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Date: 2 MAY 1972

REPORT No. 954

High Strain Rate Plasticity Of Liner Materials And Jet Behavior (U)

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DEPARTMENT OF THE ARMY PROJECT No. 5B0304009
ORDNANCE RESEARCH AND DEVELOPMENT PROJECT No. TB3-0134

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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TABLE OF CONTENTS

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B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

REPORT NO. 954

LZernow/JSimon/mjf
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HIGH STRAIN RATE PLASTICITY OF LINER MATERIALS AND JET BEHAVIOR (U)

ABSTRACT

The behavior of jets from liner materials of high melting point is shown to be correlated with the crystal structure of the metal. Low melting point metals form a dispersed spray-like jet which seems to be related to their low melting point, but independent of their crystal structure.

Three examples of the effects of initial conditions of copper are discussed: copper shear-formed liners, certain anomalous electrodeposited liners, and copper liners fired at the temperature of liquid nitrogen.

Flash radiographs of jet formation for all materials discussed are included.

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I INTRODUCTION

It has long been known that copper-lined shaped charges give much better penetrations than steel-lined shaped charges and that various other metal liners give penetrations into steel targets which are not entirely consistent with the simple density law. Thus, in the best known cases the respective square roots of the densities of copper and steel are in the ratio 1.07, whereas the penetration-standoff curves show much greater differences both in peak penetration and in optimum standoff (Figure 1). Pugh (1) in 1945 qualitatively explained the differences by suggesting that copper jets remained continuous longer than steel jets. His explanation was experimentally verified essentially simultaneously at the Ballistic Research Laboratories (2) by means of flash radiographic observations and at Carnegie Institute of Technology (3) by means of Kerr cell observations.

The question of ductility or plasticity of the jet material undergoing deformation when subjected to the conditions existing during jet formation and jet flight is therefore seen to be a very important one. A logical additional question concerns the comparative behavior of the same liner material when it is put into a condition which normally would change its ductility.

As part of a systematic program involving the metallurgical and solid state aspects of the behavior of liner materials, a study has been made of the comparative behavior of various metals. In addition, studies have been conducted to investigate the effects of the initial condition of the metal.

When a shaped charge liner is collapsed by a detonation wave to form a jet and a slug, the liner material is undergoing plastic deformation at exceedingly high strain rates.(7) In the very early stages, the strain rates very likely exceed 10^5/second. As the jet is formed and stretches under the action of the velocity gradient the strain rate decreases until at the time when the jet is completely formed and distinctly separated from the slug, the strain rate has decreased to $\sim 10^4$/second. We are assuming at this stage that we are dealing with a ductile material which remains continuous during stretching. For materials which fracture early the strain rate after fracture is not given by the velocity gradient, $\frac{dV}{dX}$, but is naturally lower in magnitude.

It is apparent also that the initial jet formation at the collision point on the liner axis occurs under conditions of relatively high ambient pressure, whereas the later phases of jet flight and stretching occur essentially under negligible ambient pressure. It should be clear then, that the interesting plastic deformation is occurring in two relatively distinct stages. The first, or high ambient pressure stage which occurs at the collision point we will refer to as the dynamic Bridgman phase. The second phase will be referred to as the flight phase.

The technique for observing the behavior of various liner materials in each of these two phases has been that of flash radiography[4] [5] [6] of the liner collapse and jet flight. The sample materials used in these experiments were fabricated into 105mm shaped charge liners.

II BEHAVIOR OF VARIOUS METALS

It has been found that copper, nickel, silver and aluminum, all of which are face-centered cubic metals, behave in essentially the same way, with relatively small but noticeable differences between them. All of these have been found to behave in a ductile fashion in the dynamic Bridgman region and to stretch in a more or less taffy-like fashion in the flight phase, as shown by the radiographs of the jets in Figures 2,3,4 and 5. This suggests that gold and platinum ought to be interesting materials for shaped charge liners, not only because of their anticipated ductility based on their crystal structure, but also because of their high densities. Our viewpoint here of course is strictly academic.

Iron, which is a body-centered material, and all of the mild 1020 steels which have so far been studied as well as decarburized* steels, behave in their own characteristic fashion showing high ductility in the dynamic Bridgman region but fracturing into relatively large pieces very shortly after leaving the high pressure region, as shown in Figures 6 and 7. The body centered cubic (b.c.c.) structure of iron is of course not the closest possible packing and it has been suggested (7) that the obviously ductile behavior of the iron in the collision region (Figure 6) may be due to a collapse to the face centered cubic (f.c.c.) close packed structure under the pressures existing at the collision point.

The hexagonal metals, such as magnesium, and cobalt, also show a distinct characteristic behavior, namely, in the flight phase they break up into rather fine fragments (Figures 8 and 9). Magnesium appears to behave in a ductile fashion during the dynamic Bridgman phase, but cobalt shows evidence of anomalous behavior as can be seen from Figure 10. These radiographs suggest that cobalt (at least for the samples of electrodeposited material used) may have been fractured prior to entering the Bridgman region.

The low melting point metals cadmium (Hexagonal), zinc (hexagonal), lead (f.c.c.) and tin (tetragonal) appear to behave in a unique fashion despite the diversity of their crystal structures. The jets from these materials are generally relatively large in cross section and the radiographs have the appearance of a finely dispersed cloud or spray. This is not always true, as can be seen from the radiograph of tin in Fig. 14, but with these low melting point materials the spray type of jet is encountered most often, as shown in Figs. 11 to 13. Their common behavior in collapse is illustrated in Figs. 15, 16, 17, and 18.

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*Supplied to us through the courtesy of Dr. A. W. Hull and the General Electric Research Laboratory.

It thus appears that for high melting point metals (MP $> 625^{o}C$) the crystal structure correlates with the observed properties of the jet, whereas for the low melting point materials (MP $< 460^{o}$) the low melting point itself appears to be the property most closely correlated with the behavior of the jet.

III EFFECTS OF INITIAL CONDITIONS OF THE COPPER

Three types of initial conditions were studied in copper liners.

a. The severe plastic deformation of the liner by a process of fabrication called shear-forming (ITE)* which resembles a spinning operation.

b. The electrodeposition of copper under conditions which produced unexpected polyfurcation of the jet and poor penetration performance.

c. The cooling of the liner (and complete charge) to liquid nitrogen temperatures prior to firing.

A. Shear Formed (ITE) Liners

The behavior of the jet from a shear formed (ITE) copper liner whose microstructure is shown in Fig. 19 can be seen from the jet radiograph in Fig. 20. The jet is very badly broken up. These radiographs were obtained several years ago but were not correctly interpreted until recently. Important experiments by Winn (8) (9) showed spin compensation first in liners manufactured by a spinning process, and subsequently in shear formed liners. We have since confirmed Winn's observations (10) and have shown that these radiographs are consistent with the presence of "metallurgical" spin compensation in the shear formed liners.

The flash radiographic confirmatory evidence concerning the "metallurgical" spin compensation in these liners was obtained by observing the jet behavior when the charges with shear formed liners were rotated both clockwise and counterclockwise during detonation. The techniques used for charge rotation have been described previously (11).

The sequence of radiographs obtained in this experiment is shown in Figs. 21 to 26 inclusive. One can recognize spin compensation at -30to-45 rps** in Figs. 24 and 25. The jets from the charges rotated at frequencies

*Liners fabricated in this way are often called shear formed ITE liners after the company which first supplied the, namely the ITE Circuit Breaker Corp.

**The convention for algebraic sign of the direction of rotation has been taken as positive if rotation of the projectile is clockwise when viewed from the rear. This is the normal situation for artillery with a right hand twist of the rifling.

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both higher and lower than the compensation frequency show a symmetrical behavior. The jet degradation progresses through the stages of axial break-up, bifurcation and polyfurcation as the rotational frequency recedes from the compensation frequency in either direction. This behavior will be recognized as very similar to that of the jets from rotated smooth cones manufactured by techniques (e.g. drawing) which do not normally introduce "metallurgical" spin compensation (12).

The "metallurgical" spin-compensation characteristics of shear formed liners can be largely eliminated by recrystallization of the liner. Recrystallization by heating at 900°F for one hour changed the microstructure from that shown in Fig. 19 to that of Fig. 27. The jet from the recrystallized liner is shown in Figs. 28 and 29 in which it is evident that the recrystallization resulted in a marked improvement in the continuity of the jet.

B. Electrodeposited Copper Liners

Certain lots (relatively few) of electrodeposited copper liners whose microstructure is shown in Figure 30 also gave very badly broken jets, as shown in Figures 31 and 32.

We have since shown (13) (14) that these anomalous electroformed liners also have the "metallurgical" spin compensation property, by techniques similar to those used for the shear formed liners. The radiographs illustrating this point are shown in Figs. 33 to 40. Spin compensation is apparent in Figs. 36 and 37. The interesting observation has been made that recrystallization of these anomalous electrodeposited liners, e. g. to the structure shown in Fig. 41, does not always eliminate the break-up, as can be seen from Fig. 42. This should be contrasted with the behavior of the shear formed liners on recrystallization.

C. Cooling Copper Liners to Liquid Nitrogen Temperatures

In these experiments, the copper liner with the complete explosive charge was immersed in a Dewar container of liquid nitrogen. Evaporated nitrogen was continually replaced for a period of about 2 hours in order to assure a reasonable approach to temperature equilibrium. The front of the liner was sealed with an ogive-like cap which kept liquid N_2 out of the liner cavity and did not interfere with collapse.

Figures 43 to 47 show comparisons of the jets from such charges fired without cooling (at $\sim 25^{\circ}$C ambient temperature) and after cooling and firing from the Dewar container. Figures 45 and 46 in particular show the sharp fractures in the cooled copper jet near the rear. Fig 47 shows the jet from a charge which was cooled to liquid N_2 temperature and then thawed to room temperature. Upon firing at room temperature it shows the same type of continuous jet obtained from the uncooled one, indicating that there was no significant permanent effect of the low-temperature upon the explosive charge. A cursory experimental check of the detonation velocity

[redacted]

of Comp B at liquid nitrogen temperature showed no irregularities in the progress of the detonation curve.

This last experiment is of considerable fundamental interest since it is believed to show for the first time, a brittle behavior in copper as a result of the combination of low temperature and high strain rate.

IV SUMMARY AND CONCLUSION

The behavior of jets from liner materials of high melting point is shown to be correlated with the crystal structure of the metal. The face-centered metals all stretch more or less in a taffy-like fashion. Body-centered metals show early fracture into large pieces, and hexagonal metals show early fracture into small pieces. In both of the latter cases this fracture occurs after the jet has been formed and has left the high pressure collision region. One exception to this has been found in the case of cobalt which seems to fracture at the instant of the collision or prior to it.

Low melting point metals appear to show a common behavior, independent of their crystal structure, which seems to be related to their low melting point. They generally form a more broadly dispersed spray-like jet.

Three examples of the effects of initial conditions of copper are discussed. Copper shear formed liners are shown to produce jets which break up badly, but these liners exhibit normal behavior if recrystallized by heat treatment. Likewise, jets from certain anomalous electrodeposited liners are shown to break up badly, but these liners do not always recover upon recrystallization. Both of these phenomena are now known to be the result of "metallurgical" spin compensation. Flash radiographic evidence for the spin compensation is shown. Cooling to liquid nitrogen temperatures is shown to give evidence of brittleness in the copper under the conditions of jet formation.

