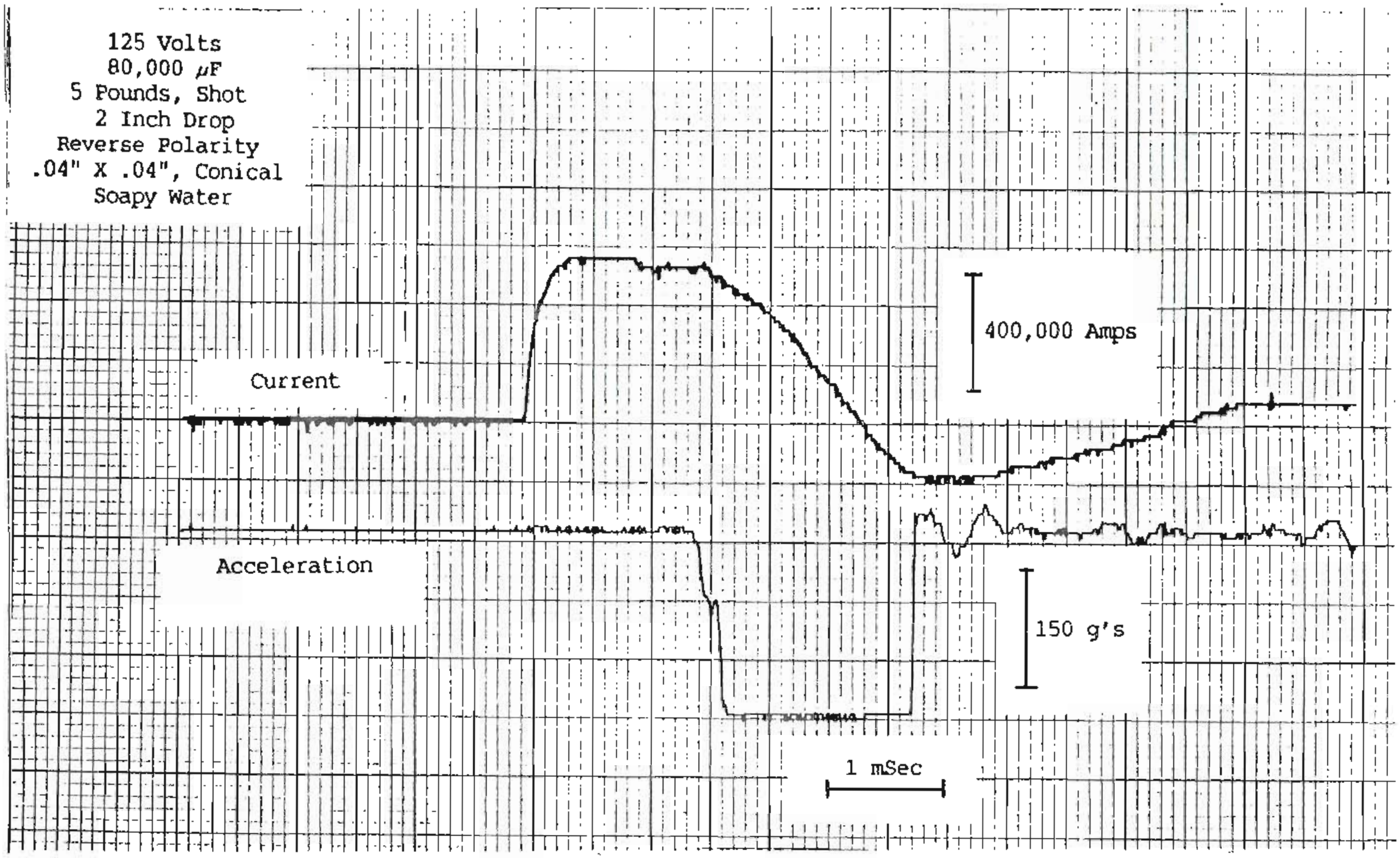

Figure 44. Current and acceleration curves, soapy water wetting agent.

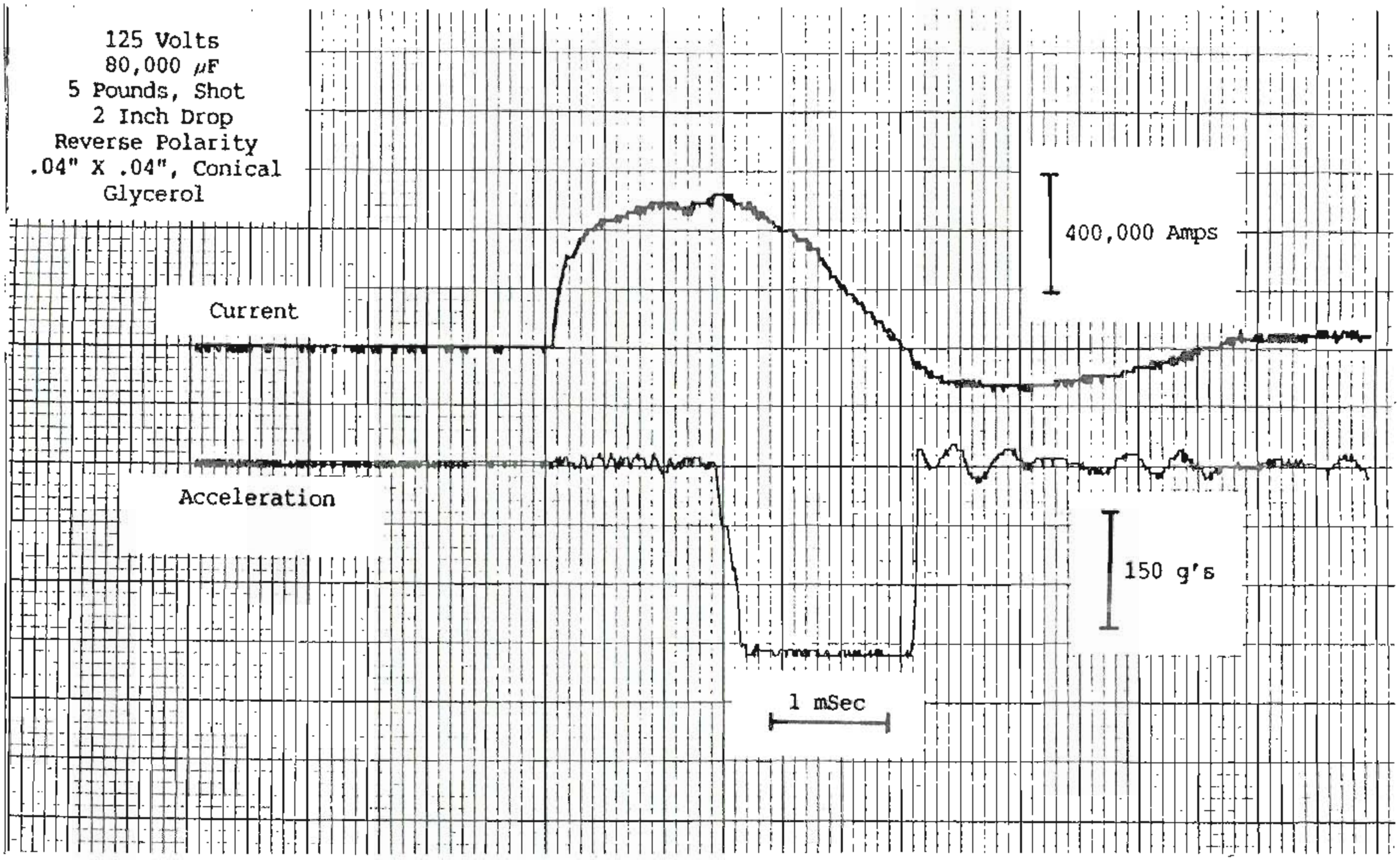

Figure 45. Current and acceleration curves, glycerol wetting agent.

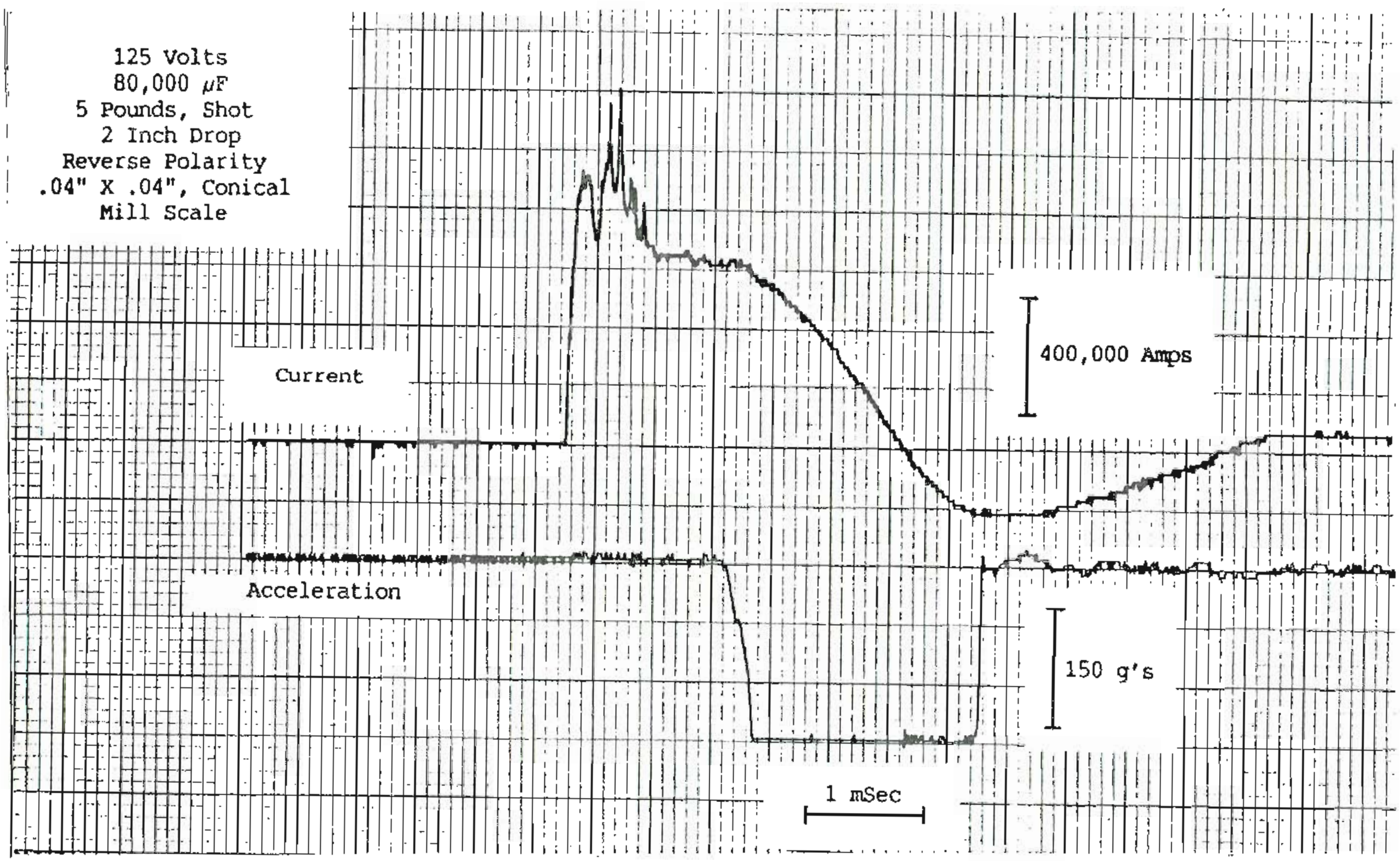

Figure 46. Current and acceleration curves, hot rolled plate mill scale surface.

