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Ballistic Limit of 6061 T6 Aluminum
and Threat to Surface Coatings for
Use With Orbiting Space Station
Space Suit Materials

by

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for

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(NASA-CR-179884) BALLISTIC LIMIT OF 6061 T6 ALUMINUM AND THREAT TO SURFACE COATINGS FOR USE WITH ORBITING SPACE STATION SPACE SUIT MATERIALS (Eloret Corp.) 29 p CSCL 06K

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Background

Since before man ventured into space, concern was expressed for the advent of an impact of the space vehicle by meteoretic particles. Then, the concern was for asteroidal particles or cometary debris. The average particle density was of the order of one-half gram per cubic centimeter (0.5 g/cc) and the average encounter velocity was on the order of twenty kilometers per second (20 km/sec). Early probes such as the Explorers and Pegasus led to laboratory experiments of impact into a variety of materials with a wide range of projectiles and velocities.

In support of this early research, this experimenter proposed a penetration criteria for a variety of metal targets at the 7th Hypervelocity Impact Symposium at Tampa in 1965. (1) This penetration criteria became known as the Fish-Summers penetration equation for thin targets. Further experimentation by others (2,3) substantiated the findings and led to adoption of the penetration criteria for single sheets into the Meteoroid Hazards Monograph (4).

As our space effort grew, early distribution theories of meteoroid population were modified to reflect the expanding knowledge of our solar system.

In recent years, however, the numbers of orbiting satellites, spent components, collisions and explosions has populated the near earth orbit with debris potentially more hazardous than the average meteoroid debris. This new debris has an average density of aluminum (2.78 g/cc) and and and average encounter velocity of 10 km/sec.

The space station will require many hours of work in this environment and there is concern over hazard to the assembly personnel. The proposed 'hard suit' design utilizes 6061-T6 Aluminum for most of its exposed area. The aluminum surface will be treated for thermal and radiation control. The basic thickness of this suit will be on the order of 1.78 mm (0.070 inches).

Since the earlier work in the sixties was performed generally with 2024-T4 and 1100-0 aluminum it was felt that some ballistics testing on 6061-T6 aluminum to verify its ballistic limit was warranted. This would allow updating the penetration criteria for the newer material. Further, it was felt that some impact testing of coated specimens was necessary to determine what if any debonding occurred during the impact process.

Test Procedures:

Preliminary Test:

Before testing the newer suit materials, a shoulder section of current suit material was to be impacted. This operational section was tested in a configuration similar to that tested at Johnson Space Center at least as far as particle size was concerned. An aluminum sphere of

0.79 mm was selected to impact at approximately 5.5 km/sec. The section was sealed, pressure tested and monitored for average leak rate. Since the section could not be subjected to extremes in pressure, an arrangement was devised to allow monitoring pressure at all times from outside the evacuated range before shooting. This was accomplished by using an evacuated accumulator tank and double gauges. See figure (1).

As the range was pumped down the closed suit section internal pressure began to rise. A valve on the external evacuated tank was opened to lower the suit pressure below its limit. When 3 to 5 mmhg range pressure was reached the accumulator tank valve was shut off to trap the suit pressure at 8 psig on the gauge located inside of the range. Under these conditions the round was fired.

A small block of wood was placed inside of the suit section to catch any debris resulting from the impact. Rapid pressure loss followed the impact. The projectile was observed to have broken up into 3 or 4 pieces which imbedded in the wood. The impact hole was readily seen but was easily patched with tape from the inside of the suit.

(Comments on this initial test)

This suit shot was an effort to try and reproduce fabric shots in an untitled report from JSC of tests performed on various components of a candidate space suit.

Several questions arose when reading this hazard assessment of a candidate 8psi space suit configuration. Some of these questions were answered in a phone conversation with Bert Cour-Palais. One of the questions posed was why the energy levels for penetration of 6061-T6 Aluminum were calculated using the hypervelocity equation cited in the report, namely:

(1) $$tp = K \times d^{(1.06)} \times (pp/pt)^{(0.5)} \times (V/C)^{(.667)} \times (BH)^{(-.25)}$$

Where d = diameter, cm

pp = projectile density ------> 2.78 g/cc

pt = Target density ------> 2.78 g/cc

V = Impact Velocity, cm/sec -----> 10E05 cm/sec

C = Sonic Velocity " ------> 5E05 "

BH = Brinnel Hardness ------> 95

K = material constant 1.75 x 5.24 -> 9.2

tp = threshold perforation, in cm

This equation was developed by Rockwell and also JPL some years ago. The penetration equation used K=5.24. JSC in this report uses a modified K which is 1.75 times the K=5.24, or K=9.2. Some earlier reports on meteoroid bumpers uses a factor of 2.0 times for a K=10.48 for a bumper of zero penetration.

Several other groups use a modified Fish-Summers equation, namely:

(2) $$tp = K1 \times (pp)^{(.1667)} \times (mp)^{(.352)} \times (Vp)^{(.875)}$$

Where pp = Projectile density g/cc -------> 2.78 g/cc
mp = Projectile mass g ------->
Vp = Impact Velocity km/sec -------> 10 km/sec
K1 = Target Material Constant Alum ----> 0.54 to 0.57
tp = threshold perforation in cm

The 1969 Meteoroid Environment Model used K1 = 0.54 for Aluminum. A 1984 MSFC report by Dallas Smith on the debris impact uses K1=0.57.

Plots of these equations are shown in figures (2) & (3). If we look at a plot of the F-S equation with K1=.54 and overlay a plot of the JSC equation with K=9.2 this is shown in figure (3). These plots show Thickness of penetration versus projectile diameter for impacts at a constant of 10 km/sec.

The foregoing discussion on which formulas are being used and the true ballistic limit of the 6061 T6 suit material will be determined in the plan to impact 6061 T6 Aluminum with Aluminum projectiles to determine the ballistic limit. This B.L. can then be used to determine the probability of no penetration of the proposed suit for the space station. The ballistic limit shots will preceed the shots to determine the effect of impact upon the protective coatings being considered.)