L. ZERNOW

Julius Simon
J. SIMON

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3. Pugh, E. M., Theory of Lined Hollow Charges, Transactions of Symposium on Shaped Charges, Held at the Ballistic Research Laboratories, Aberdeen Proving Ground, Md., BRL Report No. 837, Nov. 13-16, 1951, p. 11 (Figures 2 and 3, page 16, refer to Kerr Cell)

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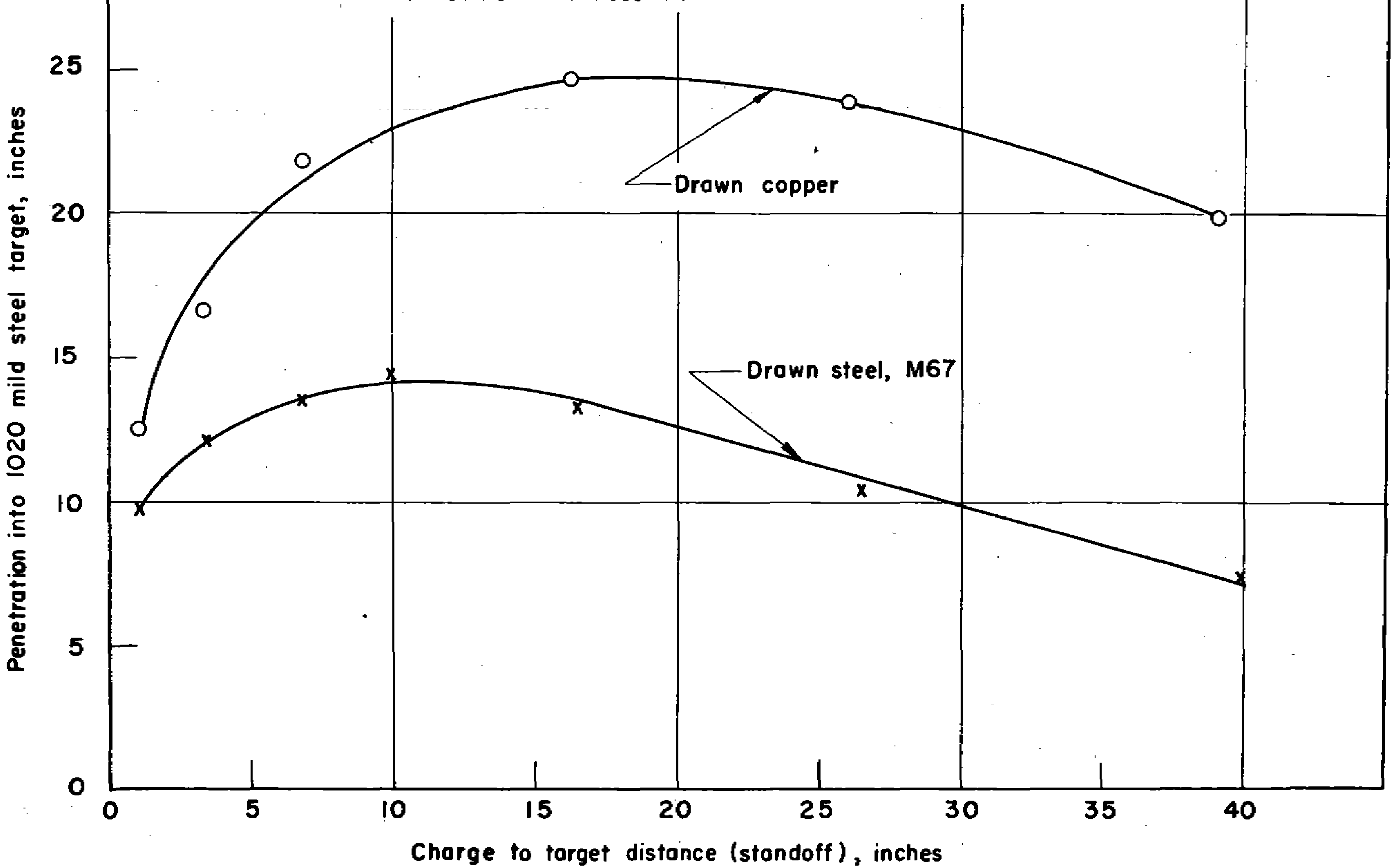
14. Simon, J. and Zernow, L., "Flash Radiographic Study of Certain Anomalous Electroformed Liners for Shaped Charges, BRL Memo Report No. 892 APG, Md. June 1955.

[redacted]

Figure 1. Penetration vs. Standoff for Comparison of 105mm. Steel and Copper Liners Assembled in Heavily Confined Bodies.

The target consisted of stacked 7" x 7" x 3" plates of Brinell hardness no. 135.



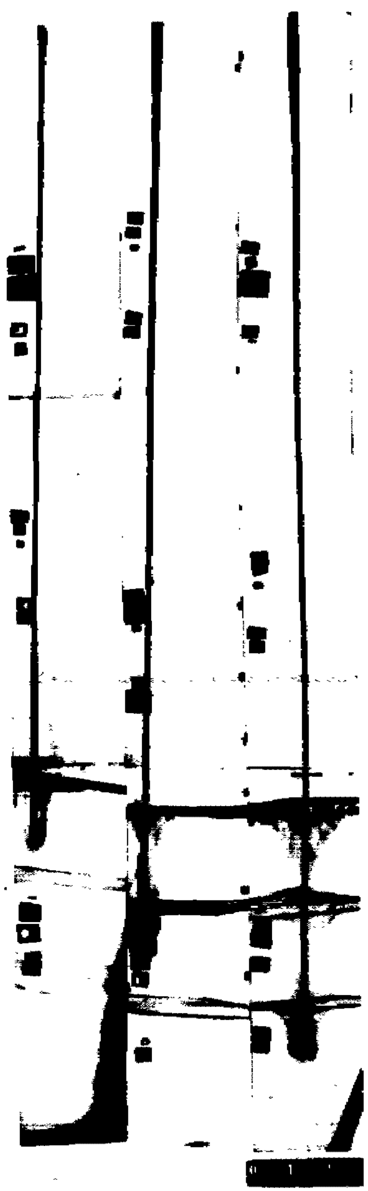


FIG. 2

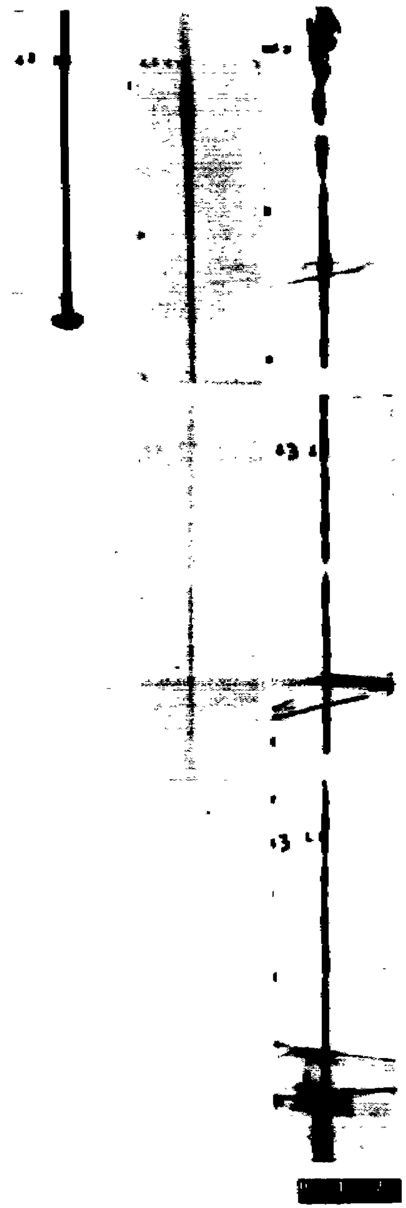


FIG. 3

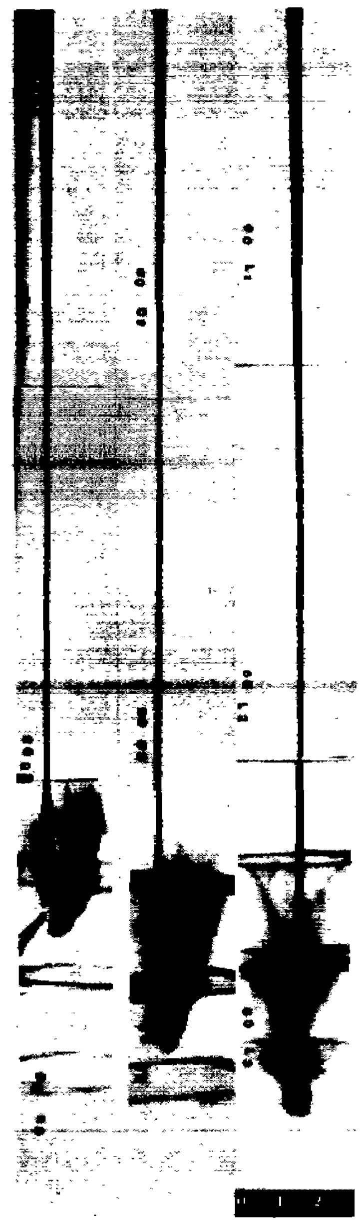


FIG. 4

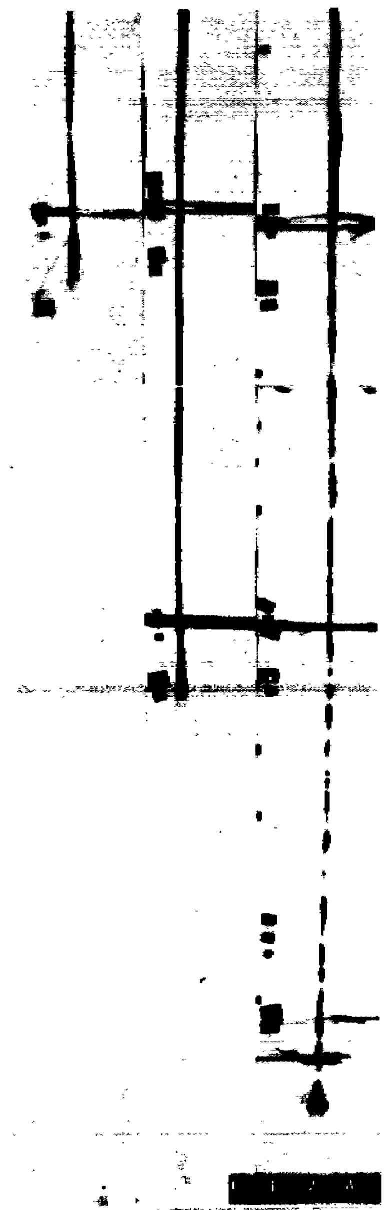


FIG. 5

Triple flash radiographs of jets from 105mm liners, face-centered cubic metals: FIG. 2. copper, FIG. 3. nickel, FIG. 4. silver, FIG. 5. aluminum.

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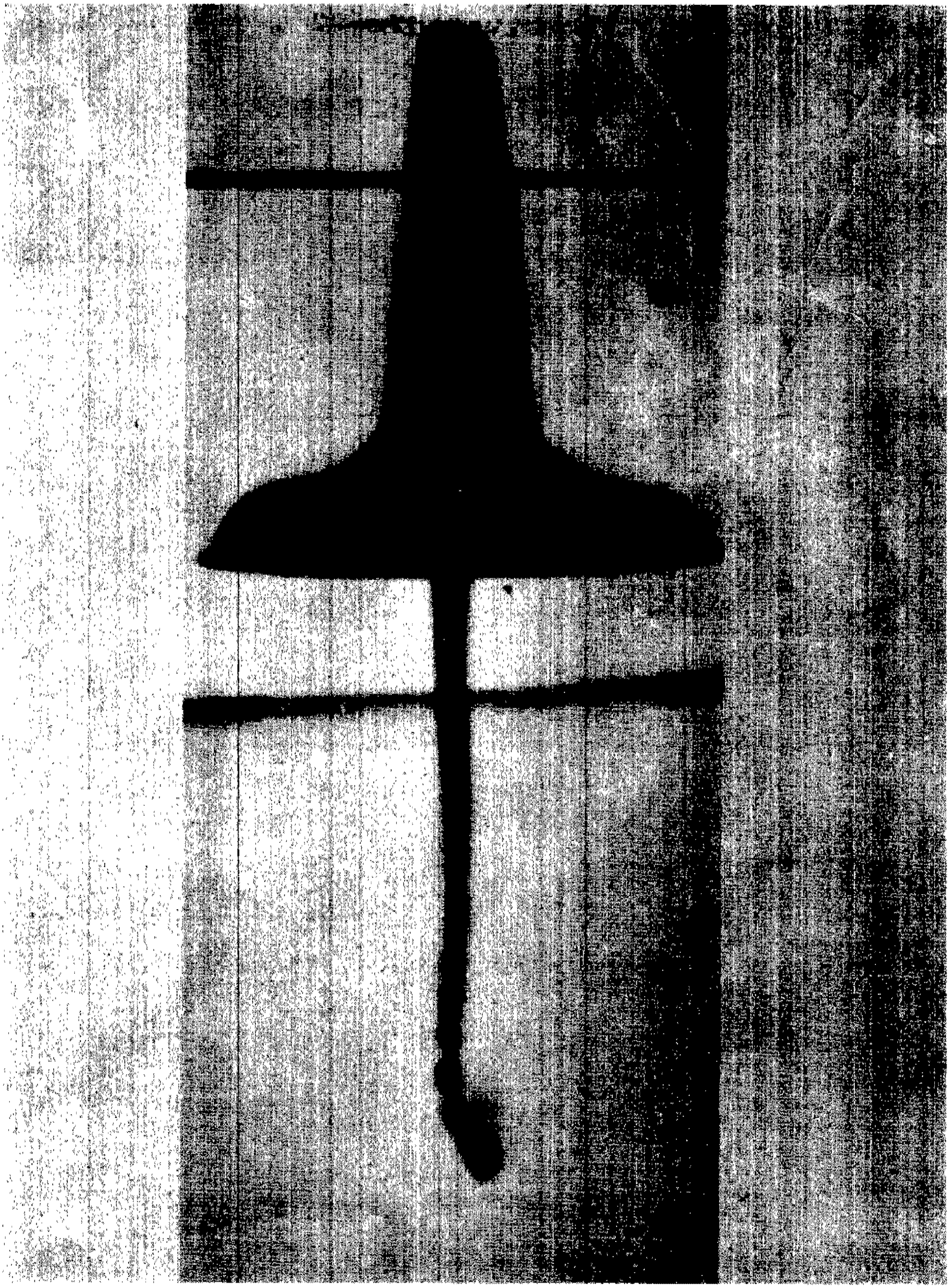

FIG. 6. A radiograph of a collapsing iron liner.