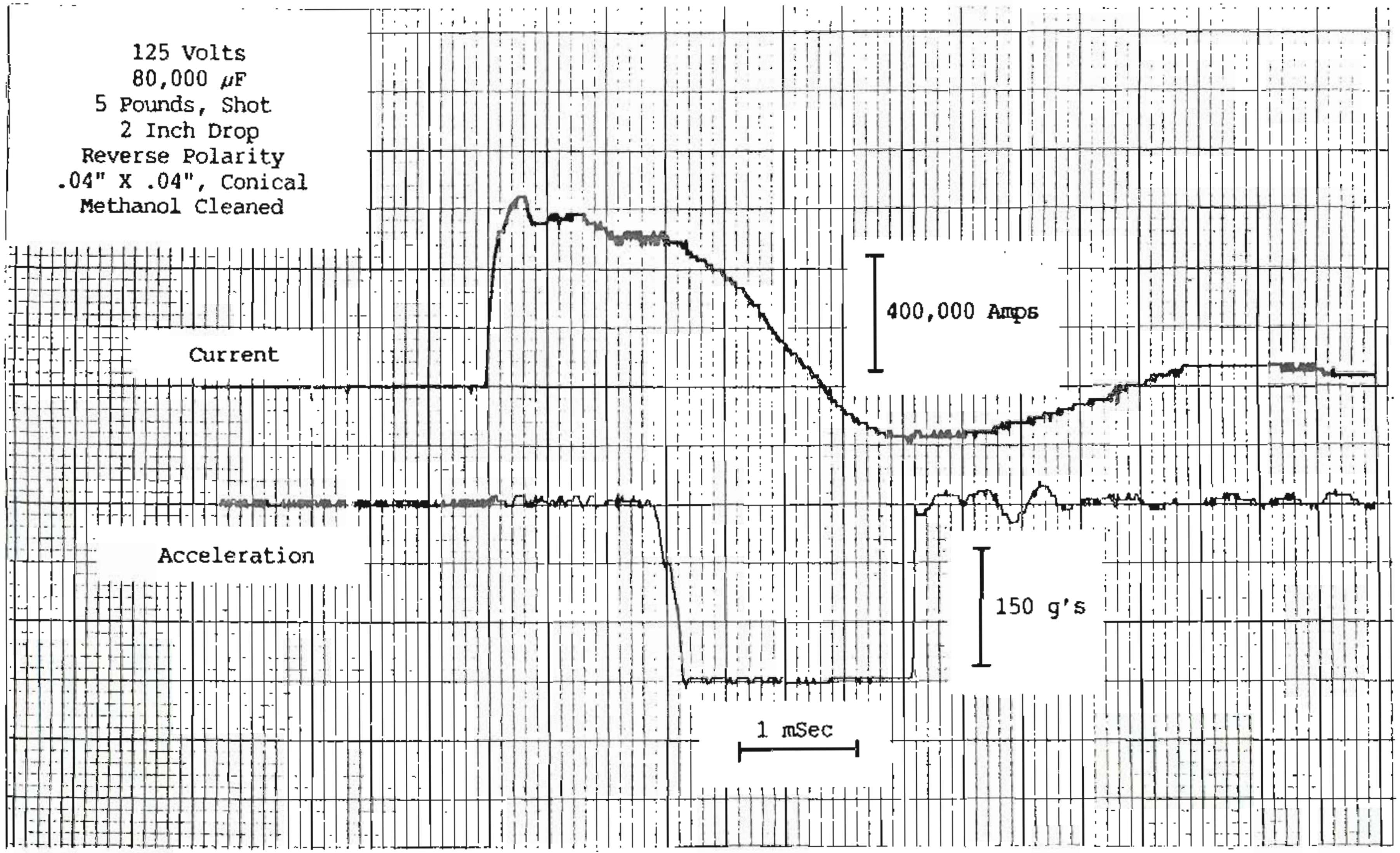

Figure 47. Current and acceleration curves, methanol cleaned surface.

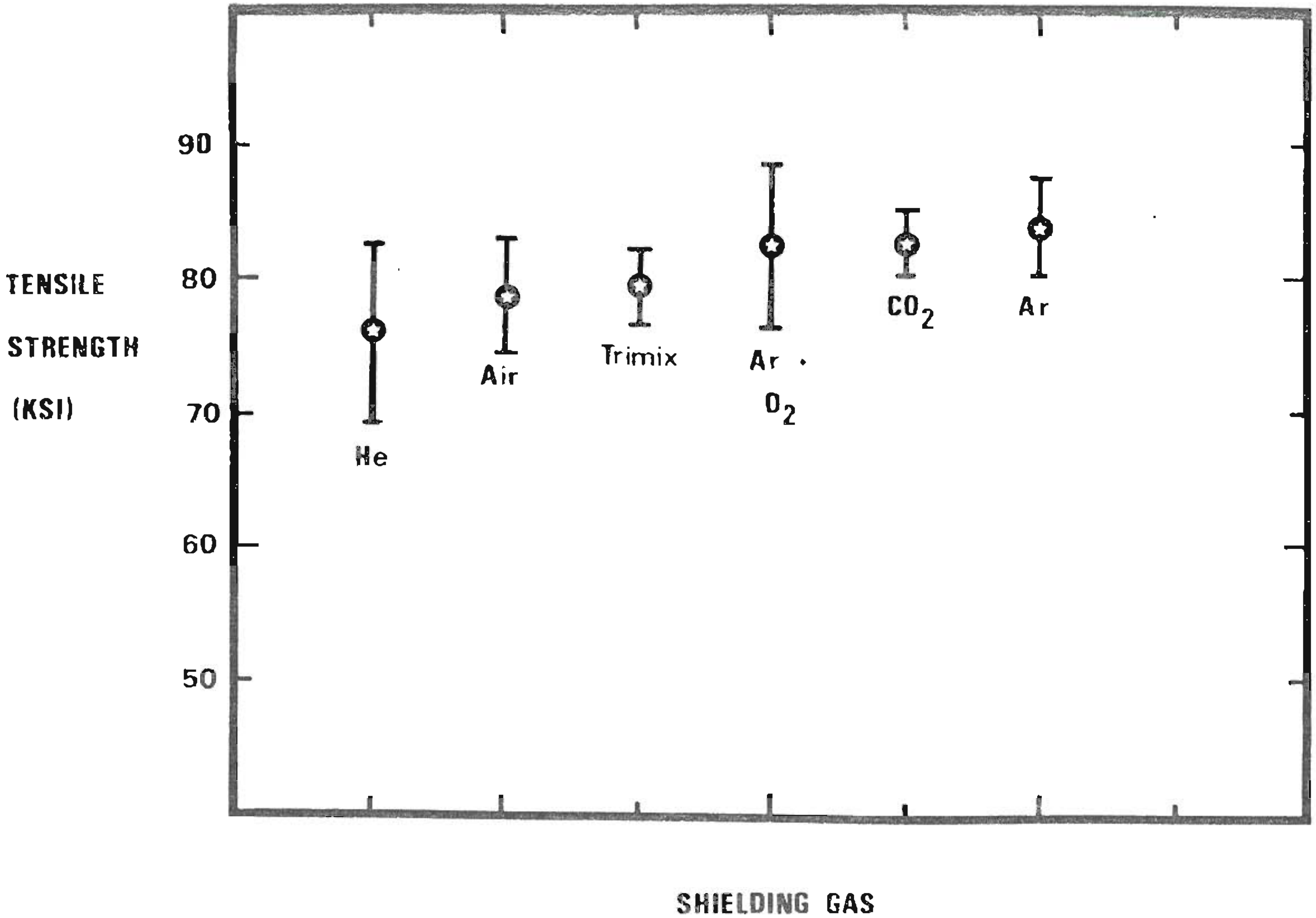

Figure 48. Tensile strength vs. shielding gas.

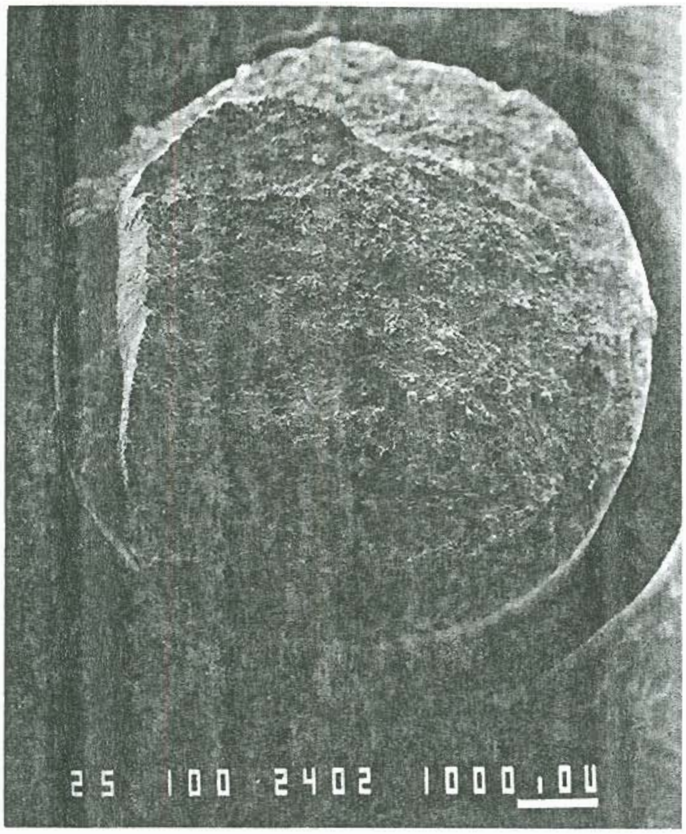

Figure 49.
Fracture surface,
argon shielding gas.
12X.

Figure 50.
Fracture surface,
trimix shielding
gas. 12X.

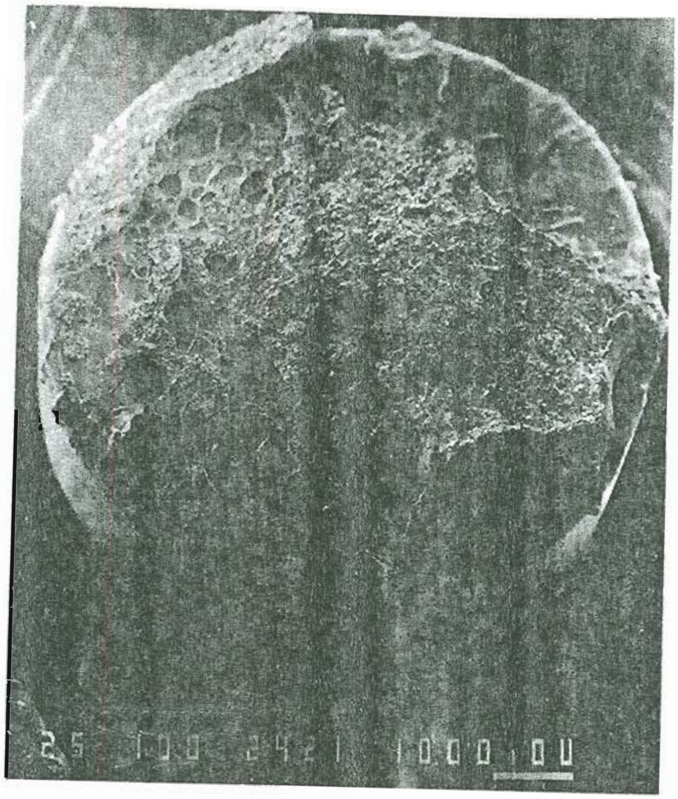

Figure 51.
Fracture surface,
helium shielding
gas. 12X.