Ballistic Limit of 6061-T6 Aluminum:

An initial series of impacts using various sizes of projectiles was conducted into target plates of 6061-T6 aluminum. The projectiles all of aluminum and spherical. Figures (4) & (5) show a cross-section of sheets impacted with 0.79 mm (0.03125inch) and 1.59 mm (0.0625 inch) aluminum spheres at approximately 5.5 km/sec. However, the determination of velocity is very poor with projectiles in this size range. The detectors are extinction type, i.e., they look for an interruption of a bright field with the passage of the particle. When the particle size is small the beam interruption goes unnoticed being lost in-the-noise, and if a stop signal is given the range counters, one has no garrantee that the signal was due to a particle passage or not.

Therefore, it was decided to use 3.175 mm (0.125 inch) diameter aluminum projectiles since reliable velocity determination could be made. If we assume that the behavior of 6061-T6 aluminum to be similar to that of other aluminums we can use the Fish-Summers equation to predict the approximate perforation velocity limits and reduce the number of shots required for this series of tests.

If we take the modified Fish-Summers equation cited above, namely:

(2) $tp = K1 \times (pp)^{(.1667)} \times (mp)^{(.352)} \times (Vp)^{(.875)}$

Where pp = Projectile density g/cc -------> 2.78 g/cc
mp = Projectile mass g ------->
Vp = Impact Velocity km/sec -------> 10 km/sec
K1 = Target Material Constant Alum ----> 0.54 to 0.57
tp = Thickness penetrated in cm

We may use either K1 = 0.54 or K1 = 0.57 initially to get an impact velocity near that assumed for penetration of the specimens chosen for the impact tests. Figure (6) is a plot of penetration thickness versus impact velocity for a one-eighth inch diameter aluminum projectile into an aluminum target with K1 = 0.54. We see that a projectile of this size with a velocity in the range of 5 to 6 km/sec should penetrate an aluminum target ranging from 0.9 cm to 1.0 cm. Using 0.953 cm (0.375 inch) 6061-T6 aluminum plate as a target material to match the 0.3175 cm (0.125 inch) aluminum projectile should allow determining threshold perforation within the capabilities of the Vertical Gun Range Facility.

Several rounds were required to zero in on the threshold perforation limit, which was found to be 5.02 km/sec. This suggested that the value for K1 target constant for 6061-T6 aluminum should be 0.57. Figure (7) is a plot of thickness versus impact velocity for 1/8 inch diameter aluminum projectile and a target constant K1 = 0.57. The threshold perforation point is noted on the plot.

Figure (8) is a plot of suit thickness versus debris diameter with an impact velocity of 10 km/sec. This suggests that for normal impact the suit thickness of 1.78 mm (0.070 inch) would be perforated by debris diameters greater than 0.35 mm at 10 km/sec.

If we consider the appearance of the target cross-section at threshold perforation, earlier work (a) pointed to the difference between highly ductile and brittle materials. Consider figure (9), (a) & (b), where (a) is a drawing of a brittle material and (b) is that of a ductile material of the same density.

We see that the brittle material, while still retaining a roughly hemispherical crater at threshold perforation, fails through cracks to the rear surface where spall material has been ejected by the reflected shock wave interaction.

For the highly ductile material, (9b), the crater shape has distended to a conical section, failure occuring through a hole at the base of the crater, and the spall products retained in petals below the crater.

If we compare these figures with figure (10) of the threshold perforation of 6061-T6 aluminum, we see some distension and spall retension like a ductile material but with some cracking through like that of a brittle material. This is indicative of behavior of 6061-T6 aluminum with a balance between brittleness and ductility.

What happens at other than normal impact? Certainly all impacts will not be normal to the surface. Figure (11) shows 6061-T6 aluminum impacted at 30 degrees to normal. The point is just below threshold perforation. Compare this figure with that of the previous shown figure (10) for threshold perforation at normal impact. The cross-sections are almost identical in appearance. The velocity is about 0.5 km/sec higher than the earlier impact. The cratering phenomena occurs due to the pressures developed at impact which sets off shock waves at right angles to the surface at the impact point. For all but extremely low angles of impact, the craters will not betray the impact angle.

The pressures developed will be governed by the normal component of the particle velocity, that is, a function of the cosine of the impact angle. We could probably rewrite the modified Fish-Summers to include this angular dependence.

(3) tp = K1 x (pp)**(.1667) x (mp)**(.352) x (V)**(.875) x (cos(phi))

Where tp = Thickness penetrated
pp = Particle density AL = 2.78 g/cc
mp = " mass
V = " velocity
phi = angle of impact (from normal)
K1 = Target constant (0.57 for 6061-T6 AL)

Impact of Coated Specimens:

Determination of the best available thermal and radiation control coatings was arrived at by a separate study. Two candidate coatings in different configurations were presented for impact study. These were Aluminum and Gold in both polished and satin finishes. Also satin finished specimens of each were subjected to low-speed, high-mass impacts from tumbling with other materials such as tools, etc. These latter specimens had a large number of burnished areas resulting from these impacts. The specimens were dimensioned about 2 inch by 4 inch by 1/4 inch thick. It was felt that maximum effect would occur if the high speed impacts were with particles of insufficient mass and velocity to penetrate the specimens but rather provide a reasonable crater and be as uniform as possible in the impact energies.

With the 1/4 inch thick plates of 6061-T6 aluminum coated specimens it was decided to use 1/16 inch (1.59 mm) aluminum projectiles at around 5 km/sec velocity. This would keep the impacts below penetration point and not give rise to any large spall areas on their rear surfaces.

Figures (12) to (17) show the results of these shots. Figure (12) is an overall view of all the specimens, the balance of the figures show the craters close up. The areas of highest stress in the coatings, right adjacent to the craters showed many stress lines in the coatings but no evidence of any debonding or cracking of the coatings. Whatever coatings are used it appears that all tested very well under high speed impact.