[redacted]

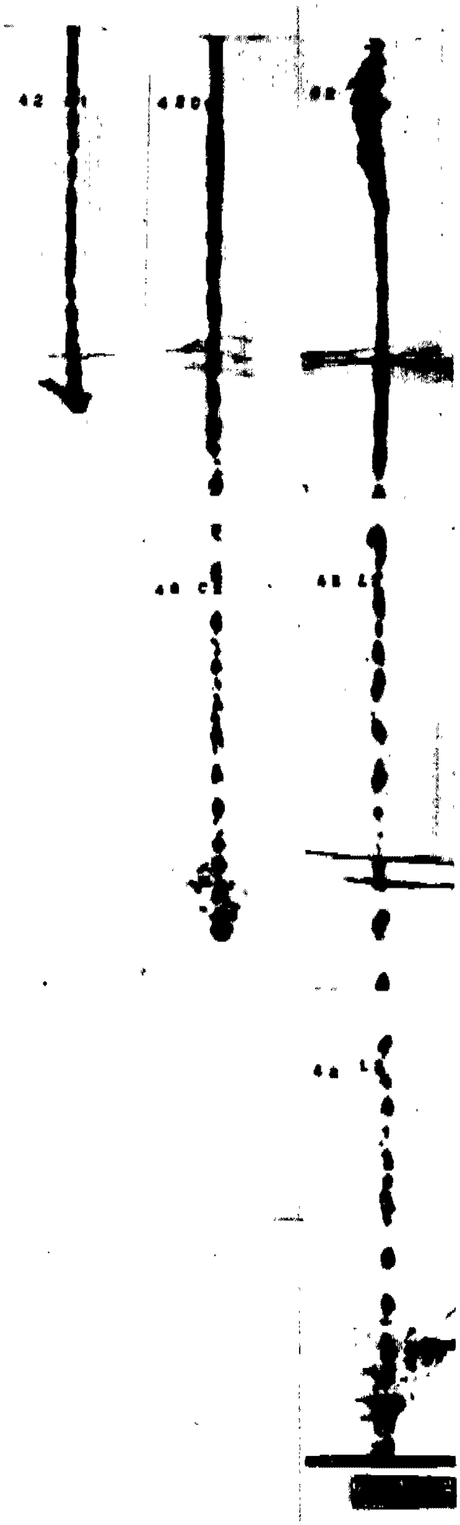

FIG. 7. A triple flash radiograph of the jet from a 105mm iron liner which is a body-centered material.

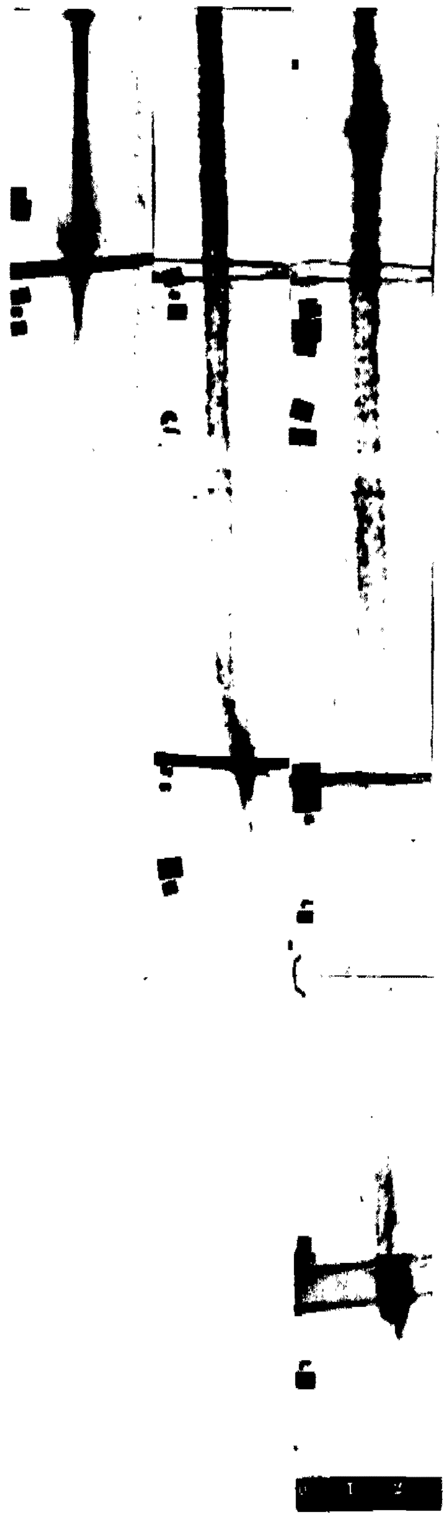

FIG. 8. A triple flash radiograph of the jet from a 105mm magnesium liner, a hexagonal structure element.

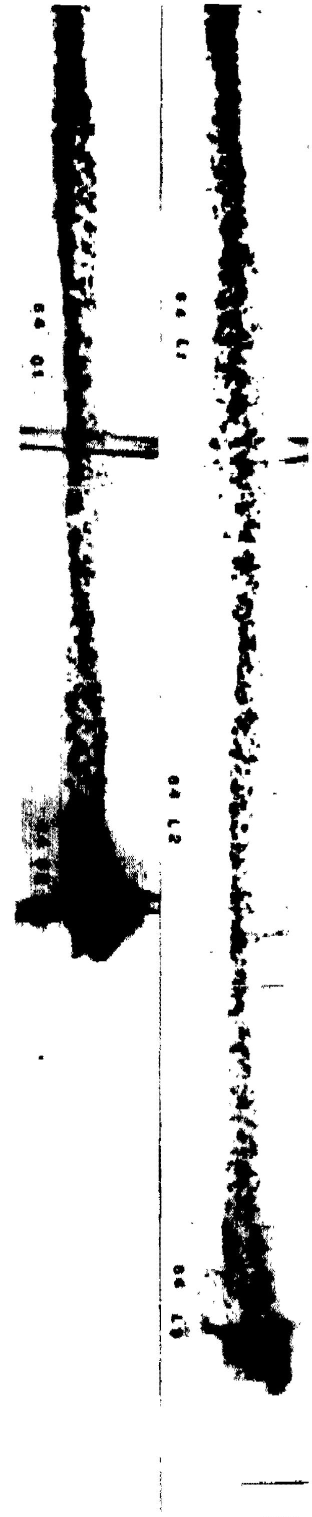

FIG. 9. A multi-flash radiograph of the jet from a 105mm cobalt liner, a hexagonal structure element.

[redacted]

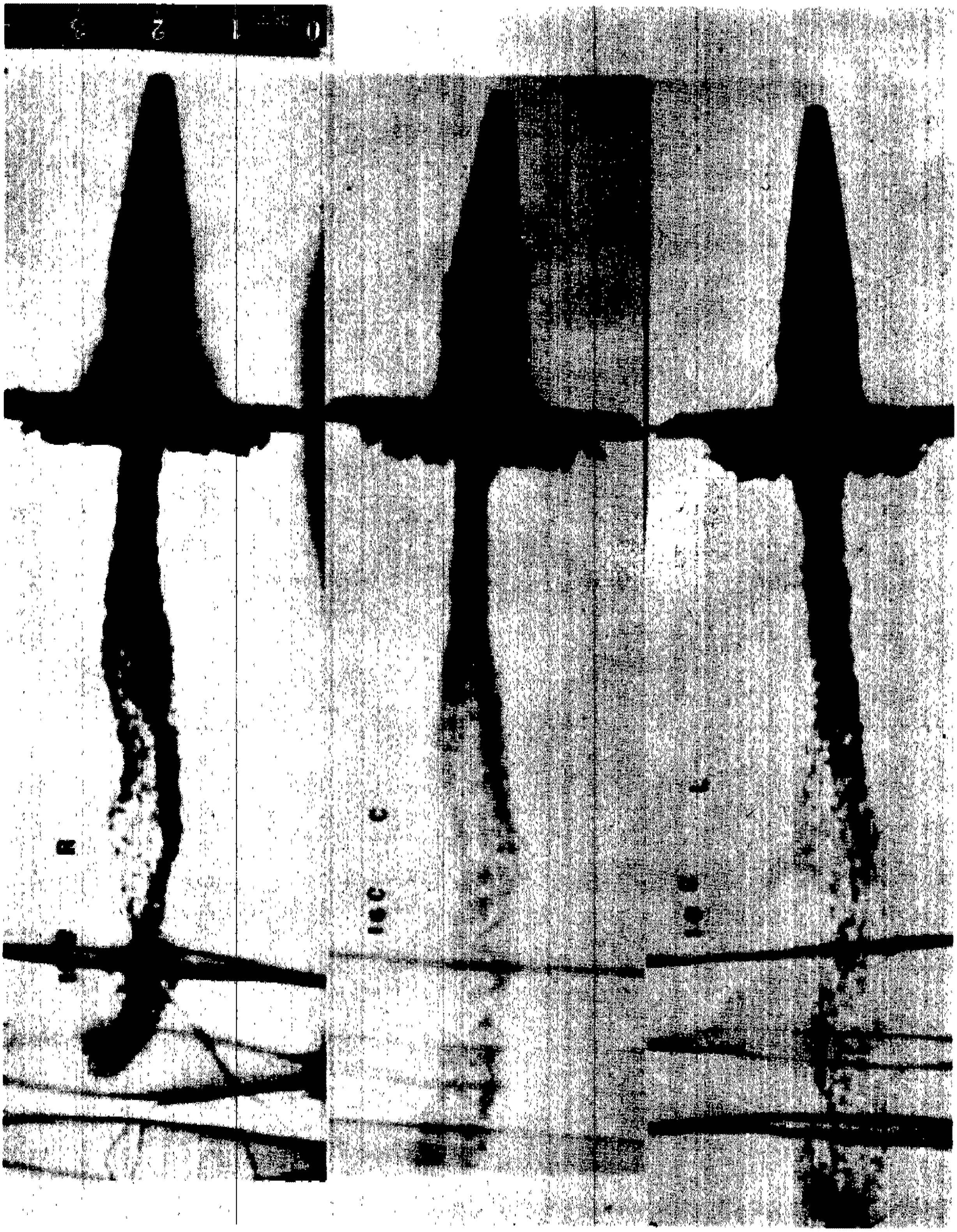

FIG. 10. A multi-flash radiograph of a collapsing cobalt liner.

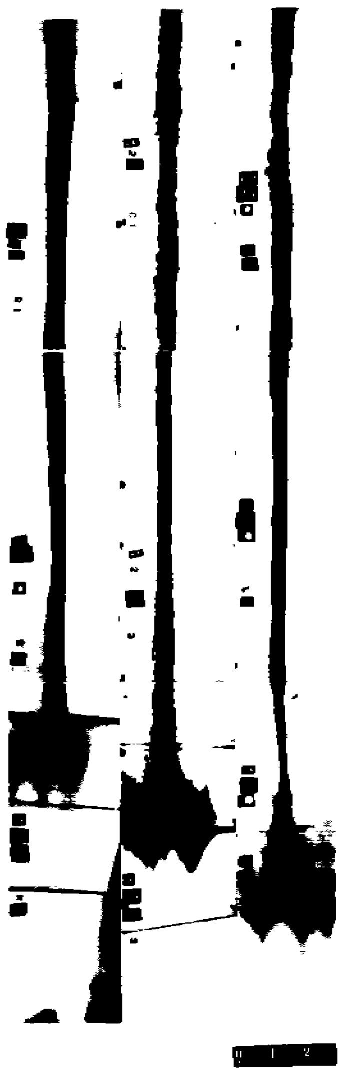

FIG. 11. A multi-flash radiograph of the jet from a 105mm cadmium liner, a low melting point metal, hexagonal structure.