Figure 52.
Fracture surface,
argon + 2% oxygen
shielding gas. 12X.

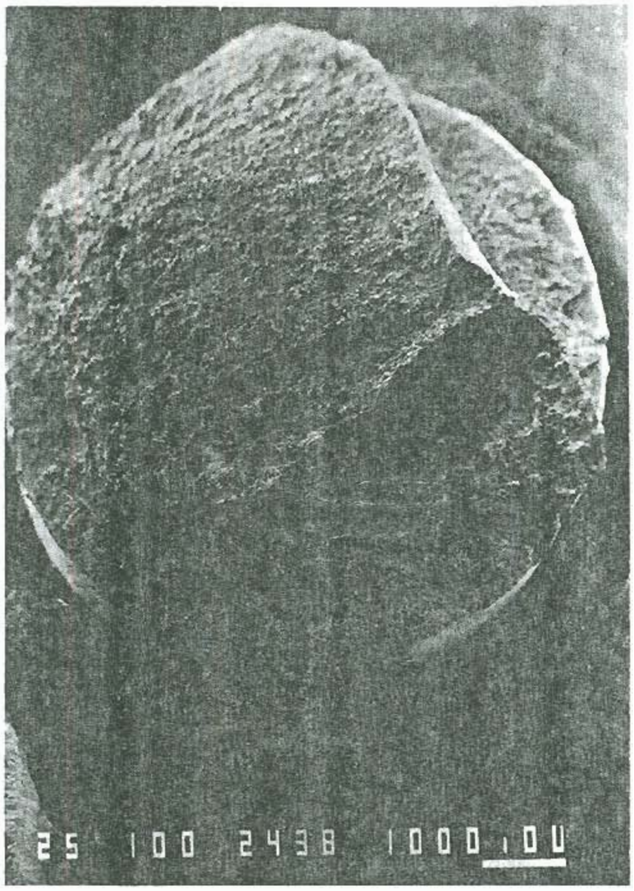

Figure 53.
Fracture surface,
carbon dioxide
shielding gas. 12X.

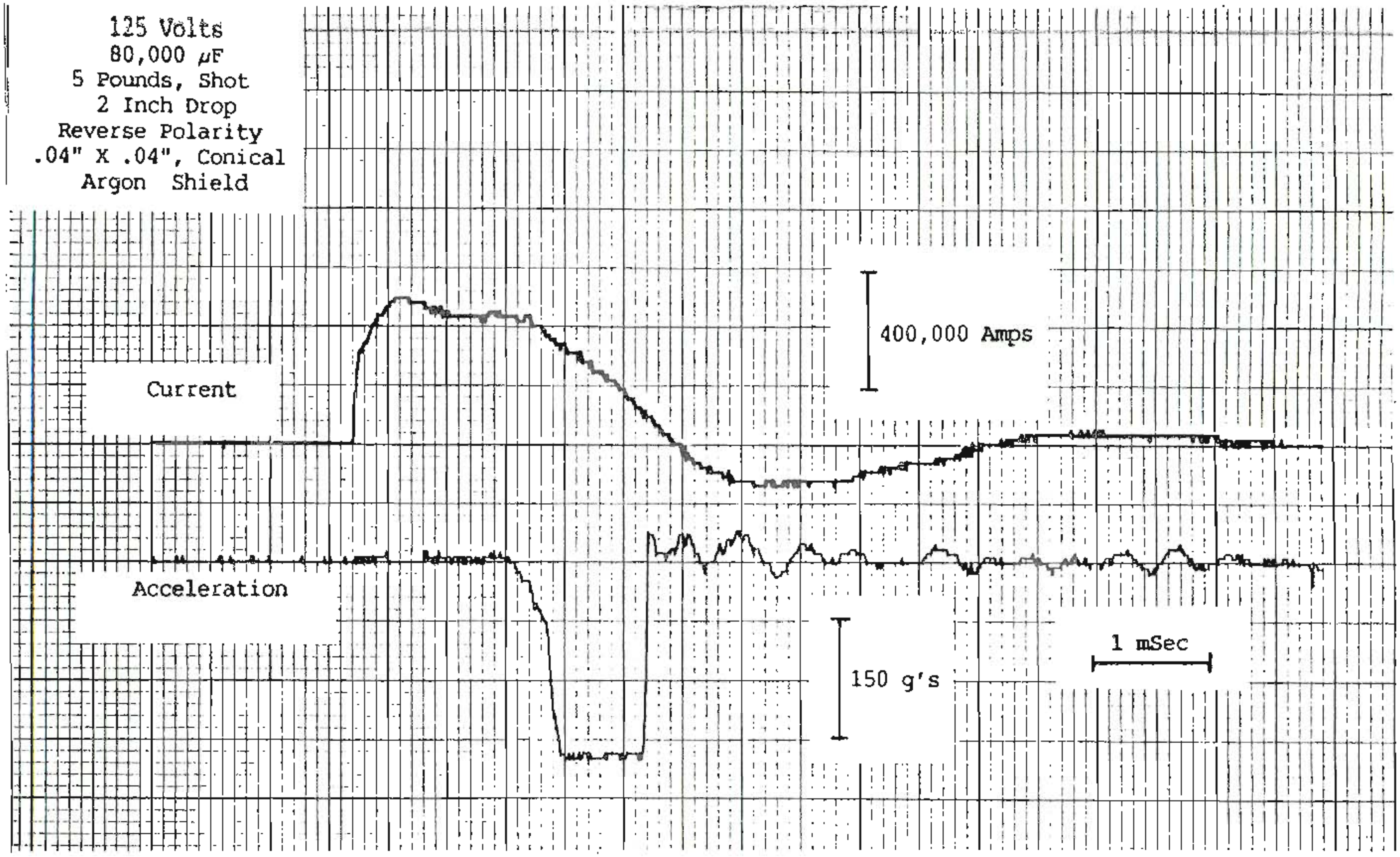

Figure 54. Current and acceleration curves, Argon shielding gas.

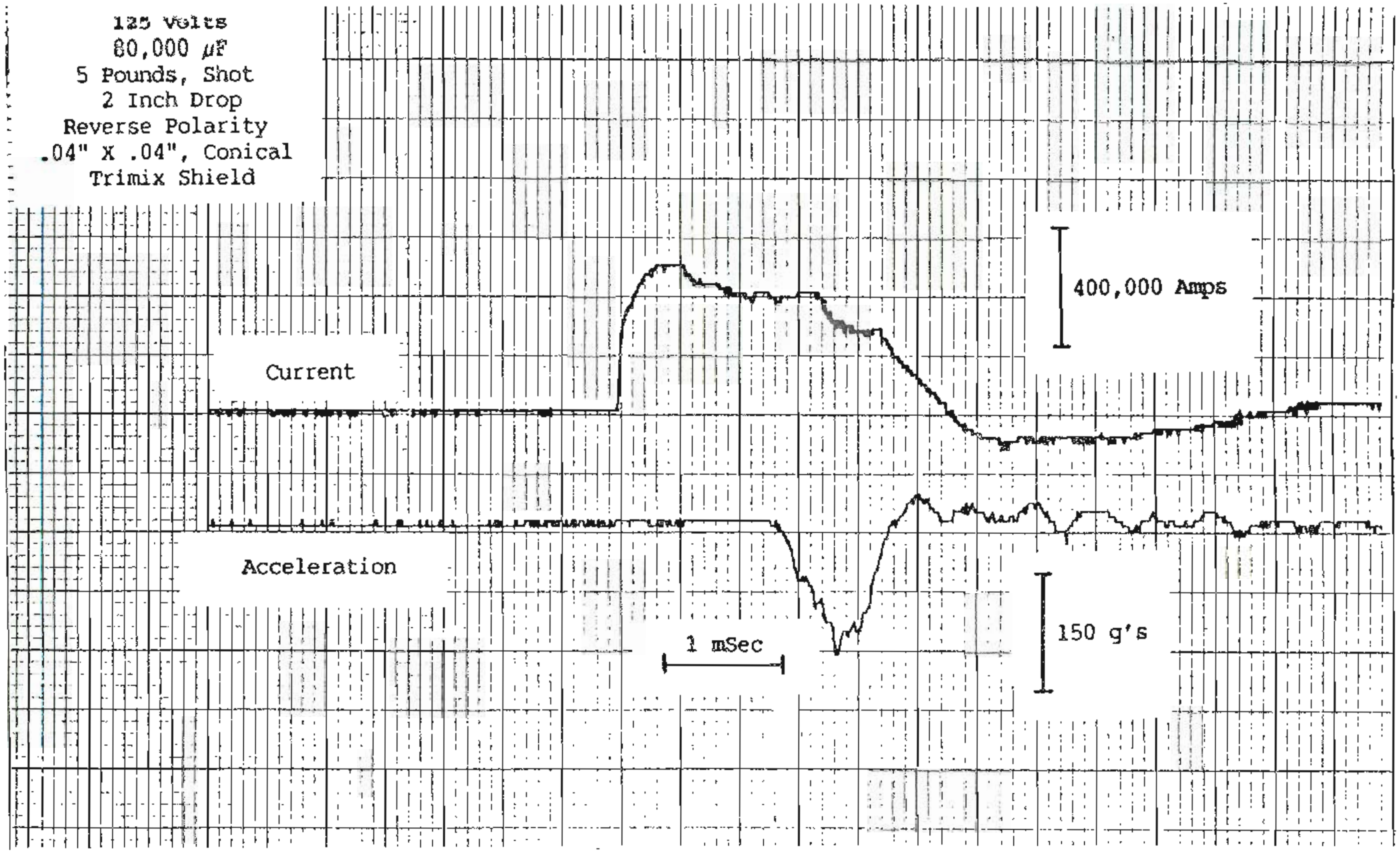

Figure 55. Current and acceleration curves, Trimix shielding gas.