Conclusions:

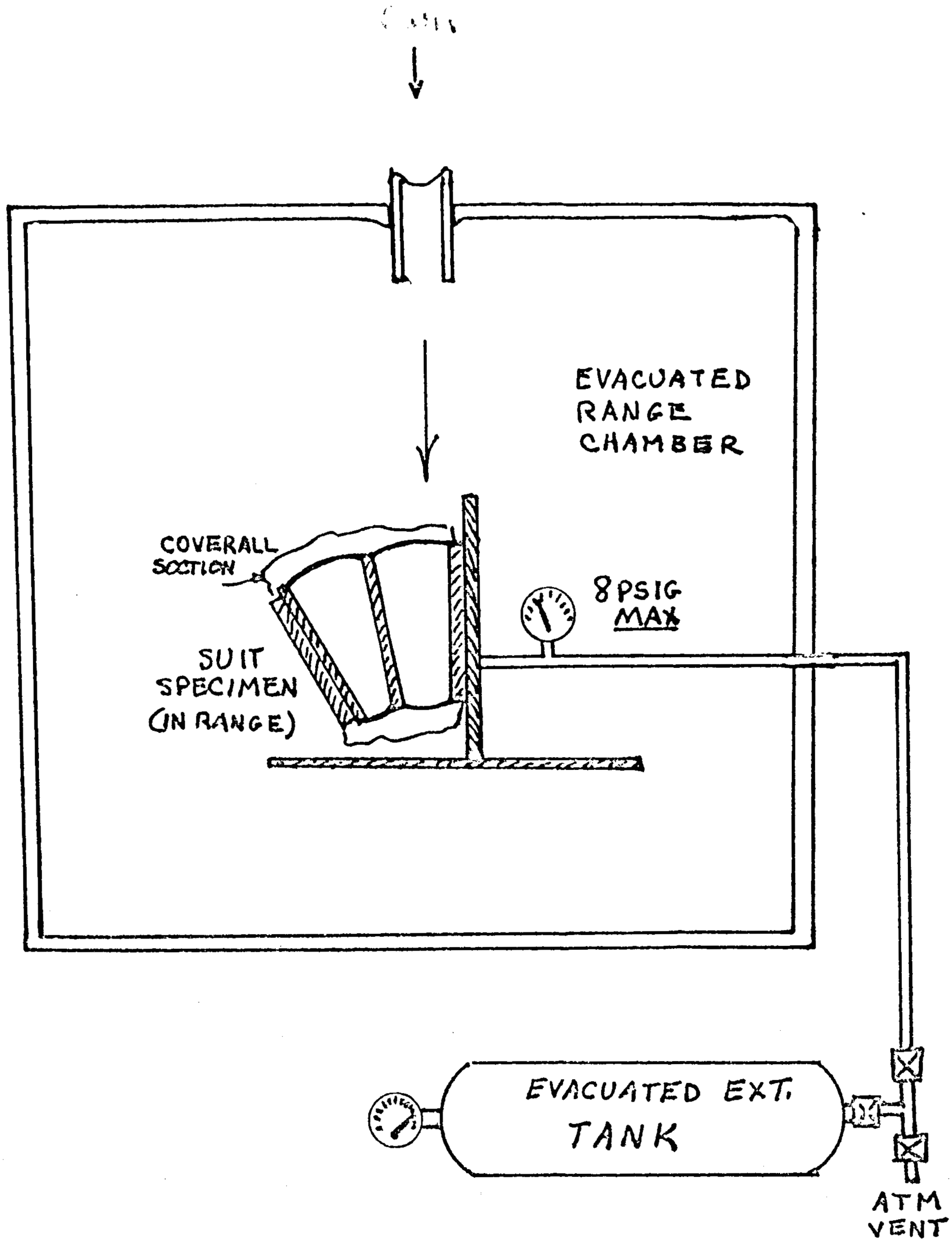
The selection of 6061-T6 Aluminum for space suits for use on the space station would appear to be worthwhile. The relatively ductile behavior of 6061-T6 aluminum is better than a choice of a more brittle material.

The coatings selected show no signs of failure occuring around the impact craters as other materials might well do.

The suit for long term orbit use will likely include insulation materials. These can only act beneficially in reducing ballistic limits.

Bibliography

(a) Fish, R. H. & Summers, J. L. Threshold Perforation of Various Materials - 7th HyperVelocity Impact Symposium, 1964 Tampa, Florida