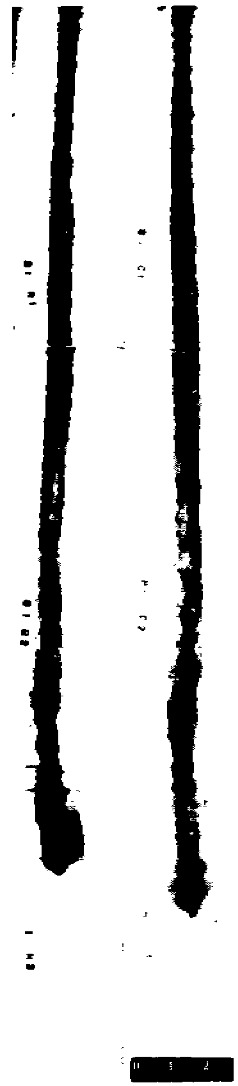

FIG. 12. A multi-flash radiograph of the jet from a 105mm zinc liner, a low melting point metal, hexagonal structure.

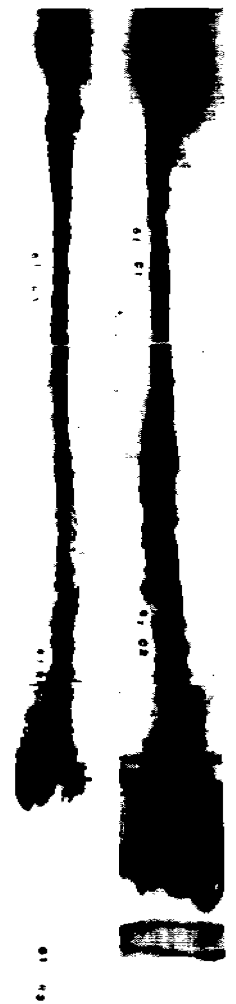

FIG. 13. A multi-flash radiograph of the jet from a 105mm lead liner, a low melting point metal, face-centered cubic structure.

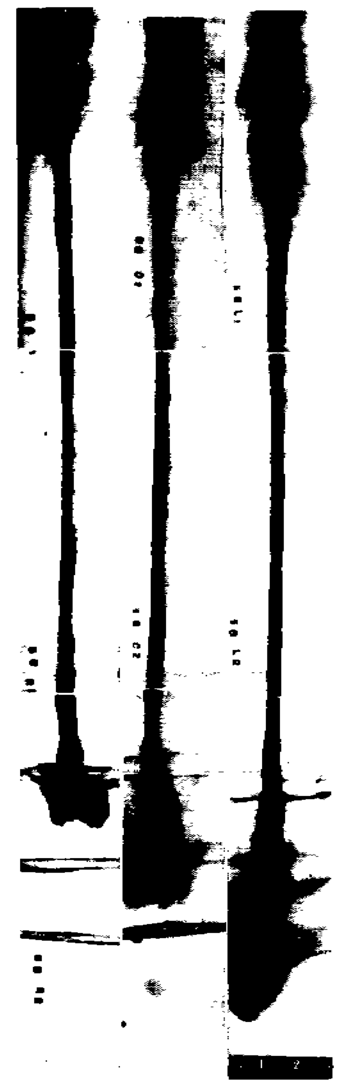

FIG. 14. A triple flash radiograph of the jet from a 105mm tin liner, a low melting point metal, tetragonal structure.

[redacted]

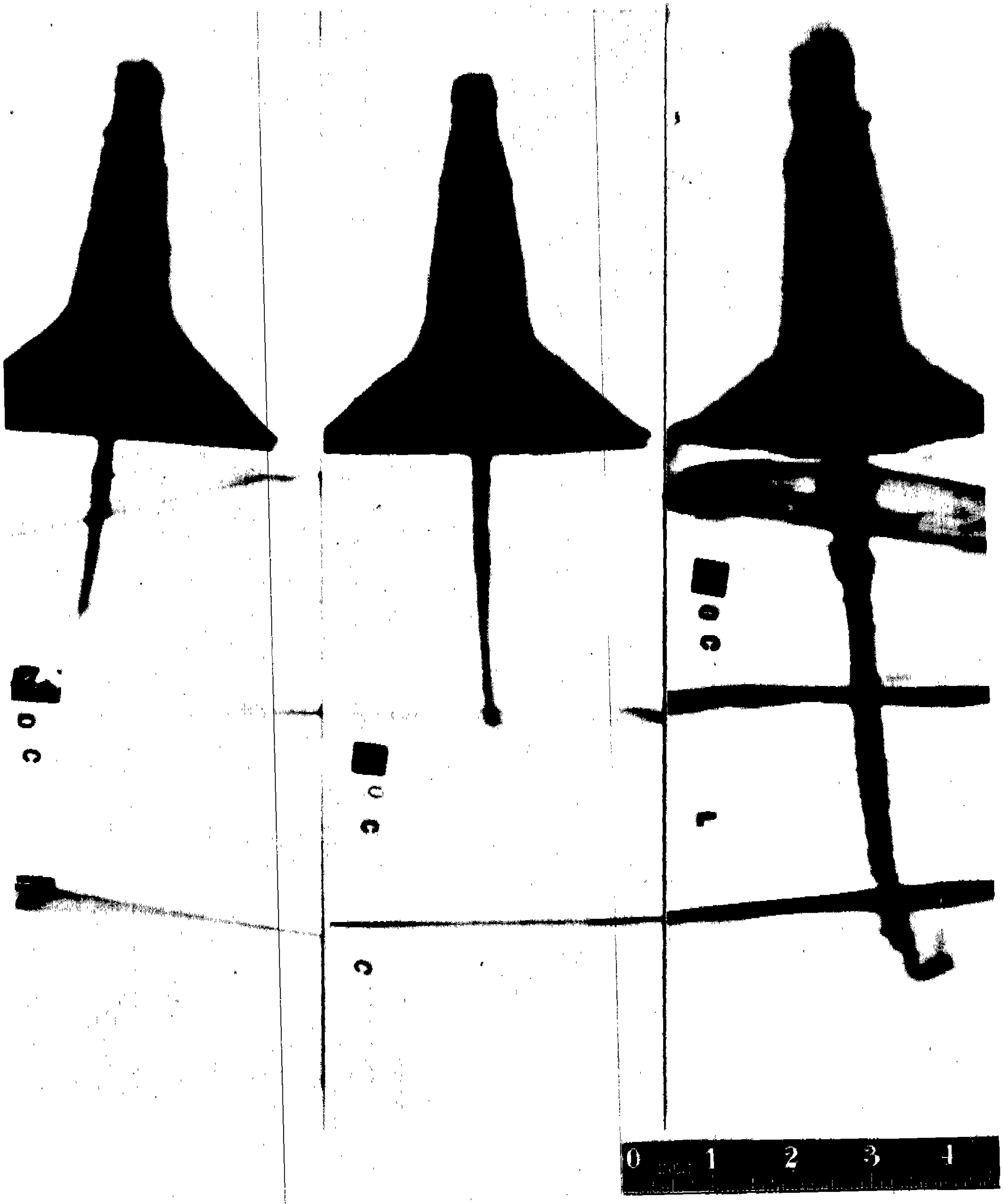

FIG. 15. A triple flash radiograph of a collapsing cadmium liner.

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[redacted]

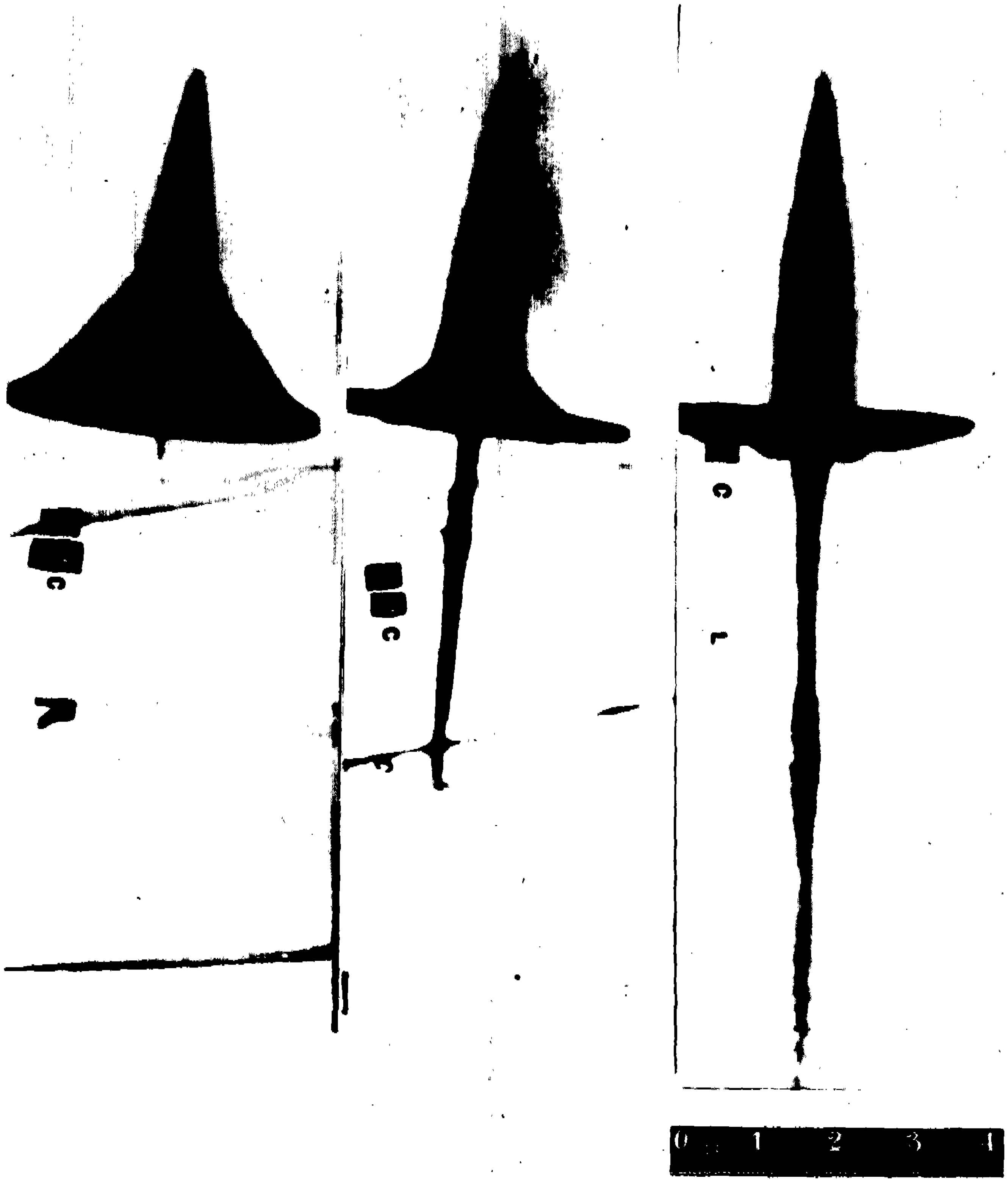

FIG. 16. A triple flash radiograph of a collapsing zinc liner.

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FIG. 17. A triple flash radiograph of a collapsing lead liner.