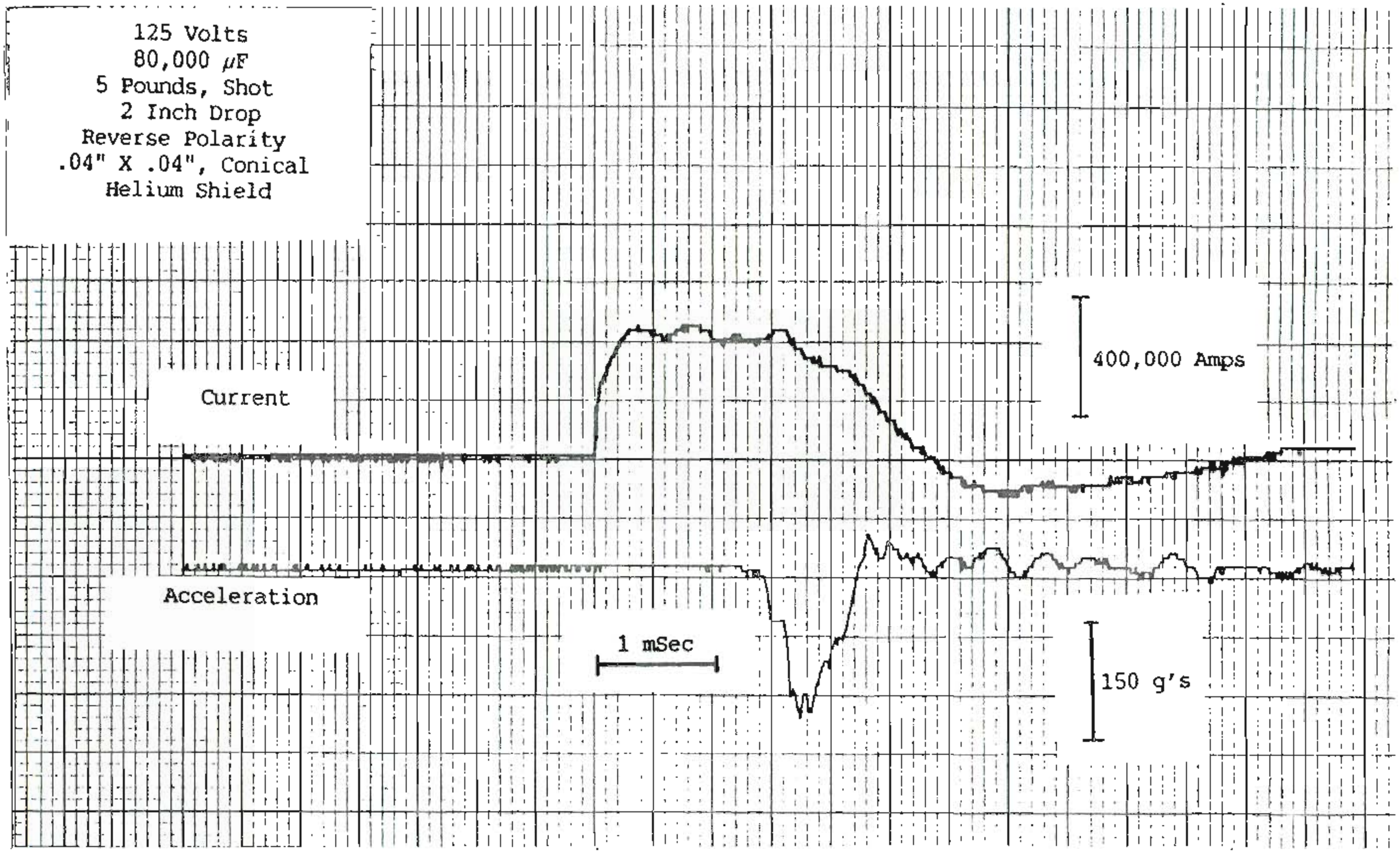

Figure 56. Current and acceleration curves, Helium shielding gas.

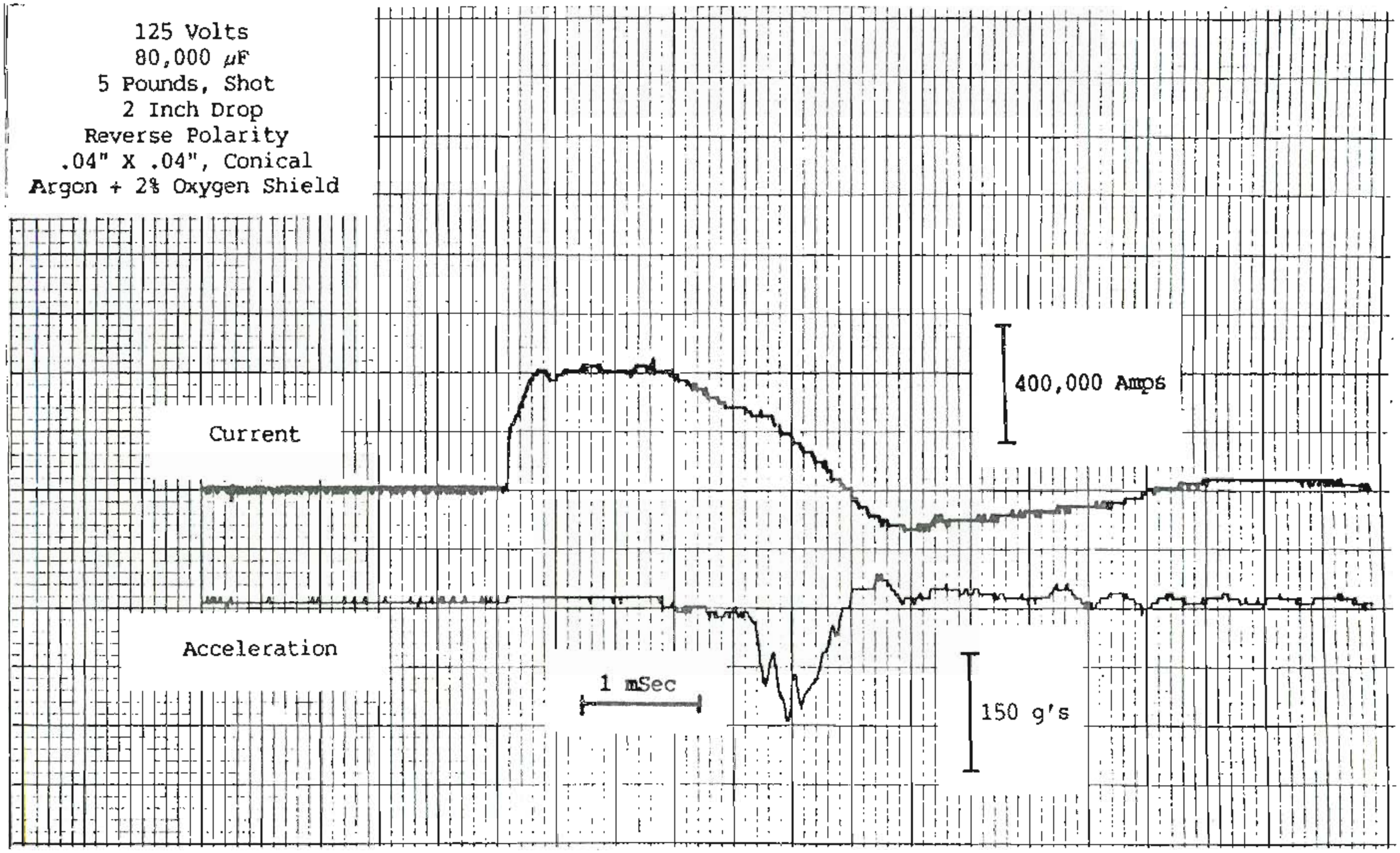

Figure 57. Current and acceleration curves, Argon + 2% O_2.

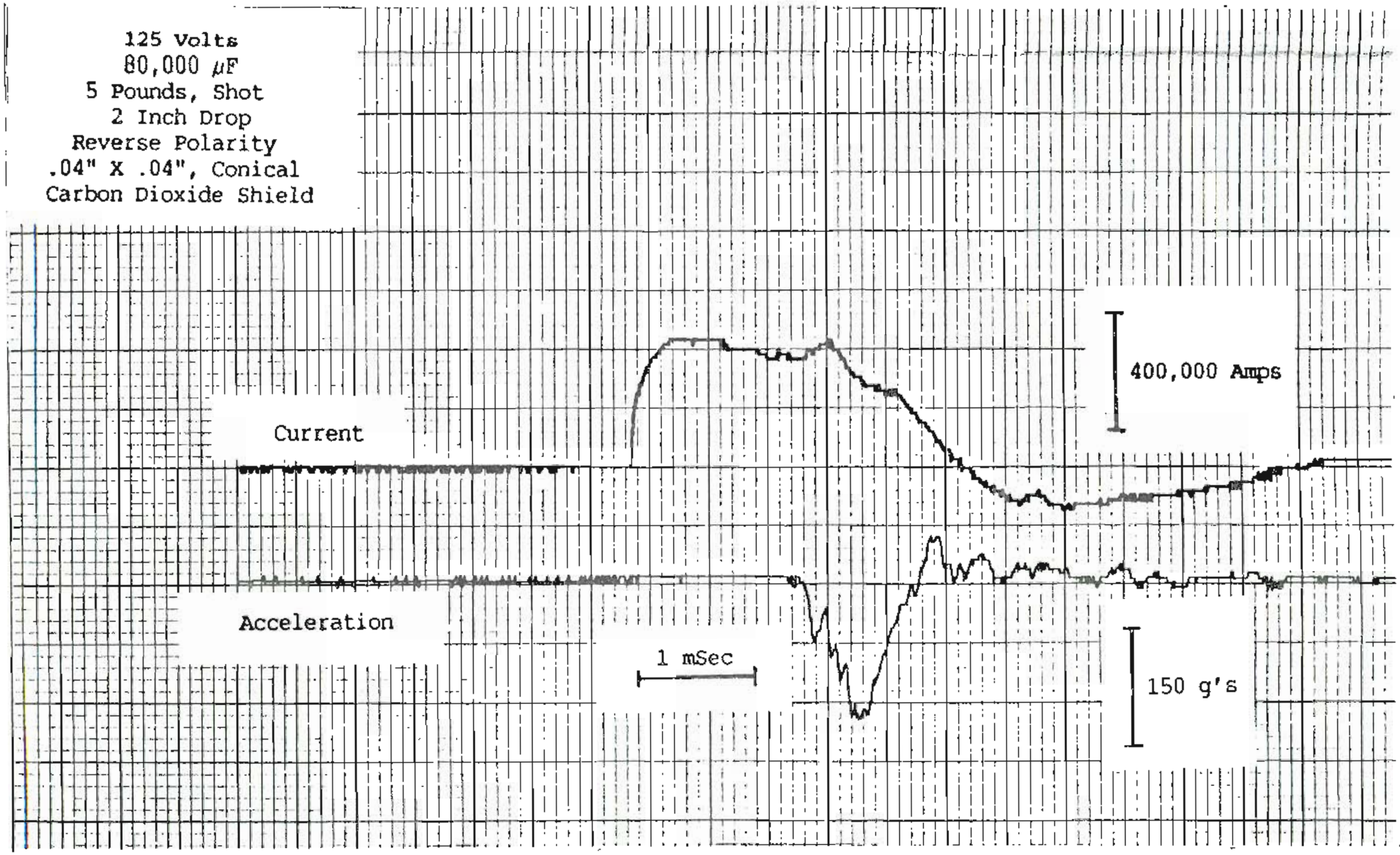

Figure 58. Current and acceleration curves, Carbon Dioxide shielding gas.

Figure 59.
Fracture surface,
straight polarity.
12X.