SUIT TEST SETUP

FIGURE

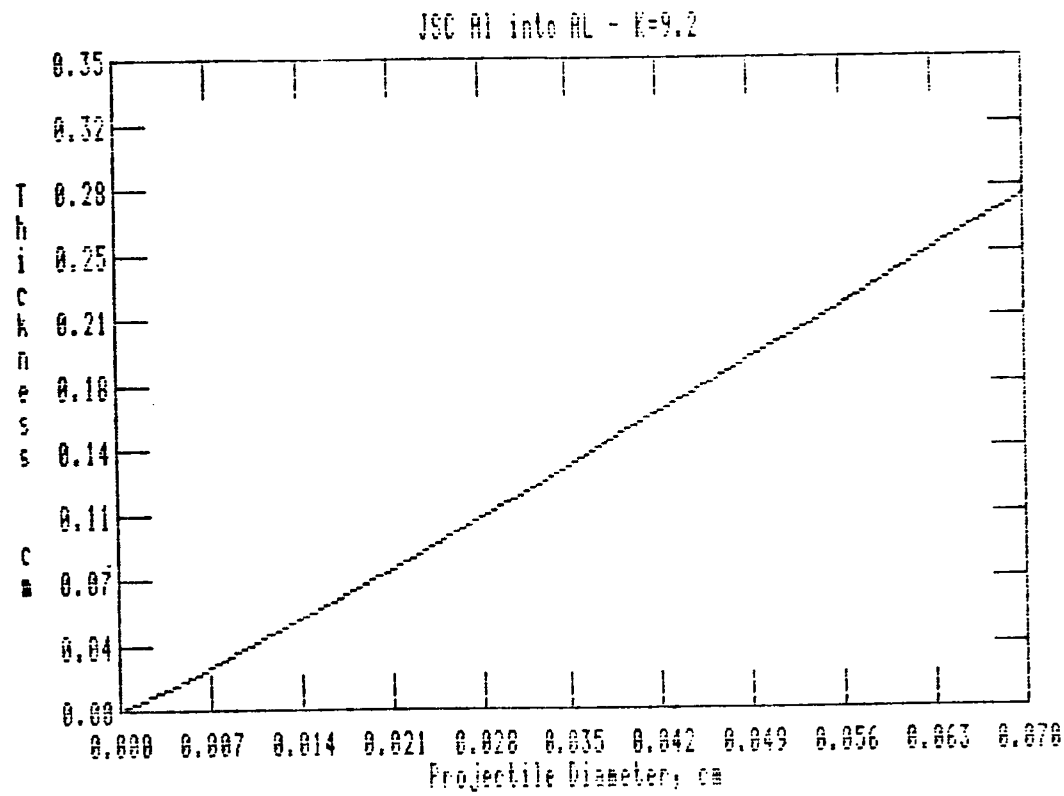


FIGURE 2

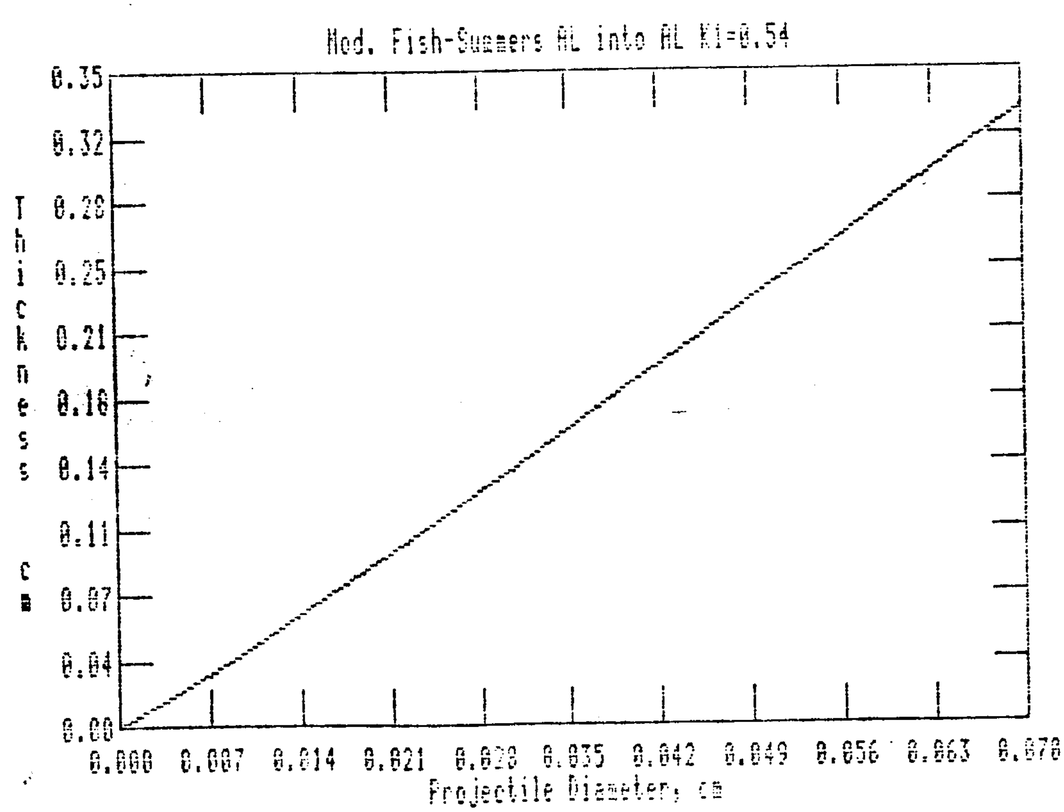


FIGURE 3

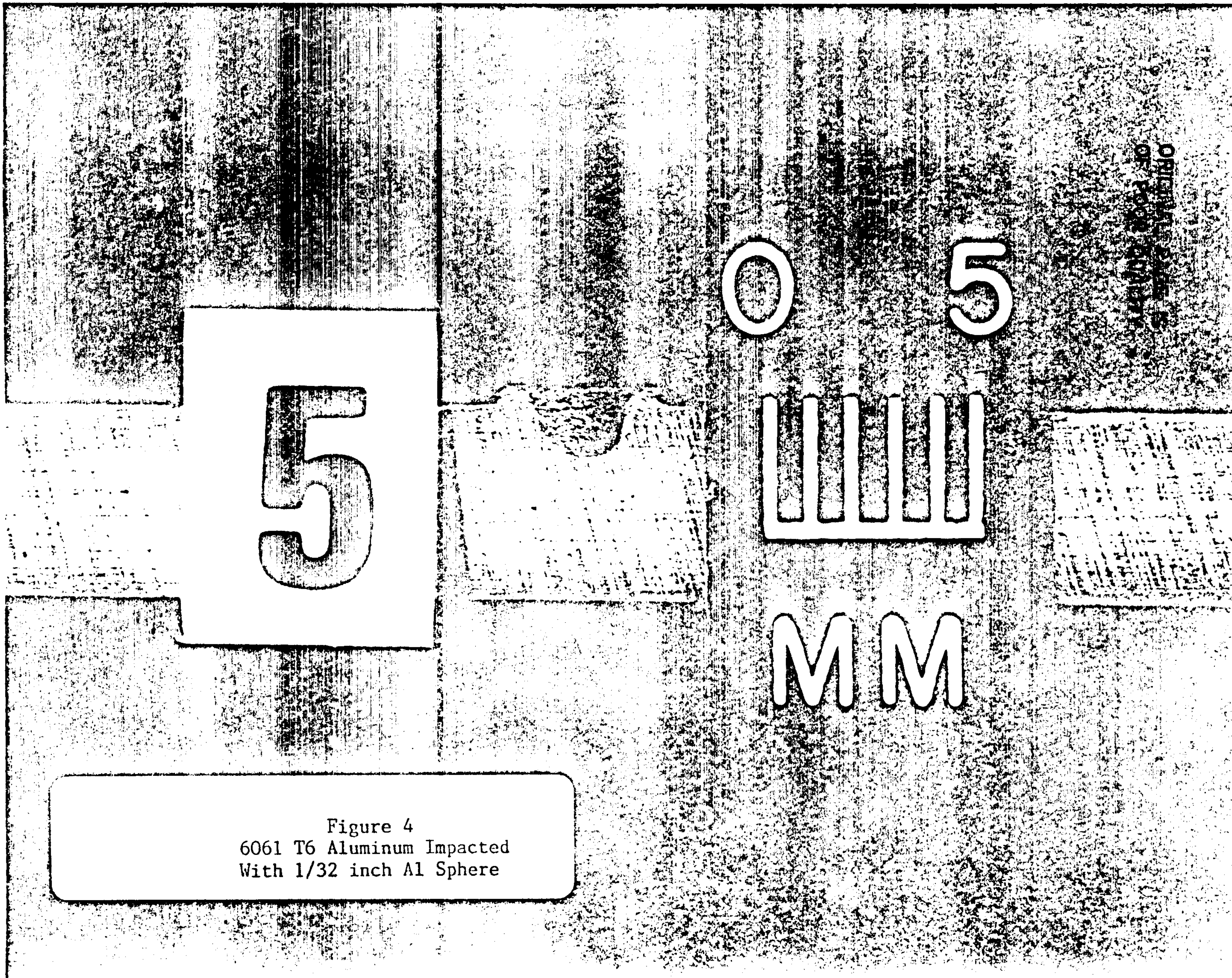


Figure 4
6061 T6 Aluminum Impacted