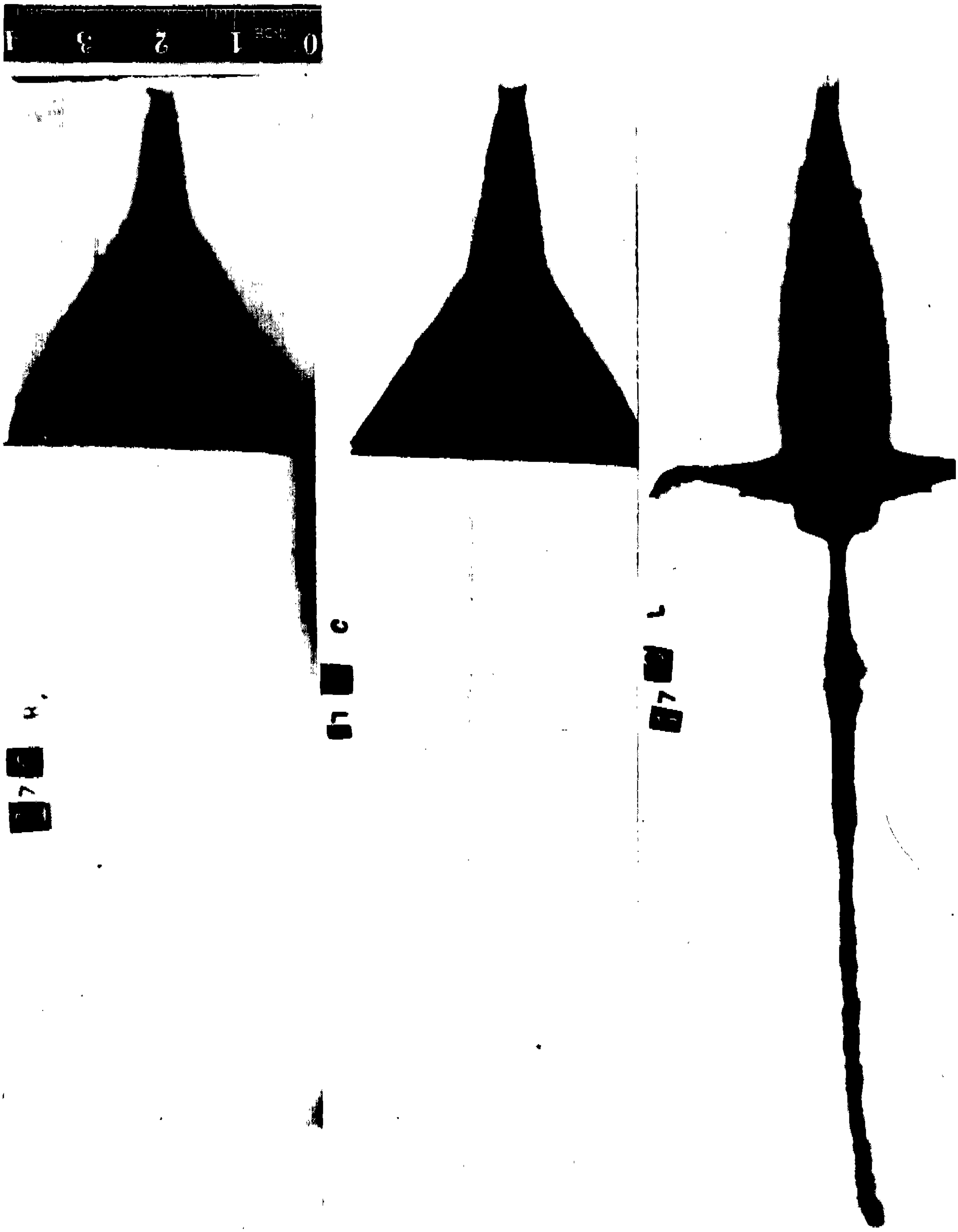


FIG. 18. A triple flash radiograph of a collapsing tin liner.

[redacted]

FIG. 19. Microstructure of shear formed liner as received. The badly distorted grain structure is clearly seen. (X100)

[redacted]

FIG. 20. Metallurgical "built-in" spin compensation of smooth shear formed liner. Triple flash radiograph of jet from 105mm shear formed copper liner non-rotated (at 0 rps). This is the earlier radiograph taken of the non-rotated liner which gave poor penetration performance.

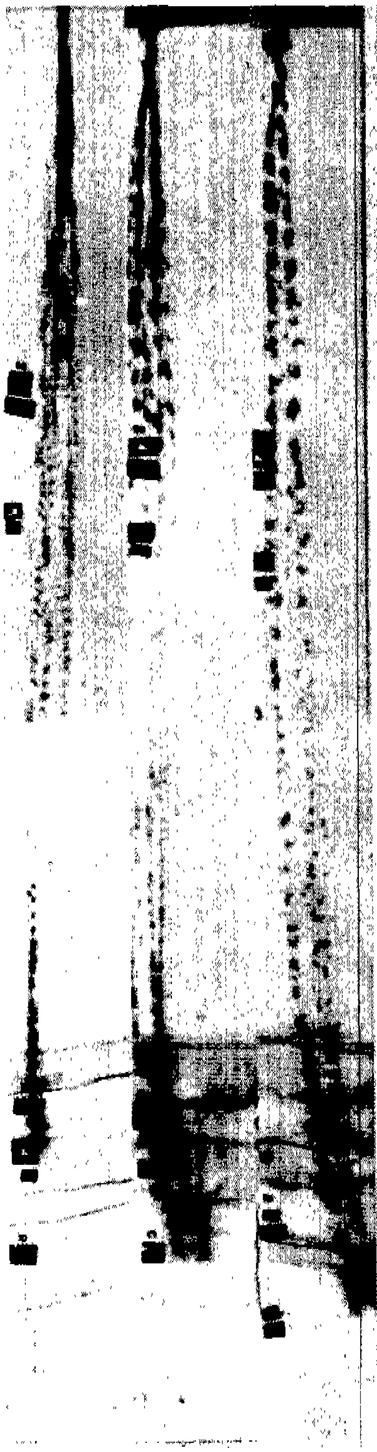


FIG. 21. Triple flash radiographs of the jet from a 105mm copper shear formed liner rotated at a rotational frequency of +30 rps. The jet is badly polyfurcated and fractured.

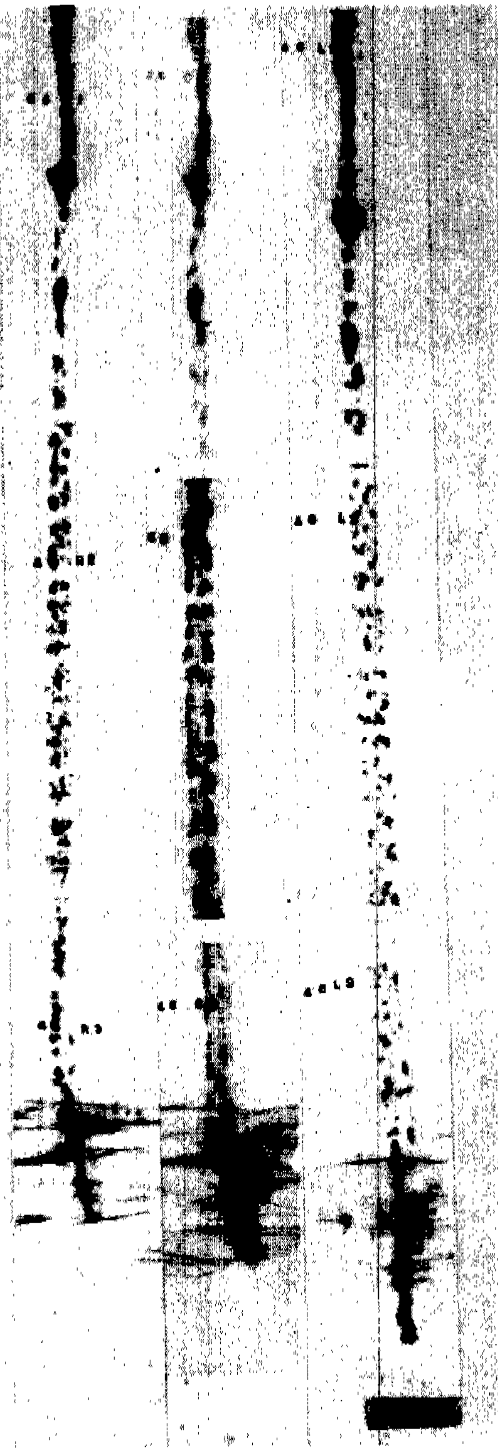


FIG. 22. Triple flash radiographs of the jet from a 105mm copper shear formed liner non-rotated (0 rps). The jet is polyfurcated to a lesser degree than the jet in Figure 21. Evidence of "built-in" spin compensation can be seen from this radiograph. The microstructure of liner has a distorted structure (cf. Fig. 19).

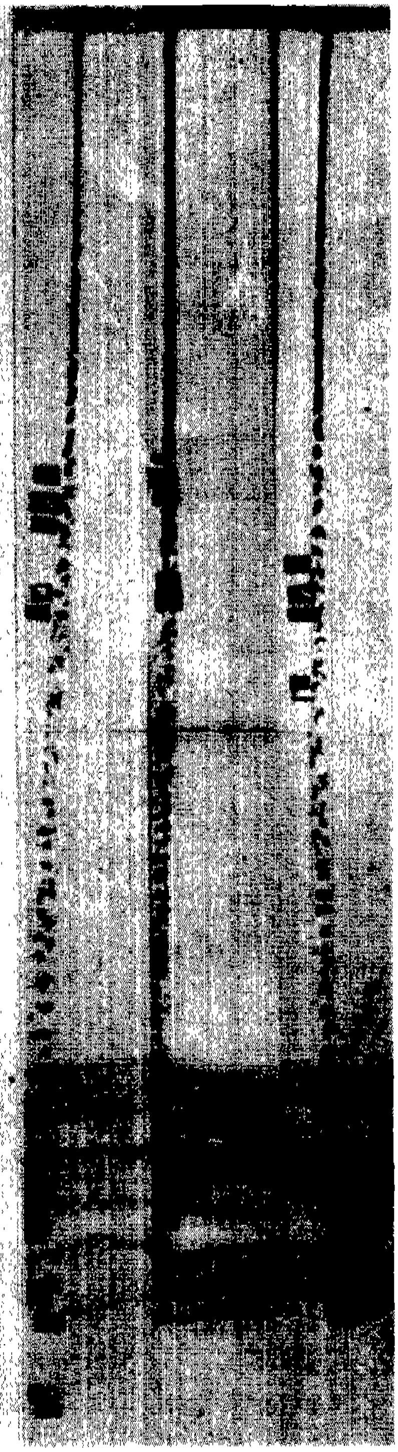


FIG. 23. Triple flash radiographs of the jet from a 105mm copper shear formed liner rotated at -15 rps. The jet fragmentation is getting less as rotation proceeds to higher negative frequencies.

[redacted]

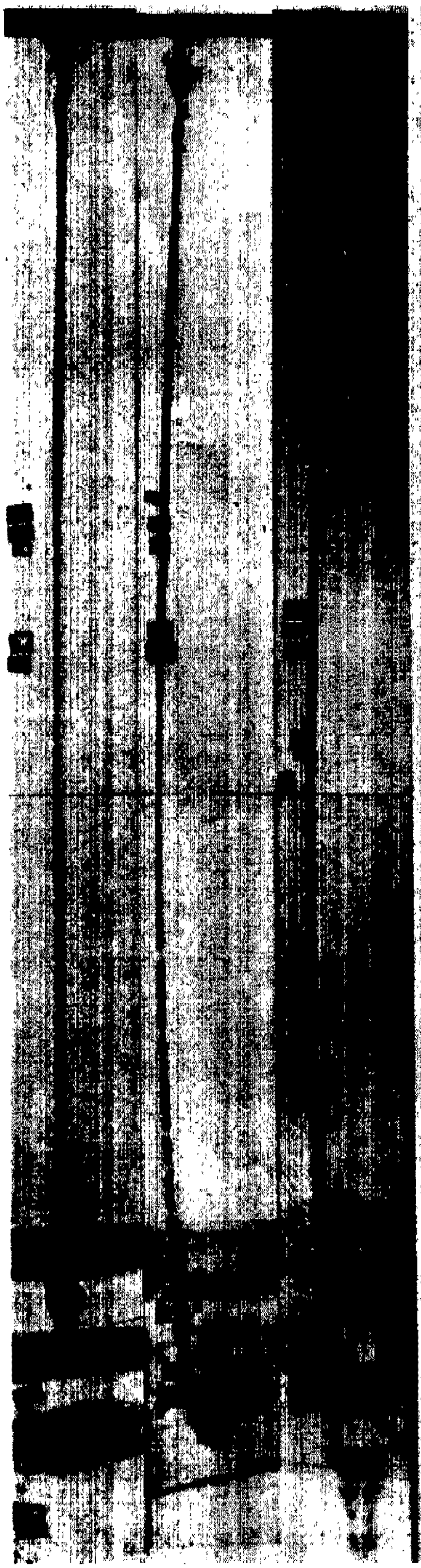


FIG. 24. Triple flash radiographs of the jet from a 105mm copper shear formed liner rotated at -30 rps. There is longitudinal break-up but jet is practically continuous. "Built-in" spin compensation of this jet is apparent.

FIG. 25. Triple flash radiographs of the jet from a 105mm copper shear formed liner rotated at -45 rps. "Built-in" spin compensation of this jet is apparent.