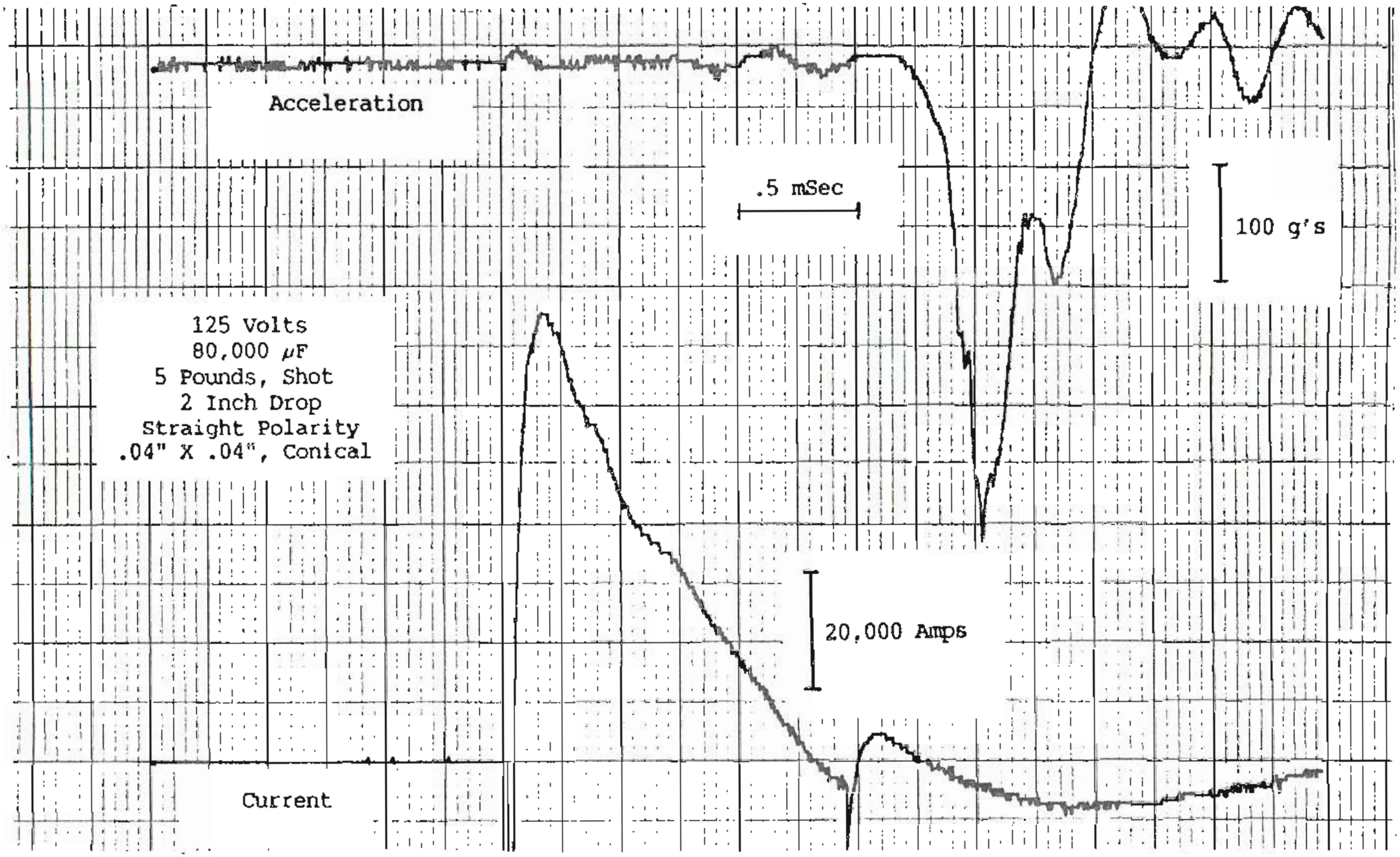

Figure 60. Current and acceleration curves, straight polarity.

Figure 61.
Fracture surface,
.04" X .06", conical
ignition tip. 12X.

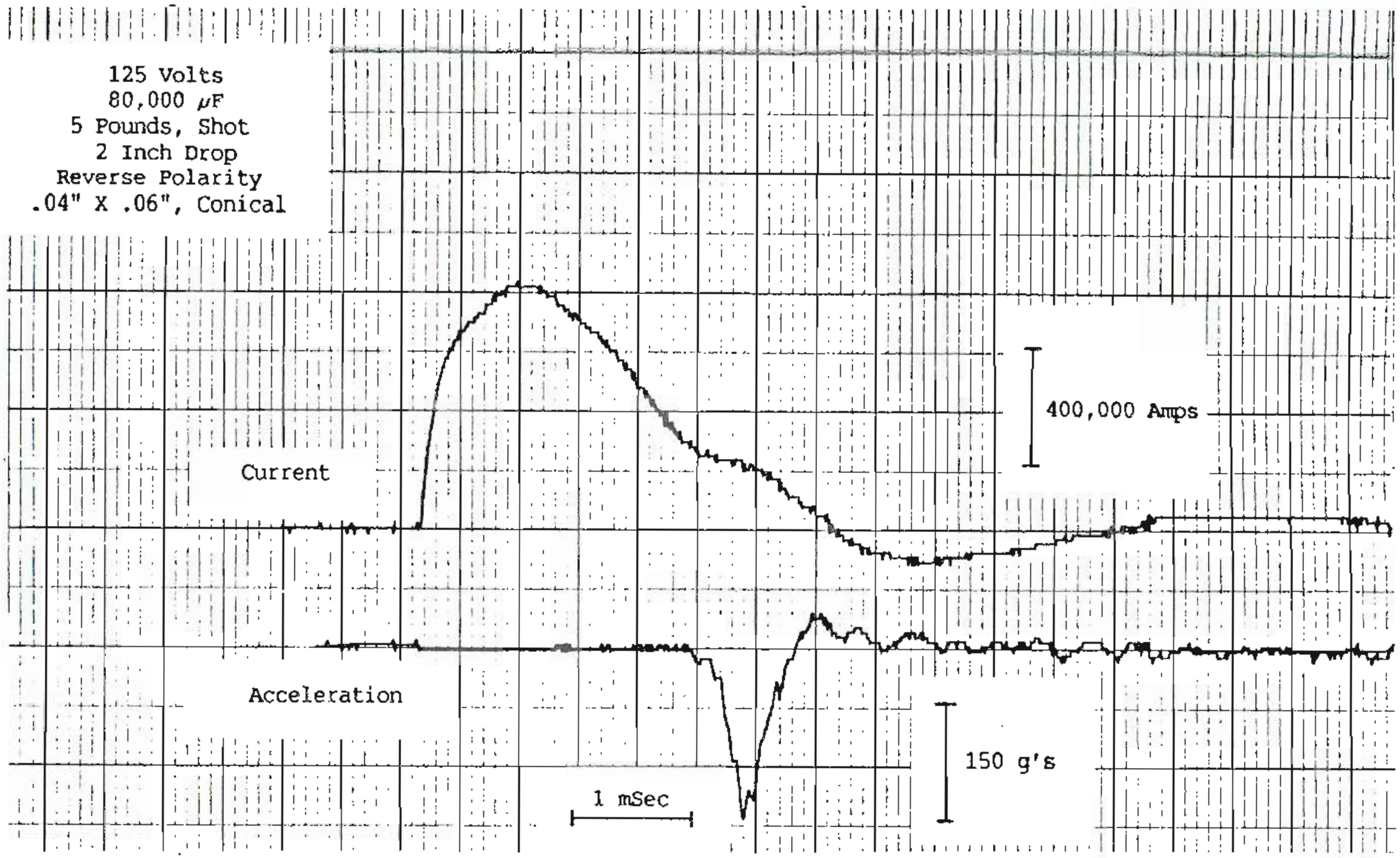

Figure 62. Current and acceleration curves, .04" x .06" conical ignition tip.

Figure 63.
Fracture surface,
.03" X .02", conical
ignition tip. 12X.

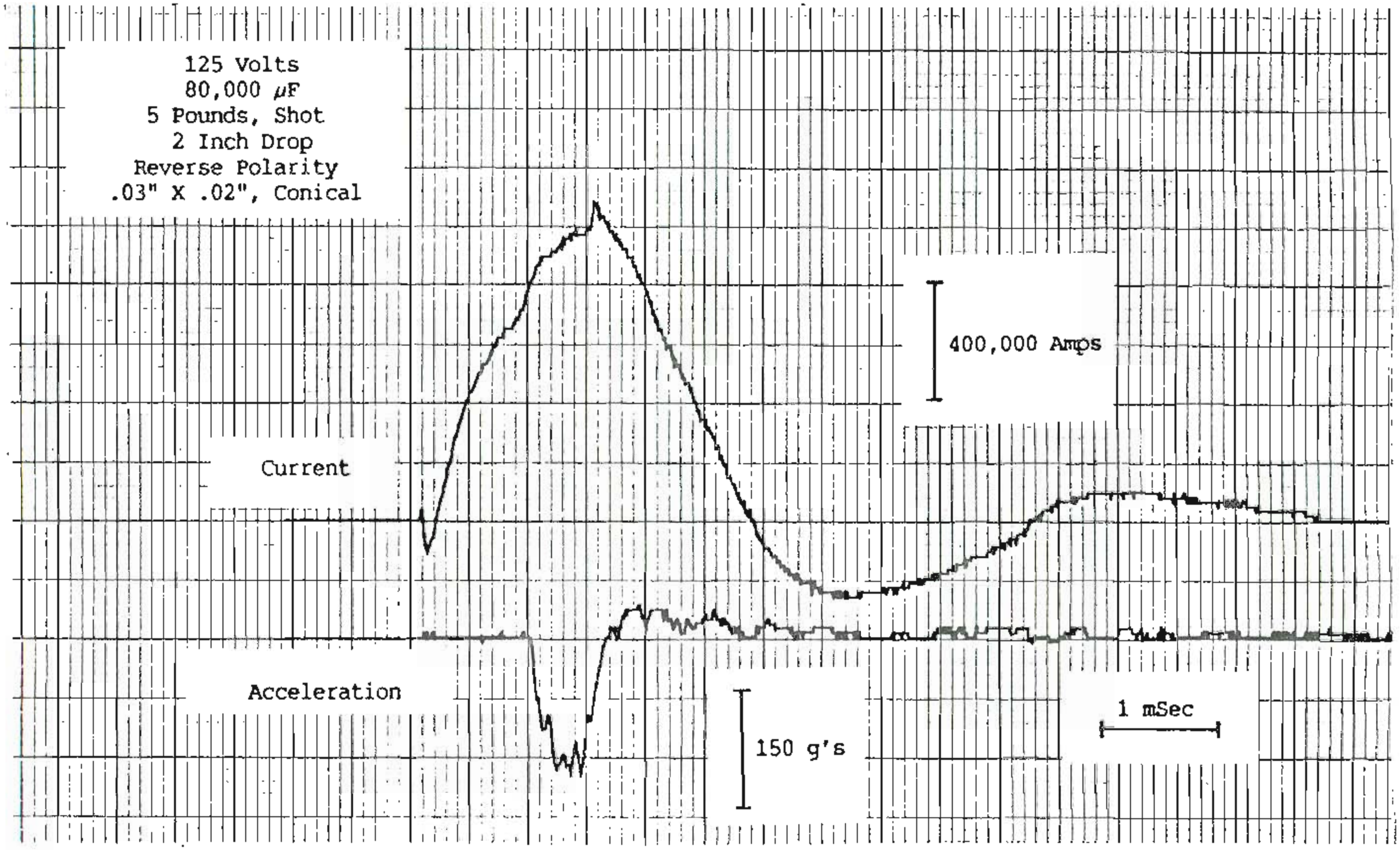

Figure 64. Current and acceleration curves, .03" x .02" conical ignition tip.

Figure 65.
Fracture surface,
.04" X .04", conical
ignition tip, no
bevel. 12X.