With 1/32 inch Al Sphere

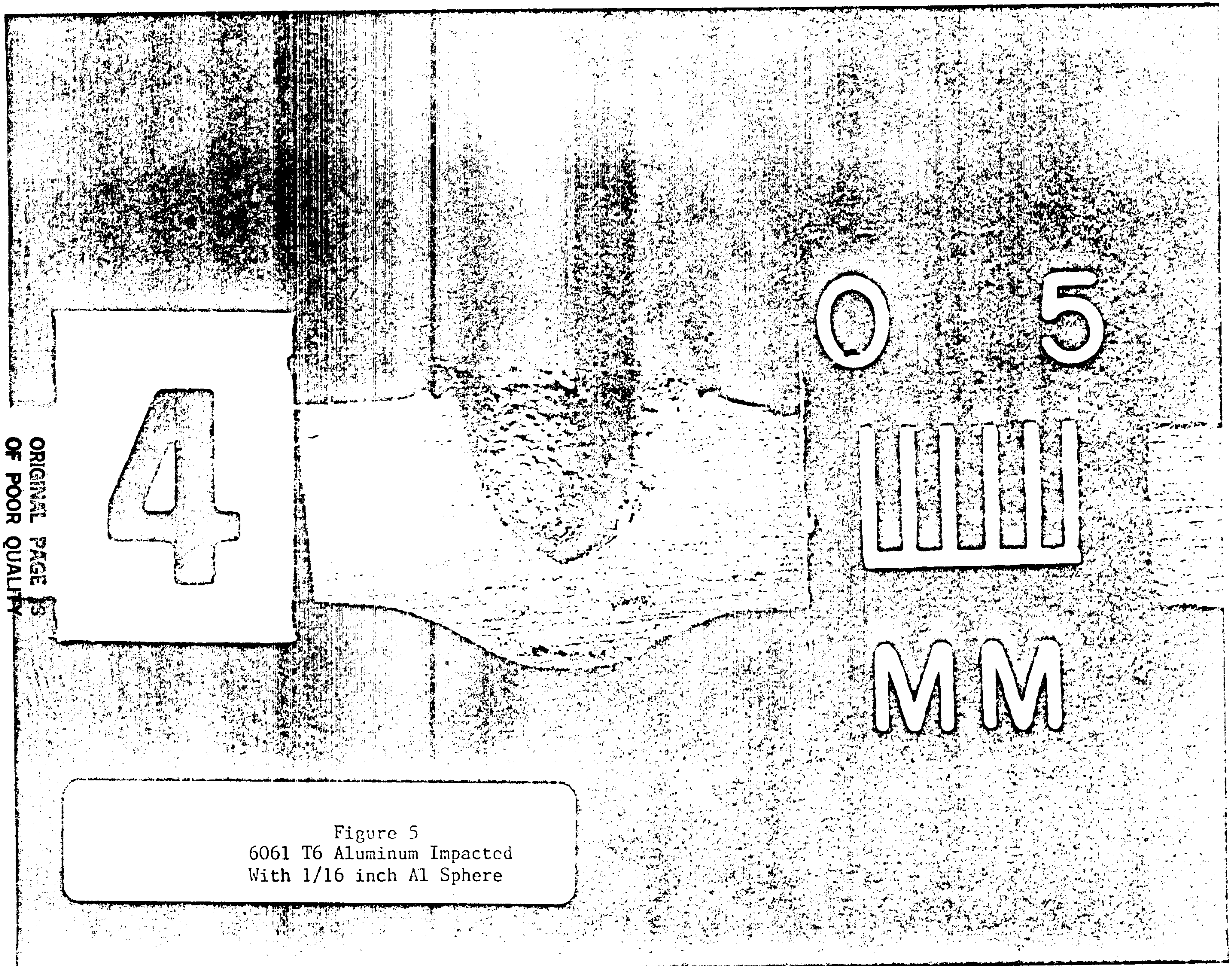


Figure 5
6061 T6 Aluminum Impacted
With 1/16 inch Al Sphere

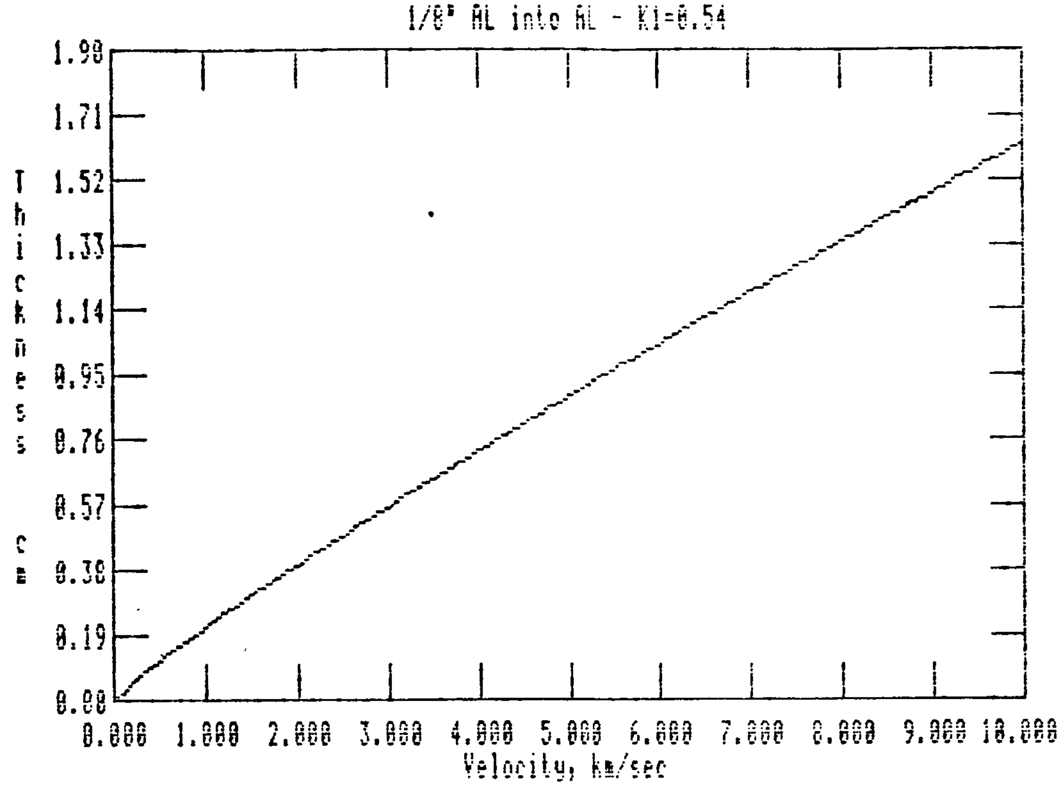


FIGURE 6