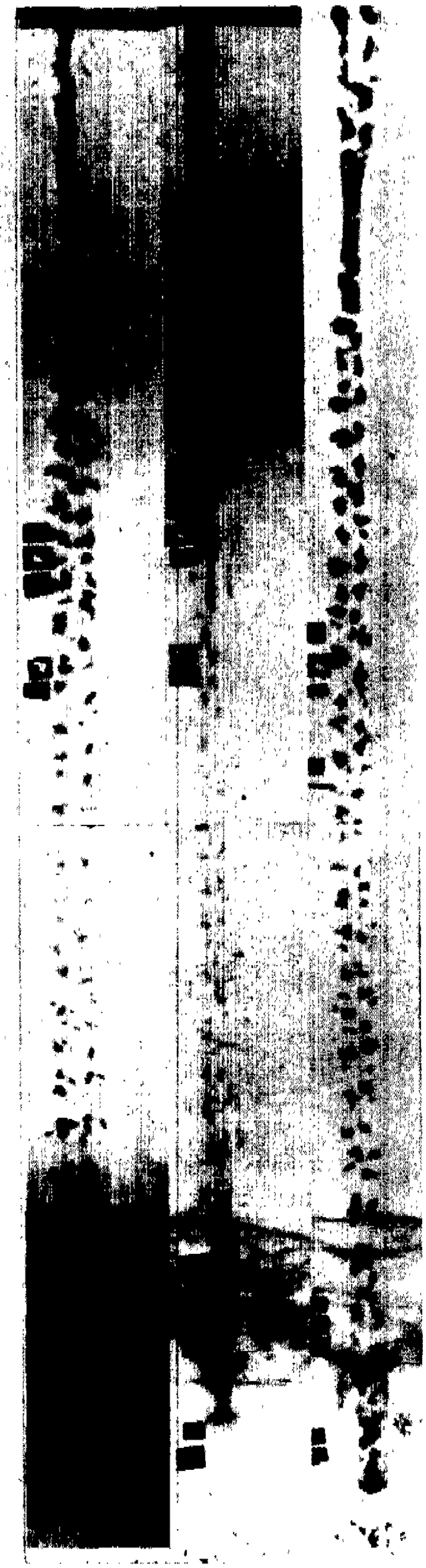
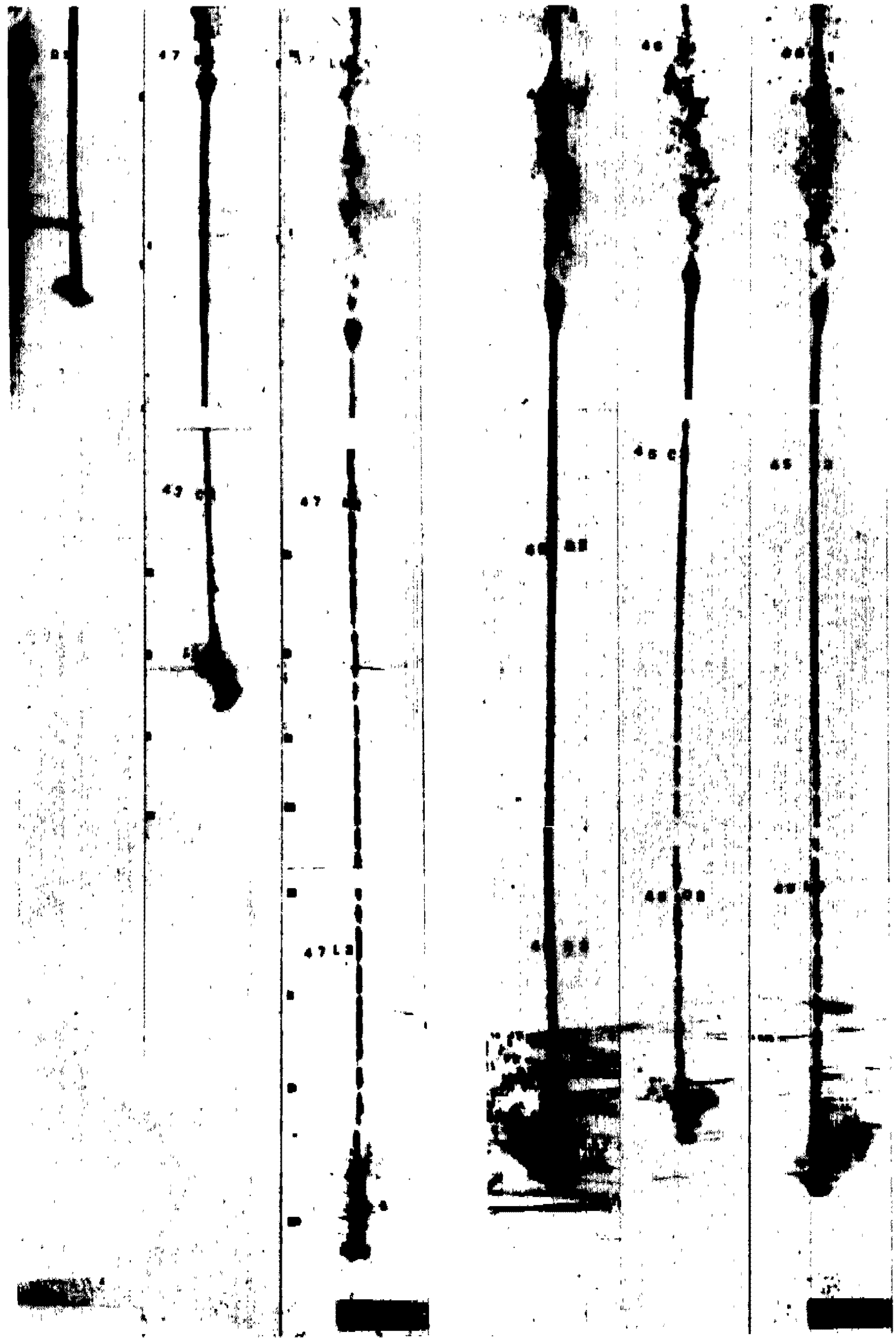


FIG. 26. Triple flash radiographs of the jet from a 105mm copper shear formed liner rotated at -60 rps. The jet is polyfurcated and fragmented as the rotational frequency recedes from the optimum rotational frequency.

[redacted]

FIG. 27. The shear formed liner has been heat treated to produce recrystallization. The grain structure is now more nearly equiaxed. (X100)



FIGS. 28 & 29. Triple flash radiograph of the jet from a 105mm shear formed copper liner (non-rotated) which has been recrystallized. The fracture seen in the jet in Figure 20 has been practically eliminated by recrystallization.

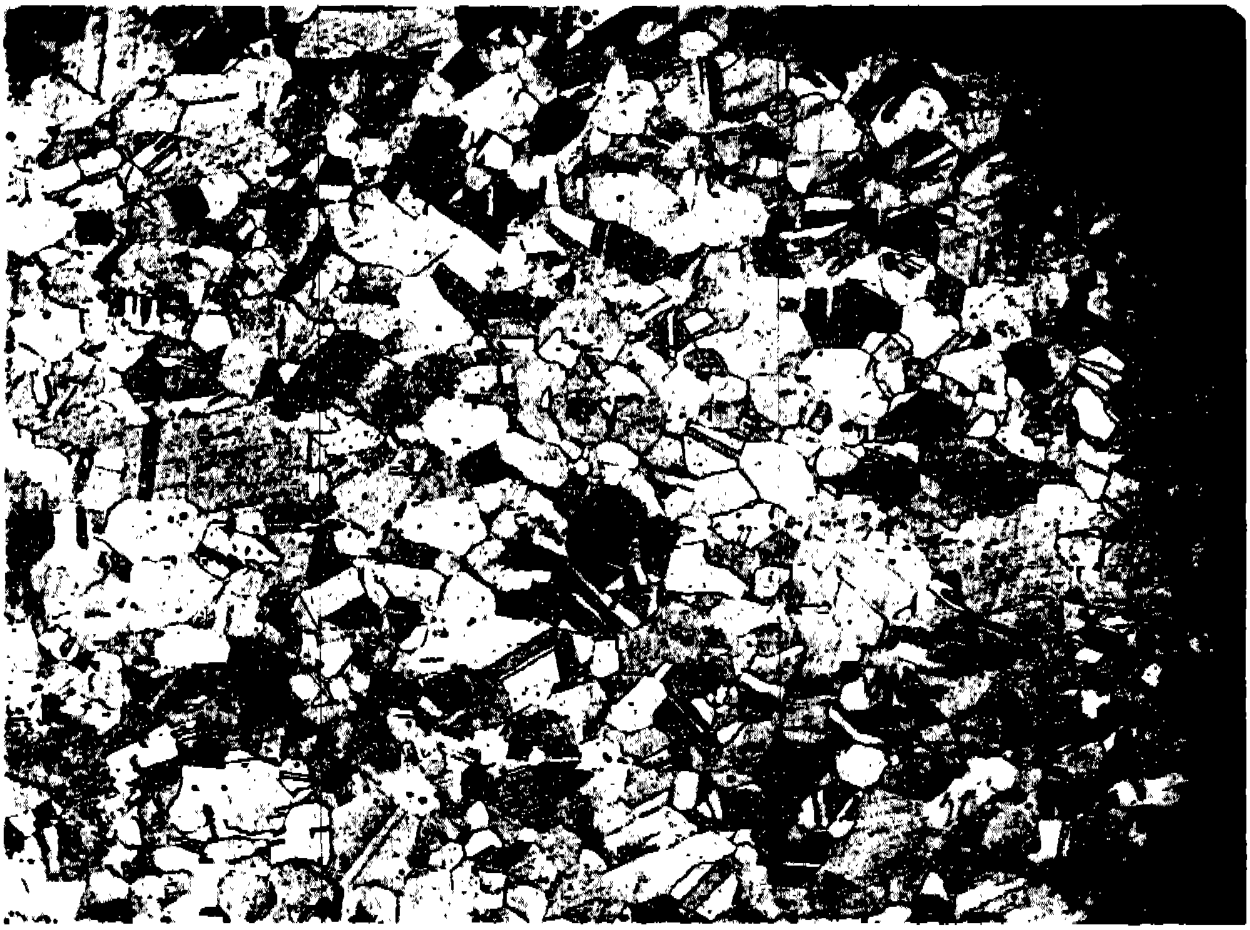
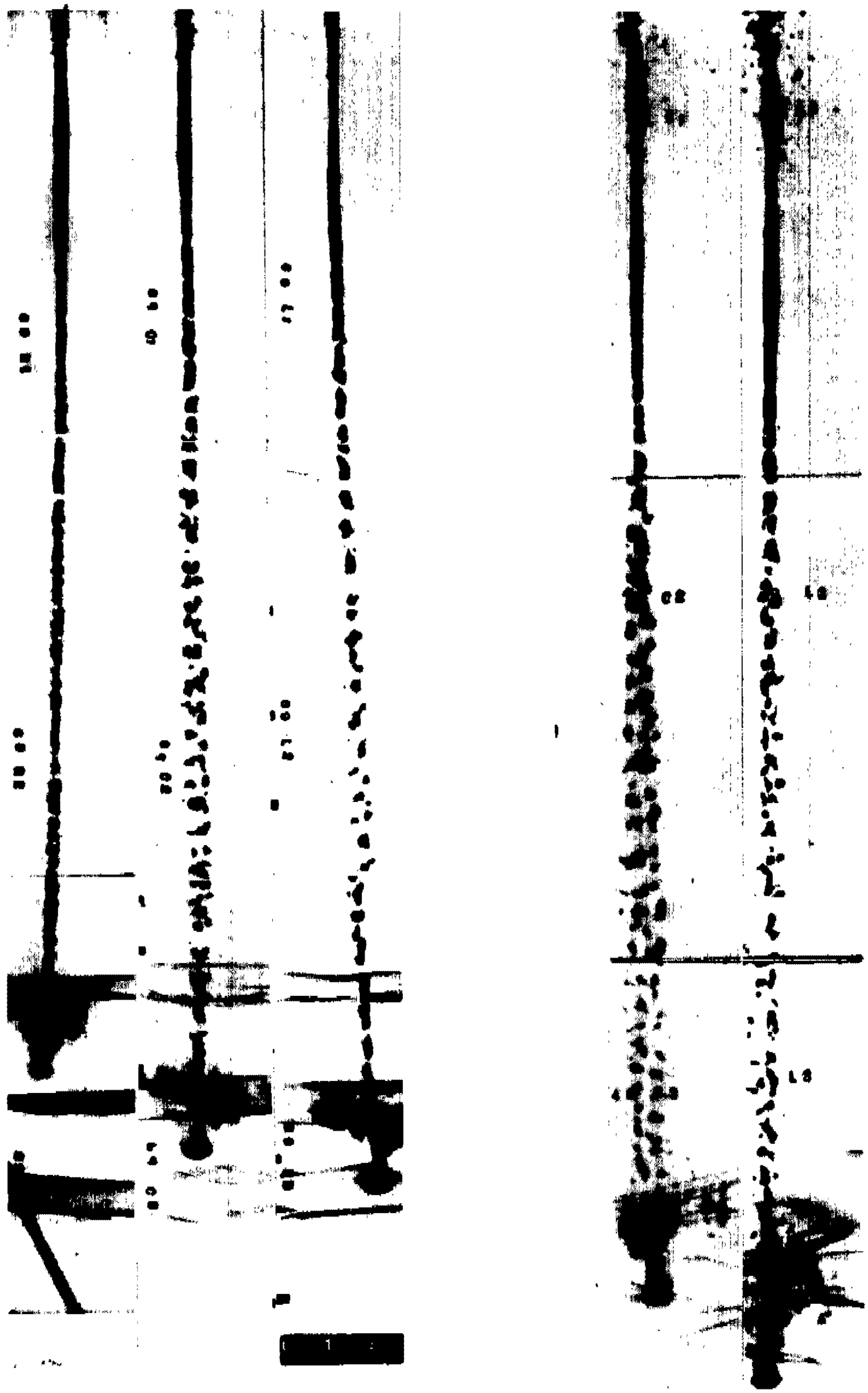


FIG. 30. Initial microstructure of electroformed liners which gave odd electro deposit. Penetration for this type microstructure was found to be poor. (X100)

[redacted]



FIGS. 31 & 32. Metallurgical "built-in" spin compensation of smooth electroformed liners. Triple flash radiographs of jet from 105mm electroformed copper liner non-rotated (0 rps). Evidence is seen of a bifurcated and broken jet.