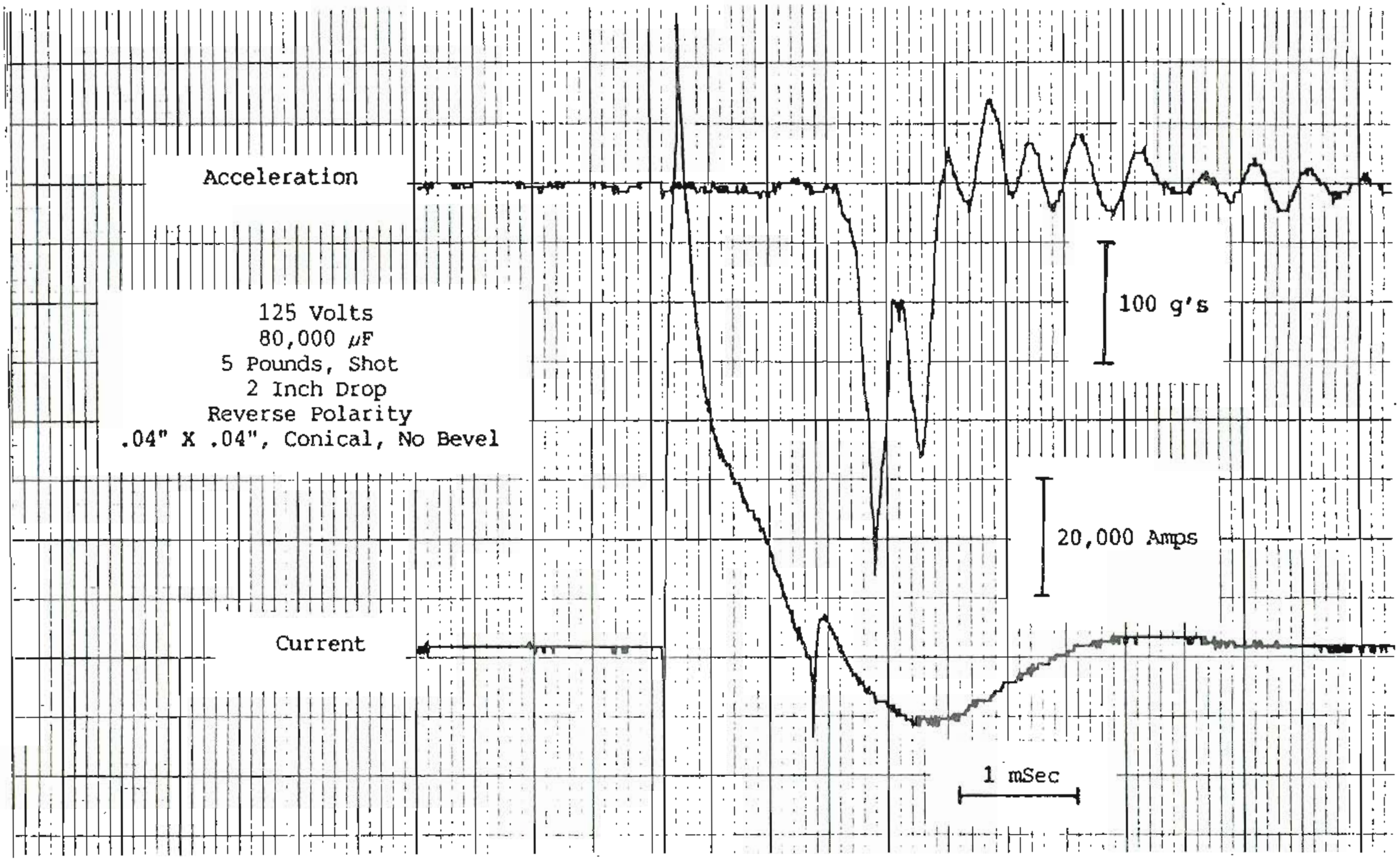

Figure 66. Current and acceleration curves, .04" x .04" conical ignition tip, no bevel.

Figure 67.
Fracture surface,
.02" X .04",
cylindrical
ignition tip. 12X.

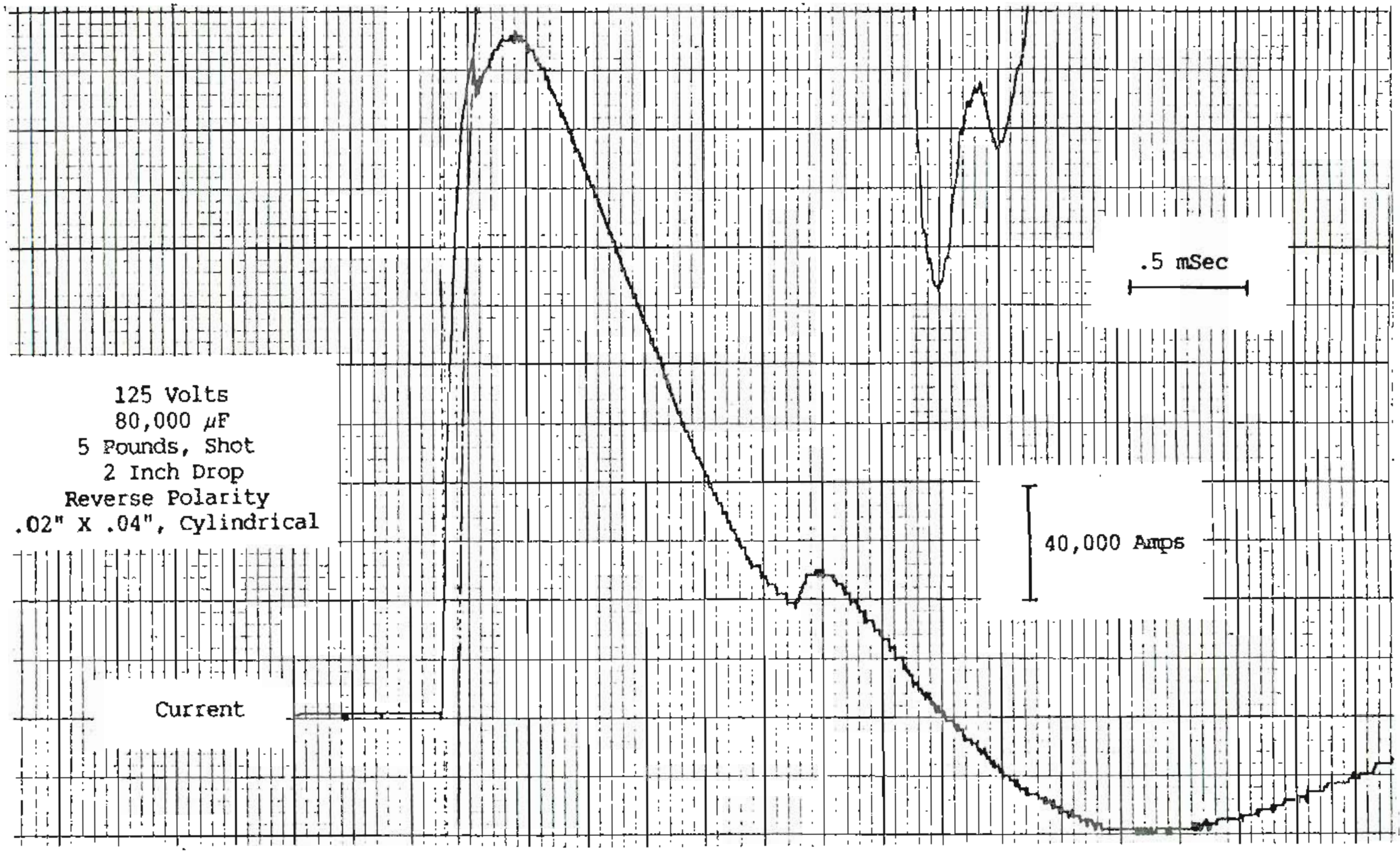

Figure 68. Current curve for .02" x .04" cylindrical ignition tip.

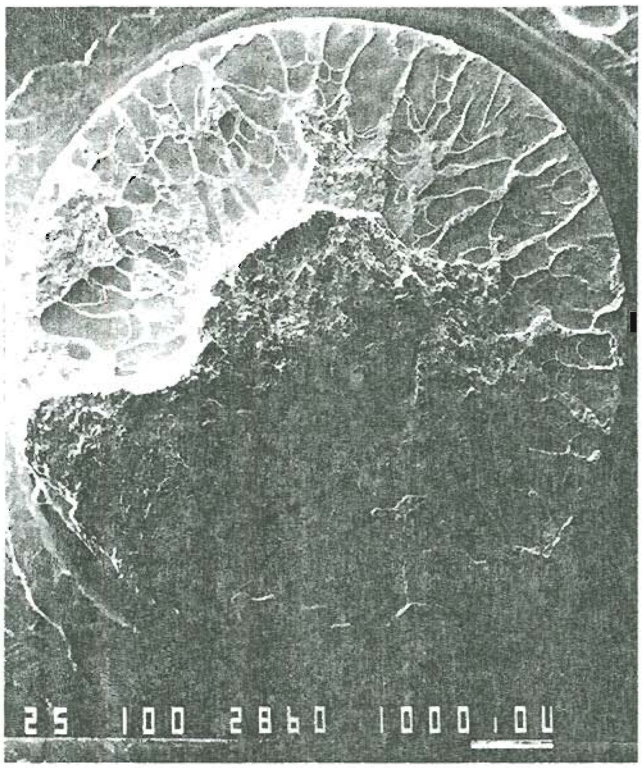

Figure 69.
Fracture surface,
.04" X .04",
cylindrical
ignition tip. 12X.