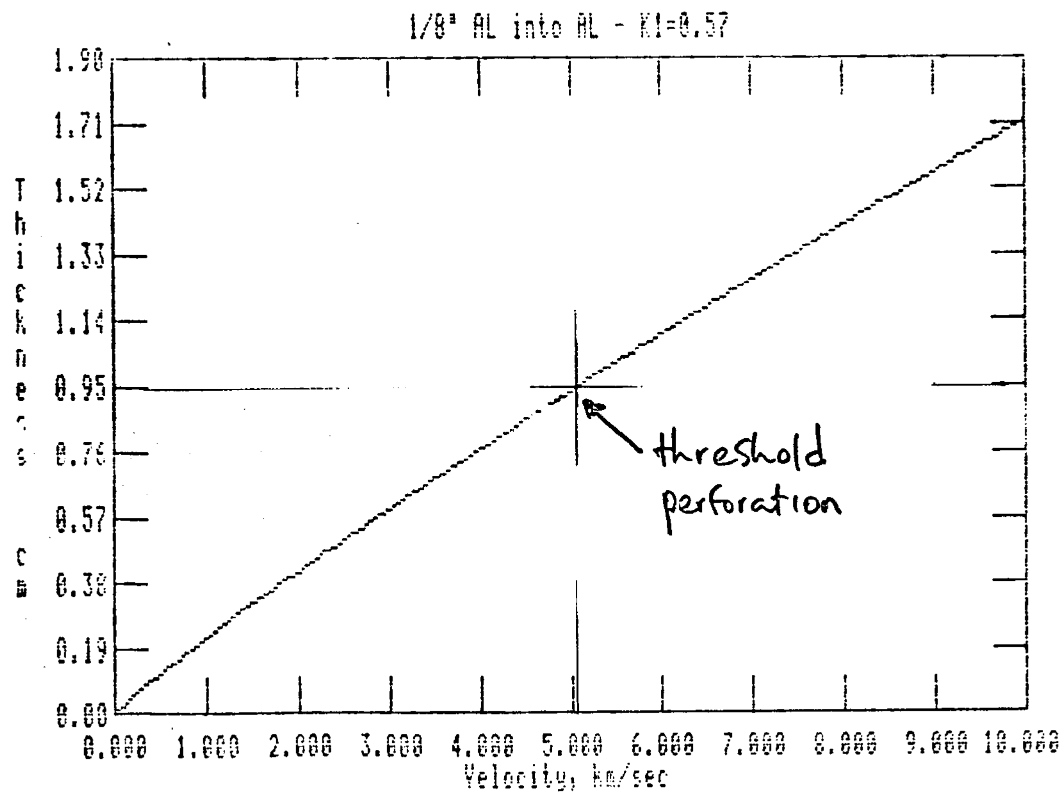


FIGURE 7

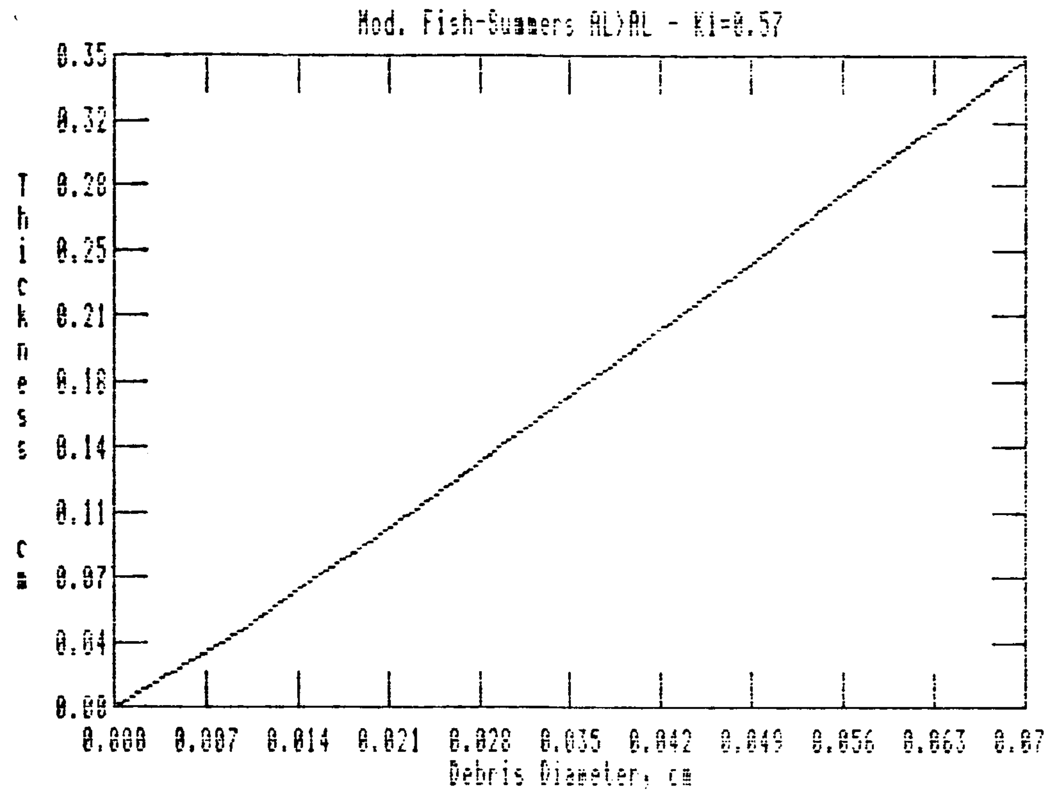
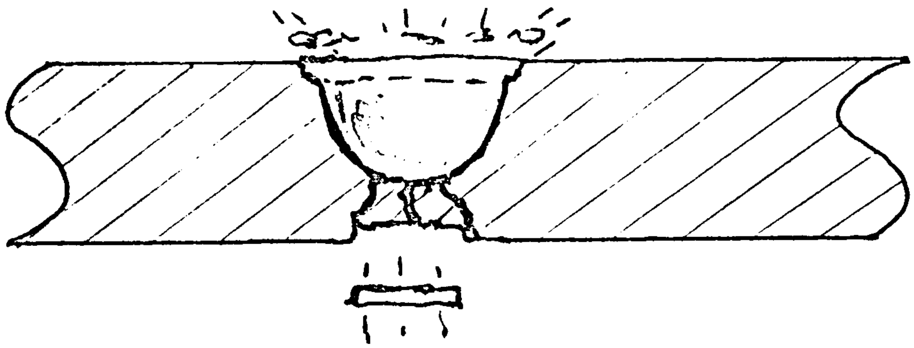

Mod. Fish-Summers AL>AL - K1=0.57
Thickness cm
0.35
0.32
0.28
0.25
0.21
0.18
0.14
0.11
0.07
0.04
0.00
0.000 0.007 0.014 0.021 0.028 0.035 0.042 0.049 0.056 0.063 0.070
Debris Diameter, cm

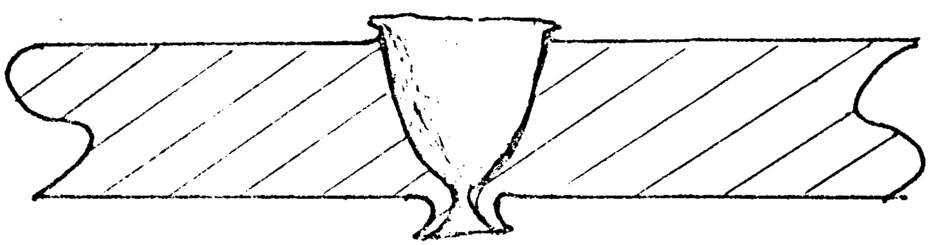
FIGURE 8

BRITTLE BEHAVIOR



(a)

DUCTILE BEHAVIOR



(b)