[redacted]

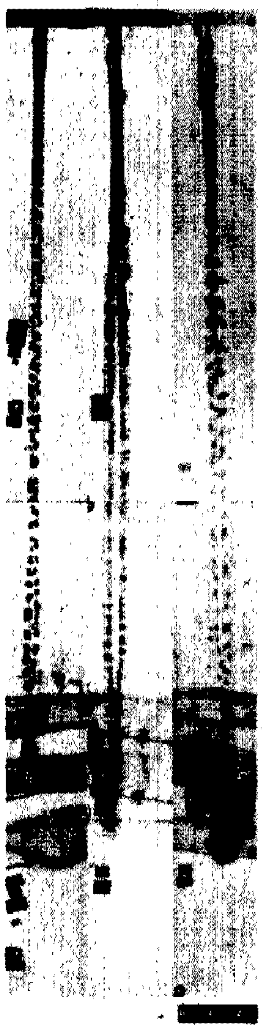


FIG. 33. Metallurgical "built-in" spin compensation of smooth electroformed liners. Triple flash radiographs of 105mm electroformed copper liners rotated at -45 rps. Note the polyfurcated jet.

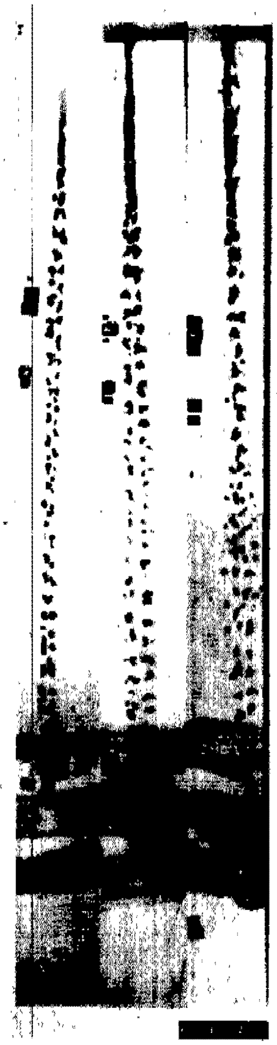


FIG. 34. Metallurgical "built-in" spin compensation of smooth electroformed liners. Triple flash radiographs of 105mm electroformed copper liners rotated at -30 rps. Jet is still polyfurcated.

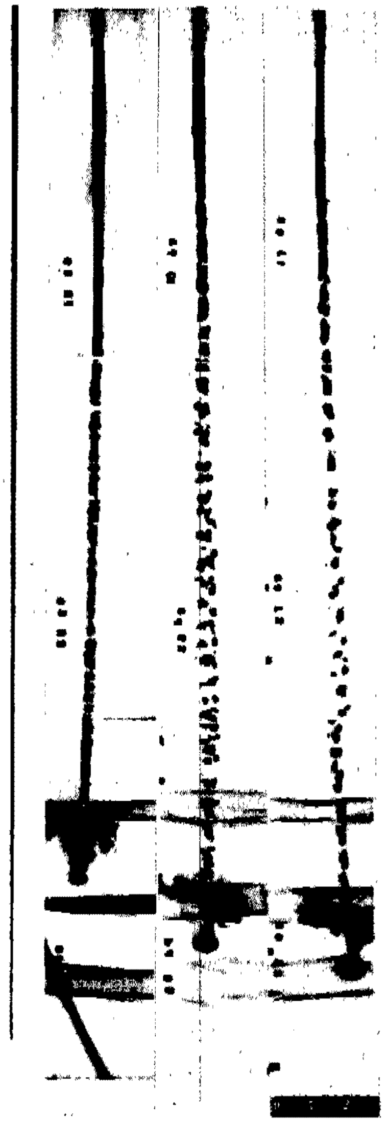


FIG. 35. Metallurgical "built-in" spin compensation of smooth electroformed liners. Triple flash radiographs of 105mm electroformed liners (unrotated, i.e., 0 rps). Evidence is seen of a bifurcated and broken jet.

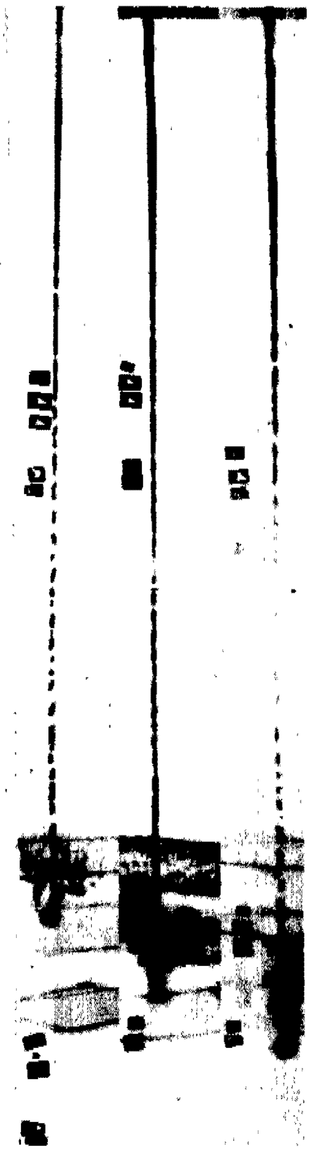


FIG. 36. Metallurgical "built-in" spin compensation of smooth electroformed liners. Triple flash radiographs of 105mm electroformed copper liners rotated at +30 rps. Improved structure of jet shows approach of spin compensation.

[redacted]

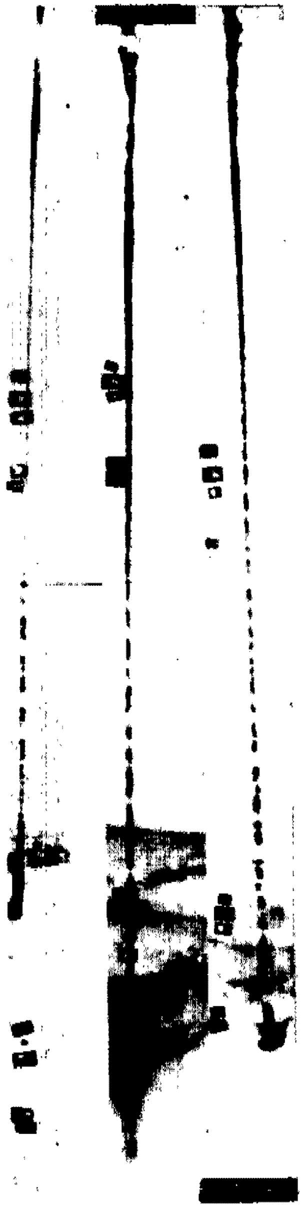


FIG. 37. Metallurgical "built-in" spin compensation of smooth electroformed liners. Triple flash radiographs of 105mm electroformed copper liners rotated at +45 rps. Again very good jet structure for electroformed liners appear at this rotational frequency. We have additional evidence that the resulting jet from this liner is much like the jet from a normal unrotated smooth liner.

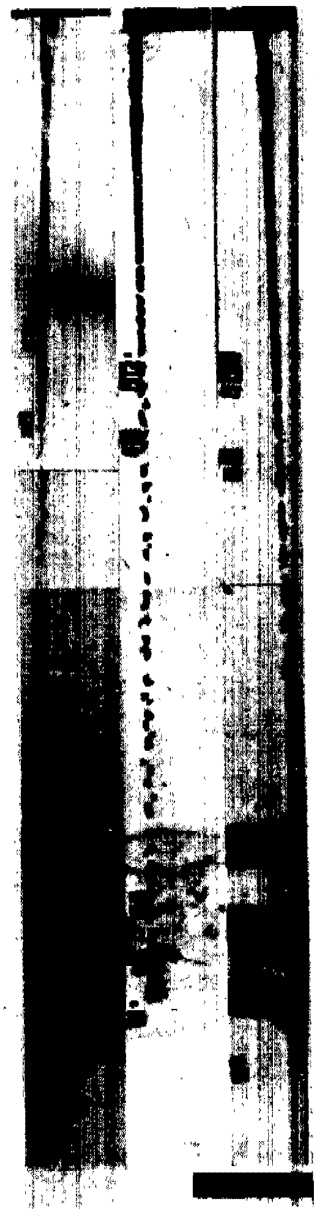


FIG. 38. Metallurgical "built-in" spin compensation of smooth electroformed liners. Triple flash radiographs of 105mm electroformed copper liners rotated at +60 rps. The jet structure shows that the optimum rotational frequency has been passed.

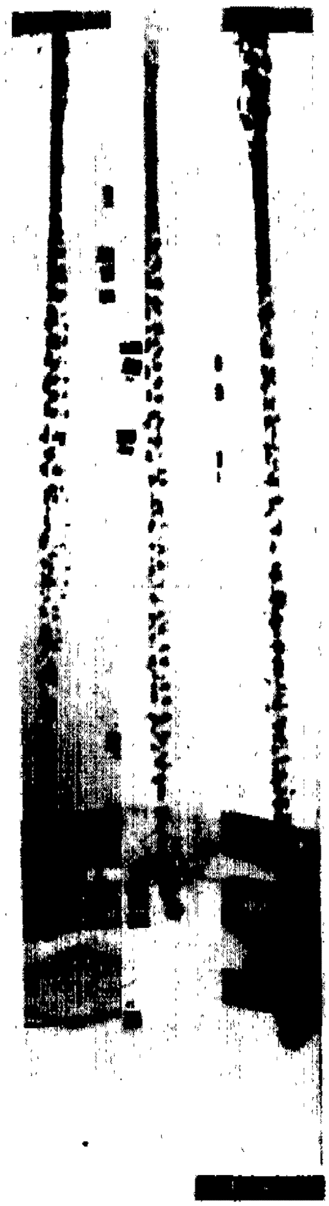


FIG. 39. Metallurgical "built-in" spin compensation of smooth electroformed liners. Triple flash radiographs of 105mm electroformed copper liners rotated at +75 rps. The jet structure becomes worse as rotation is removed from the optimum frequency.

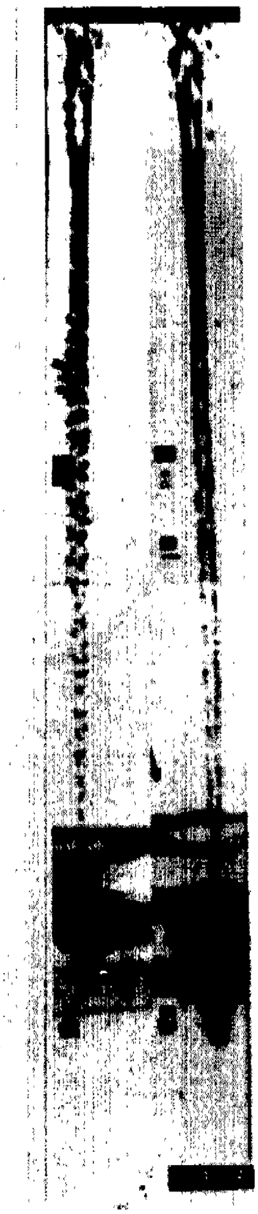


FIG. 40. Metallurgical "built-in" spin compensation of smooth electroformed liners. Triple flash radiographs of 105mm electroformed copper liners rotated at +90 rps. The jet structure continues to polyfurcate.