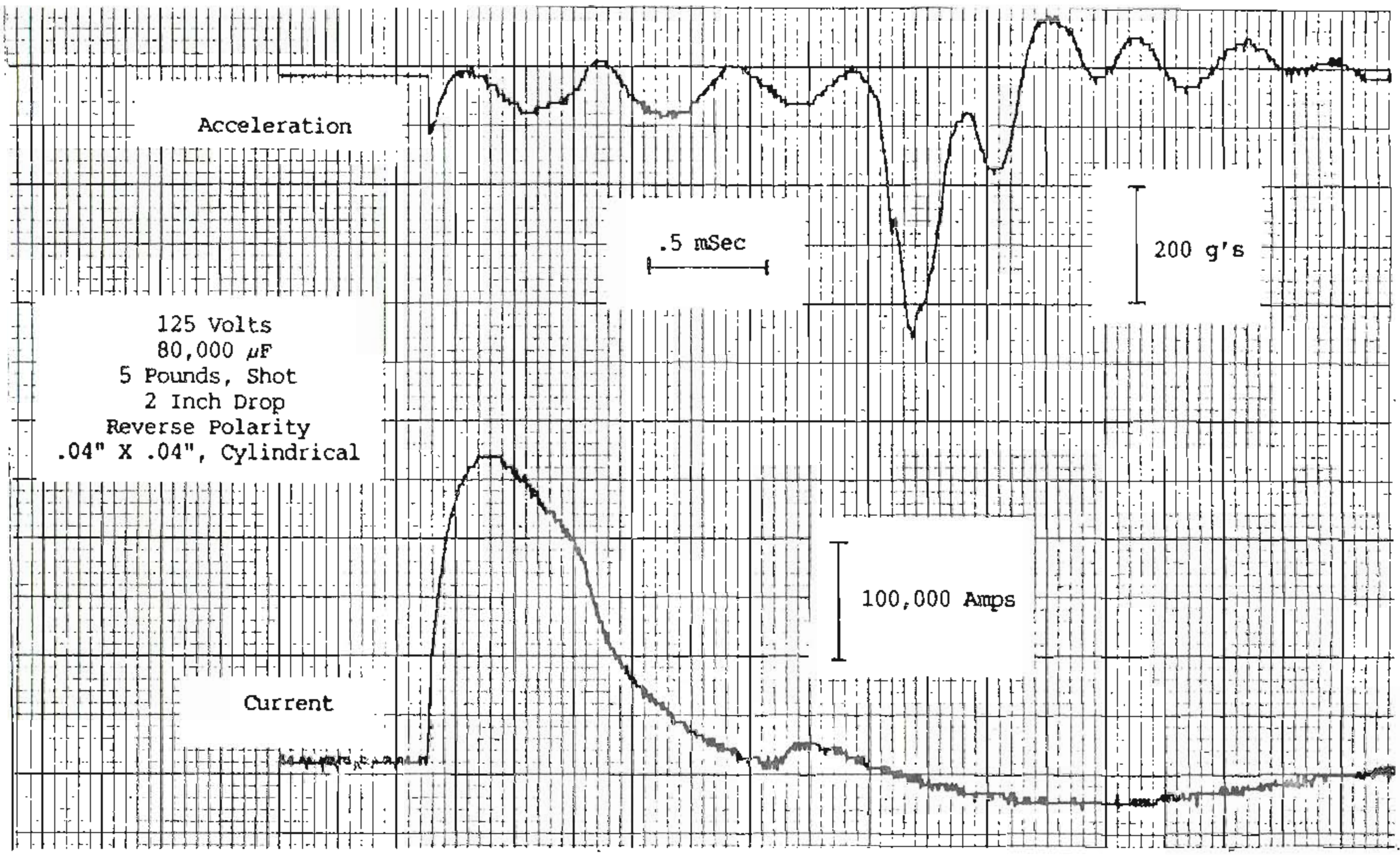

Figure 70. Current and acceleration curves, .04" x .04" cylindrical ignition tip.

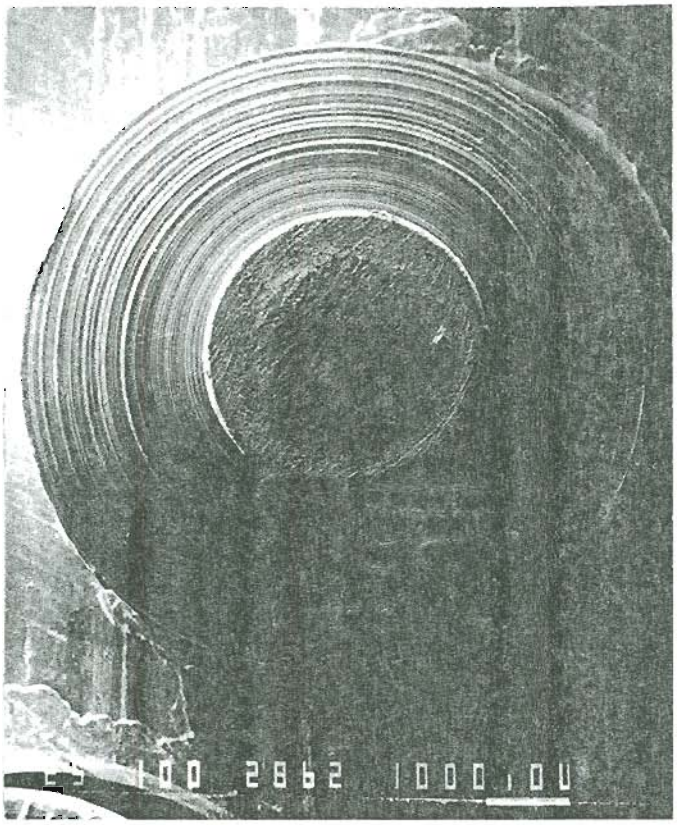

Figure 71.
Fracture surface,
.06" X .03",
cylindrical
ignition tip. 12X.

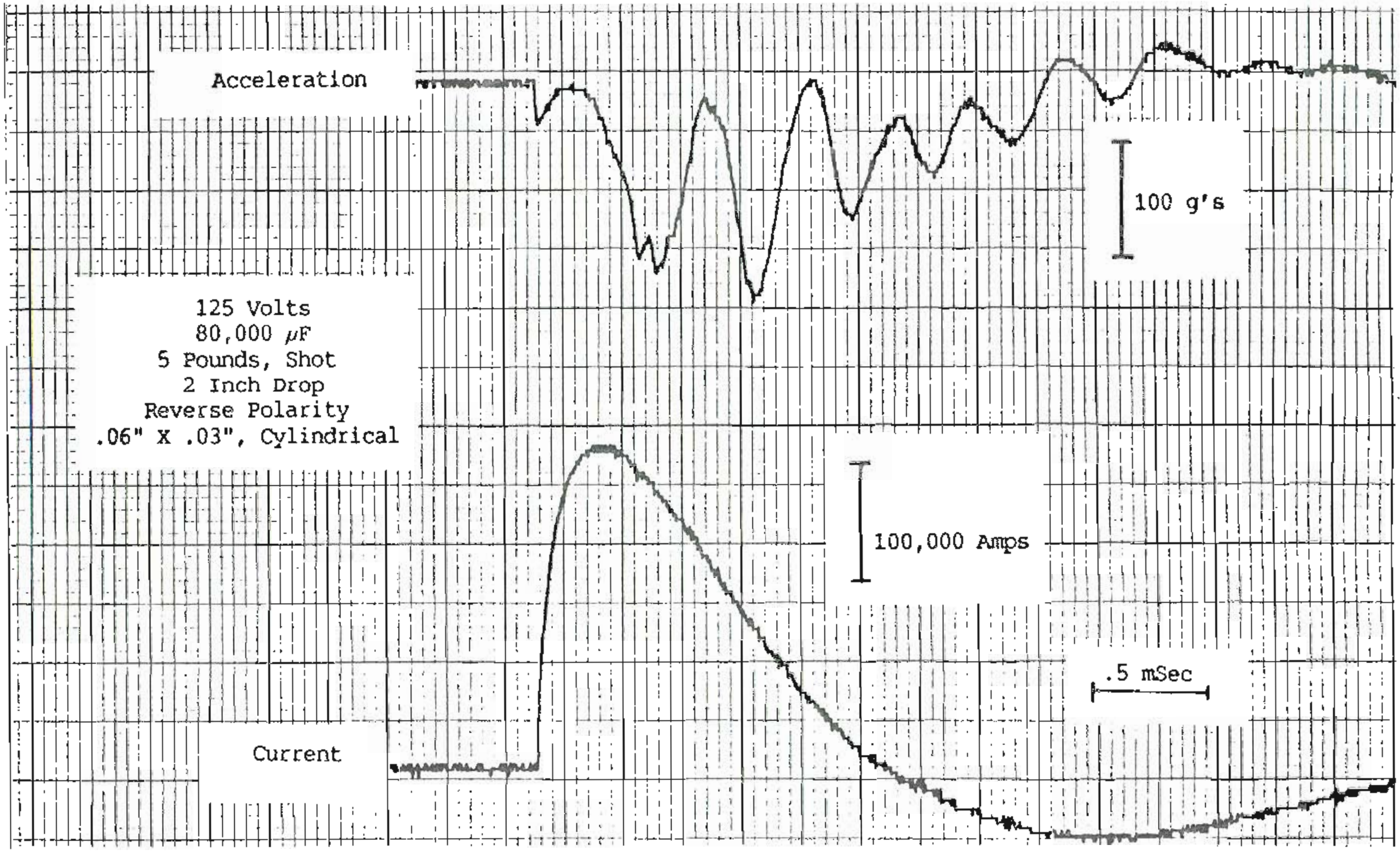

Figure 72. Current and acceleration curves, .06" x .03" cylindrical ignition tip.

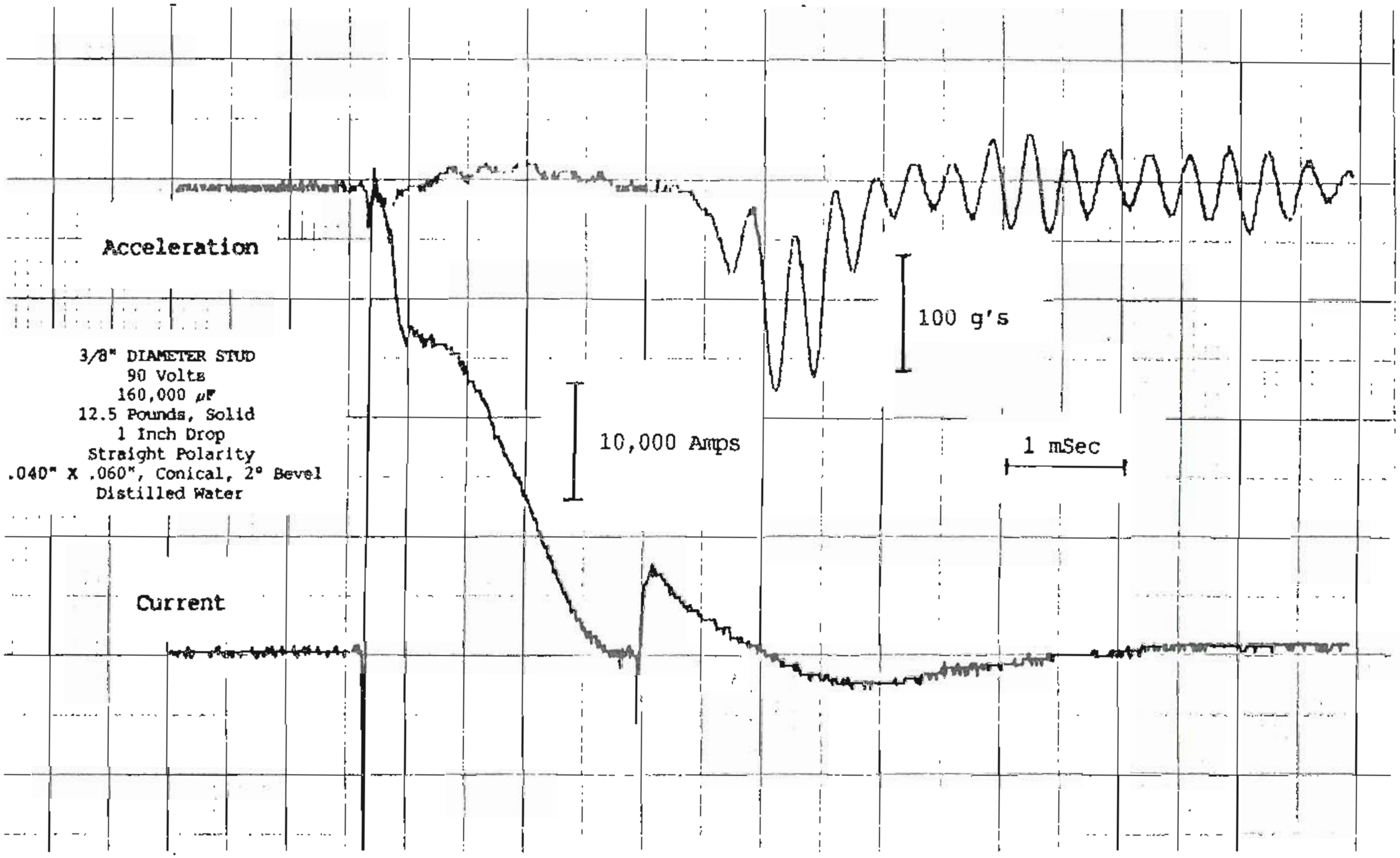

Figure 73. Current and acceleration curves, 3/8" diameter studs.

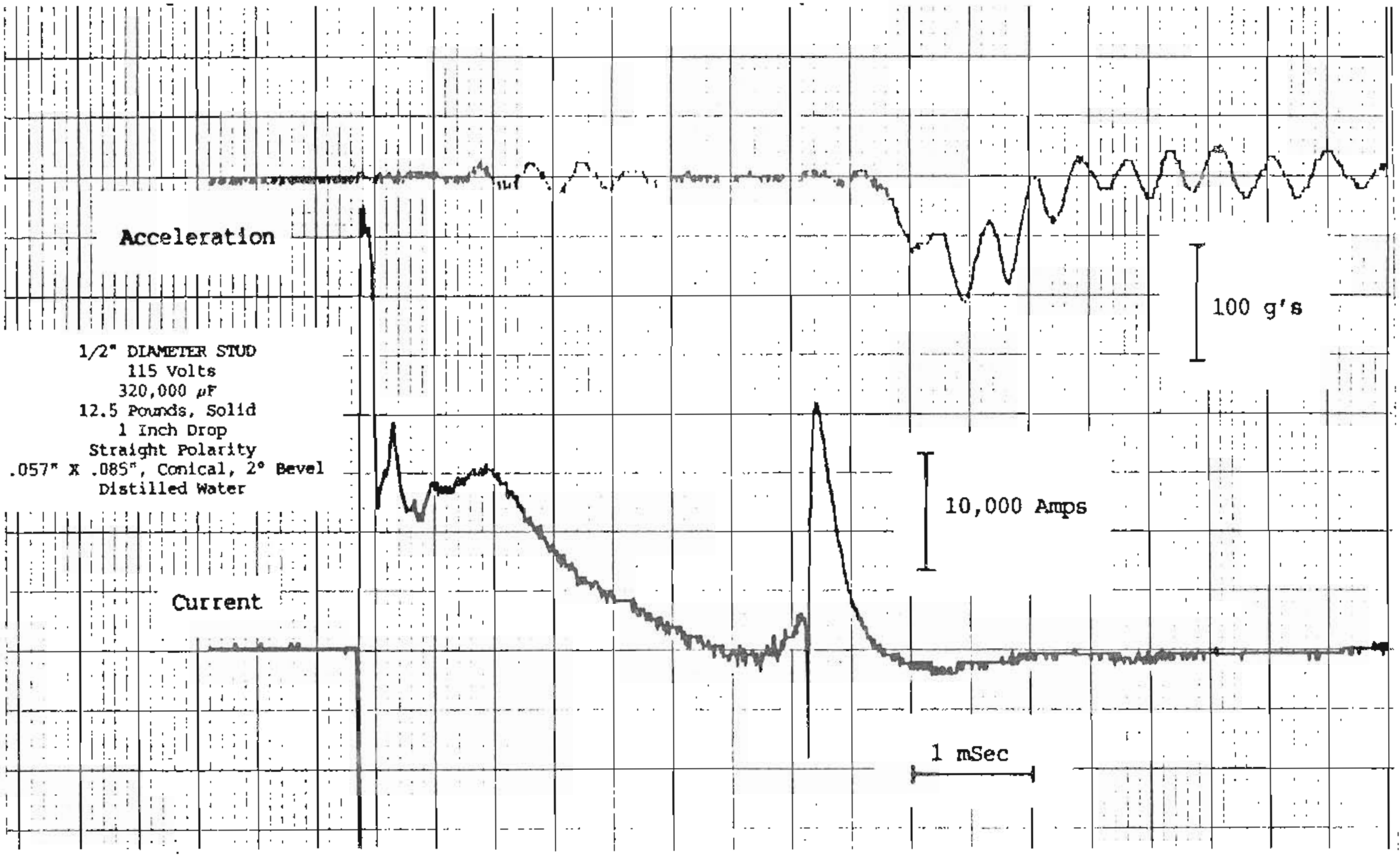

Figure 74. Current and acceleration curves, 1/2" diameter studs.

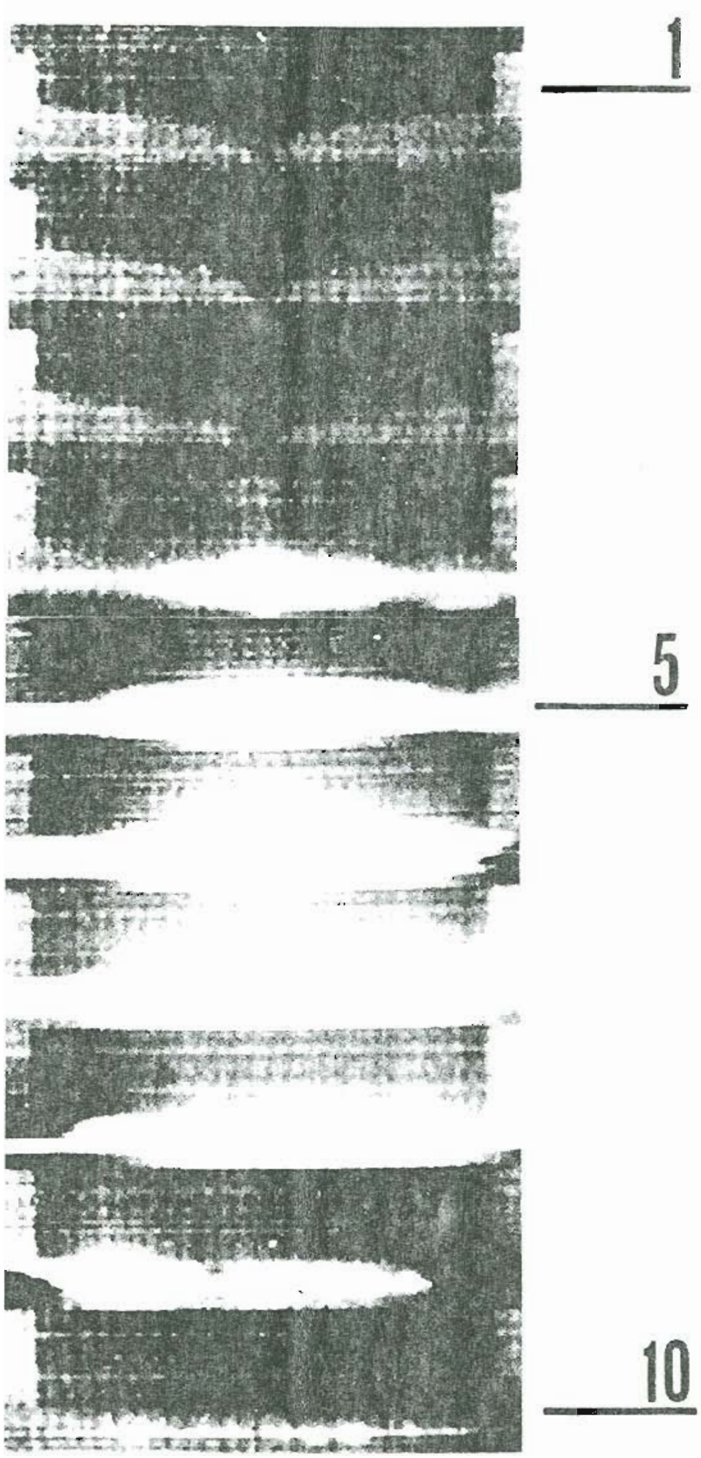

Figure 75. High speed videographic sequence of a .020" long ignition tip. The stud and ignition tip can be seen approaching the base plate in frames 1 – 3, arcing begins in frame 4, and expands only partially across the pin face before being extinguished in frame 10. 12,000 frames per second.

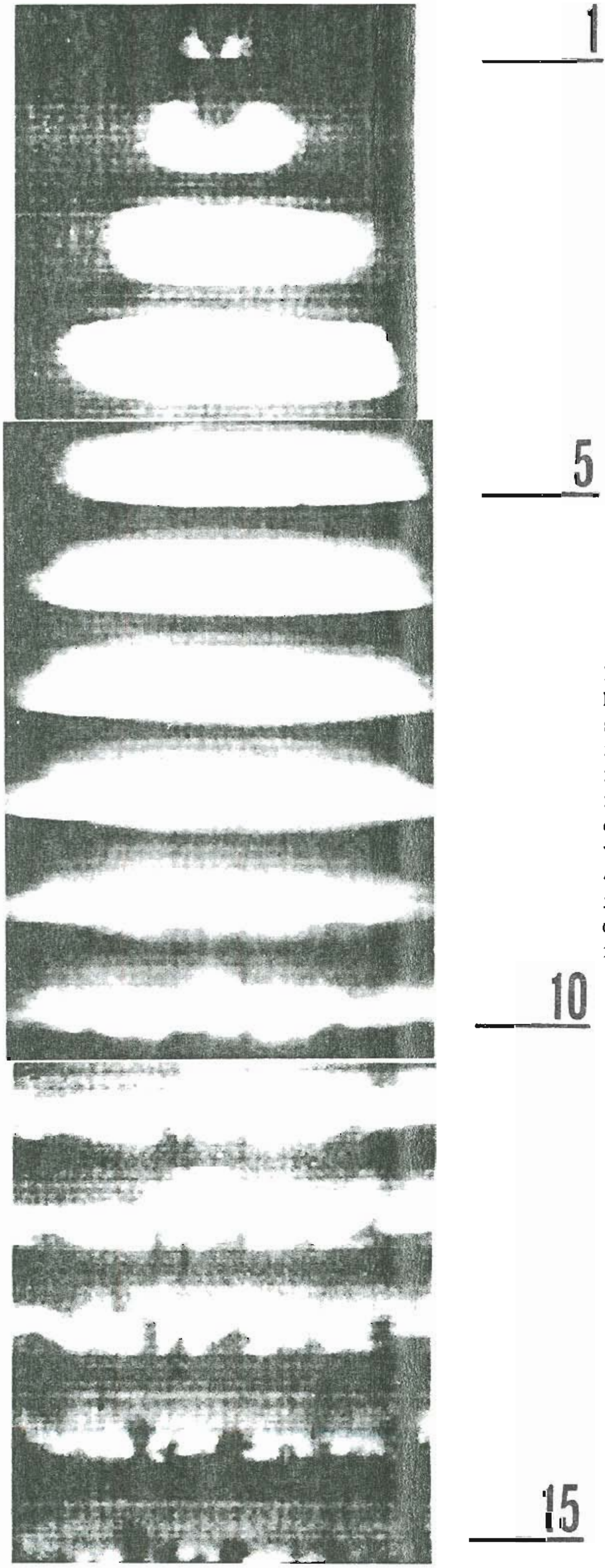

Figure 76.
High speed videographic sequence of a .060" long ignition tip. Arcing first starts around the ignition tip in frame one, continues to expand across the pin face in frames 2 - 4, and is finally extinguished in frame 15 behind drops of molten splatter. 12,000 frames per second.

BIBLIOGRAPHY

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