[redacted]

FIG. 41. Microstructure of recrystallized electrodeposited liners. (X100)

[redacted]

[redacted]

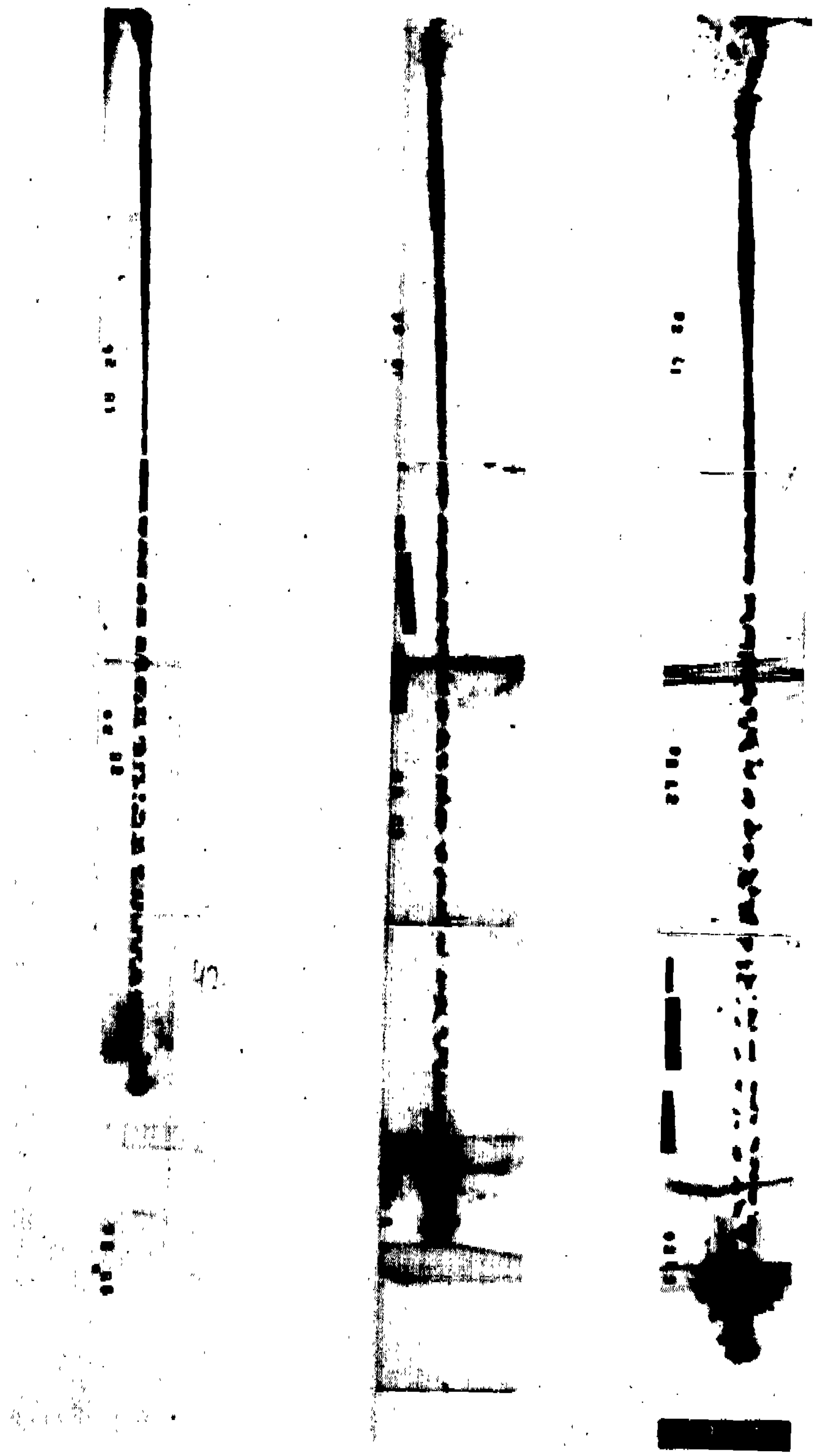
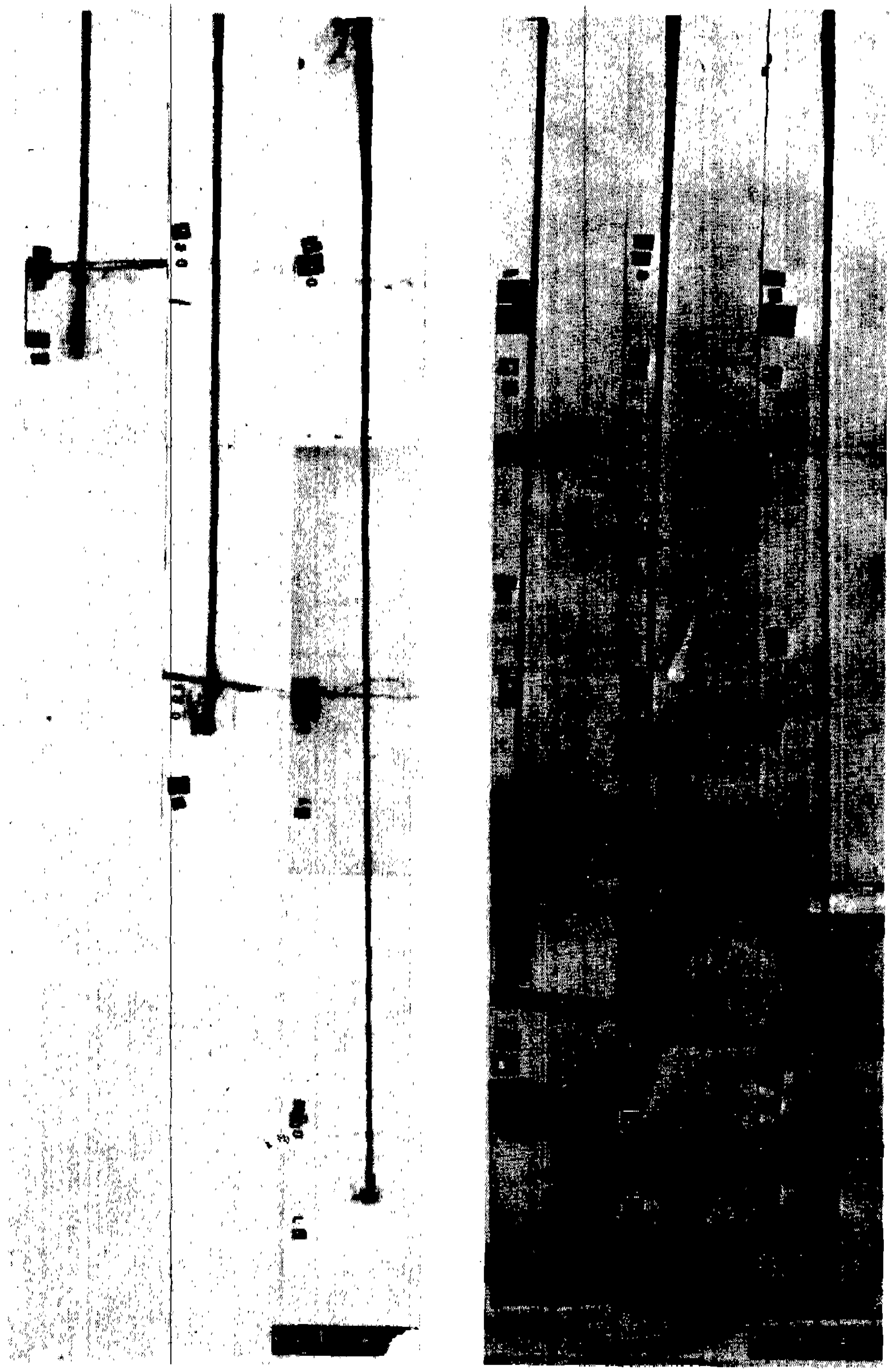
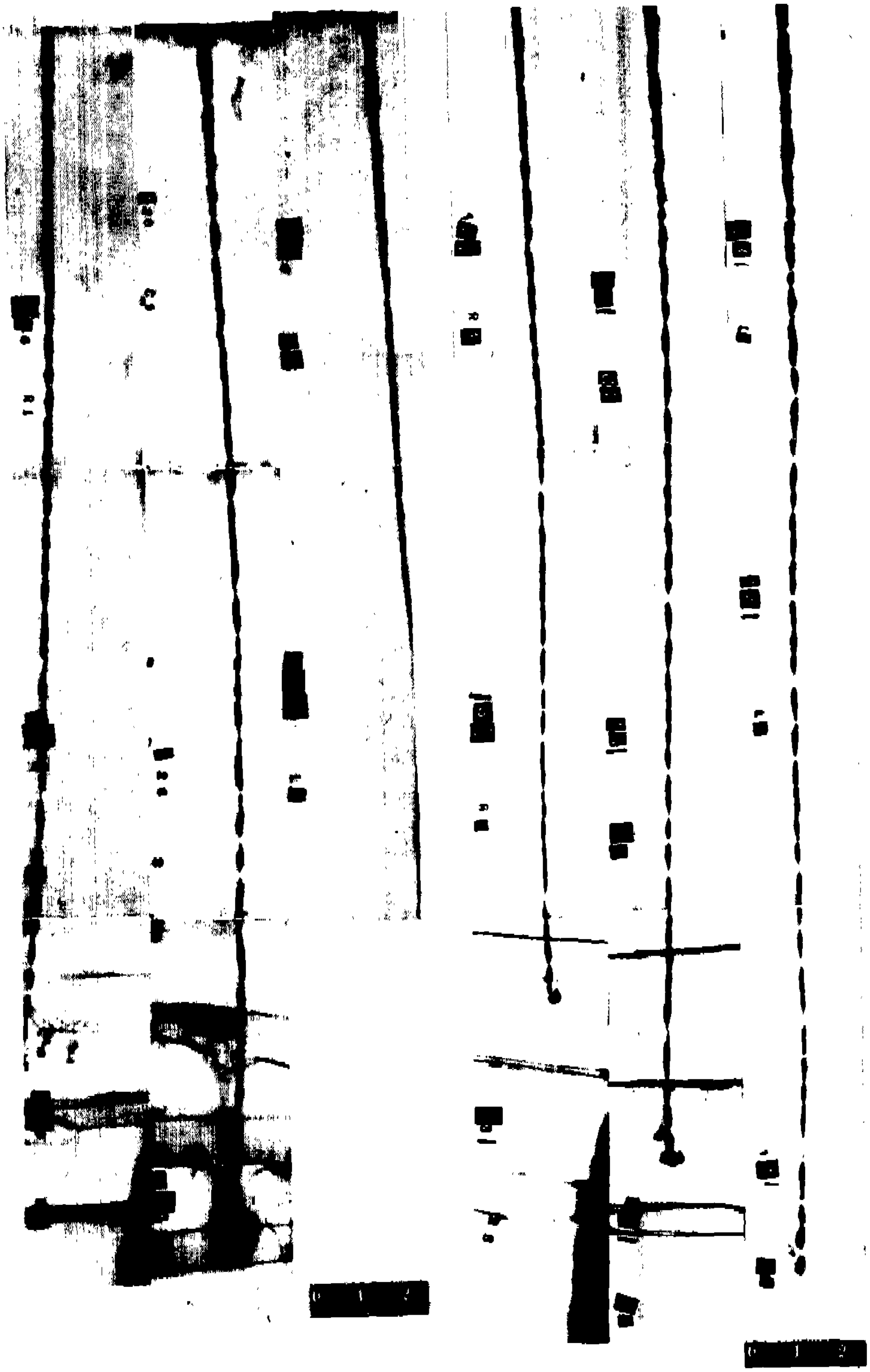


FIG. 42. Triple flash radiograph of an unrotated 105mm electroformed copper liner which has been recrystallized. The heat treatment did not improve the jet characteristic and it is still bifurcated.

[redacted]



FIGS. 43 & 44. Flash radiographs of the jet from an unrotated drawn copper liner of good quality at ambient temperature (25° C.). At normal temperatures one obtains the continuous jet characteristic of normal copper.



FIGS. 45 & 46. Flash radiographs of the jet from an unrotated smooth copper liner after cooling to liquid nitrogen temperature. The presence of sharp fractures may be seen at the rear of the jet.

FIG. 47. A multiple flash radiograph of the jet from a smooth copper liner precooled to liquid nitrogen temperature and then thawed to ambient temperature (25° C.) prior to firing.

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