THRESHOLD PERFORATION

FIGURE 9

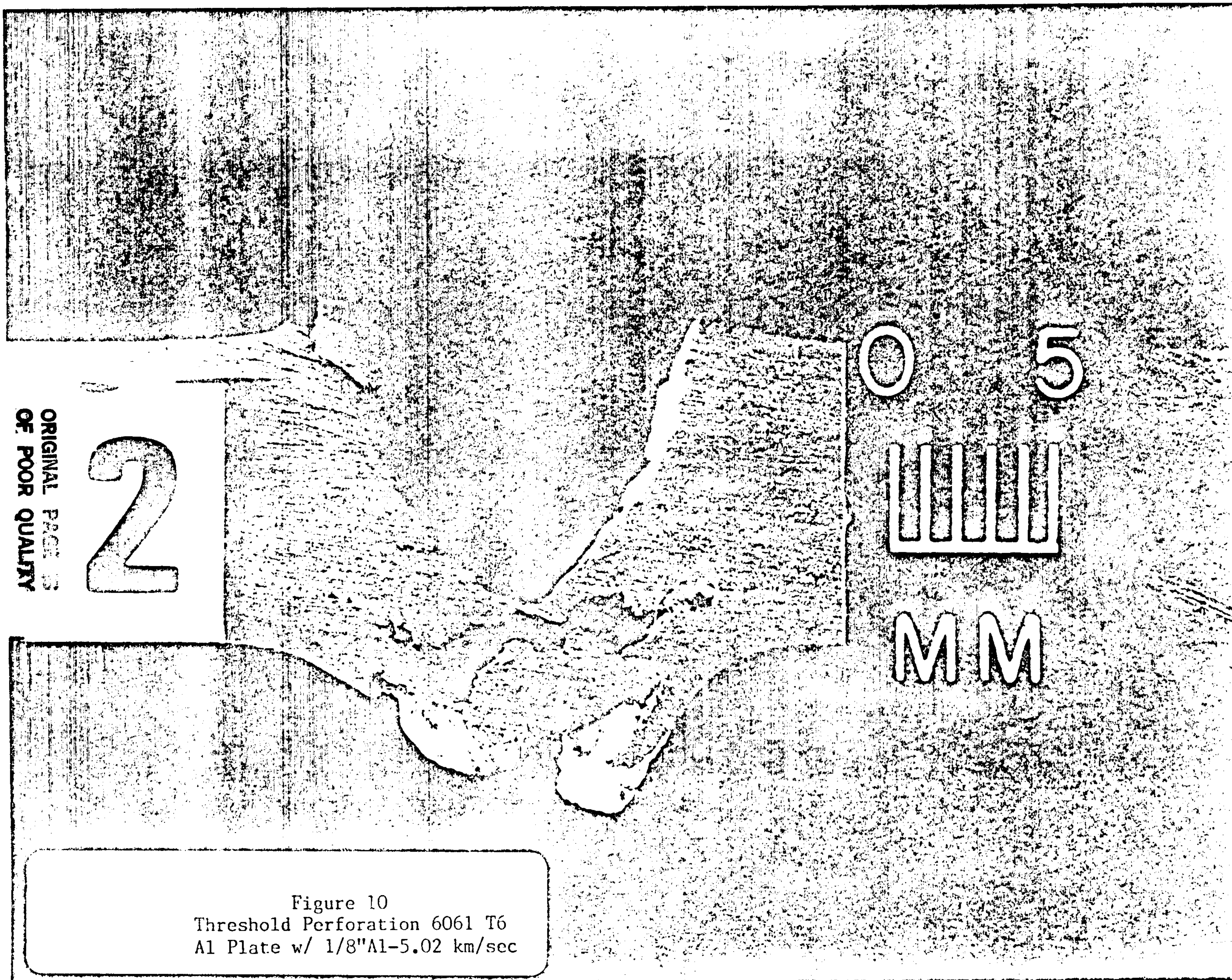


Figure 10
Threshold Perforation 6061 T6
Al Plate w/ 1/8"Al-5.02 km/sec

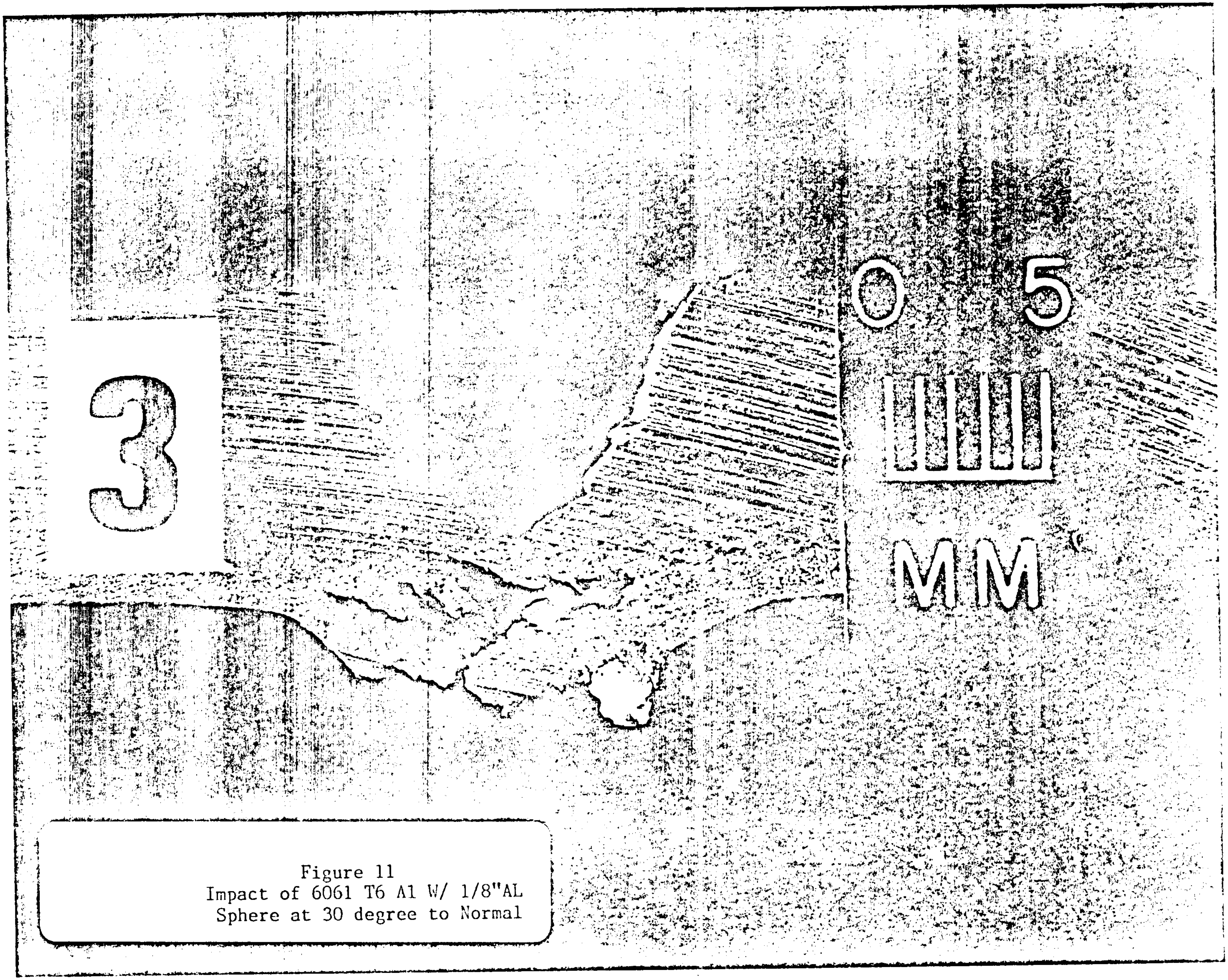


Figure 11
Impact of 6061 T6 Al W/ 1/8"AL
Sphere at 30 degree to Normal

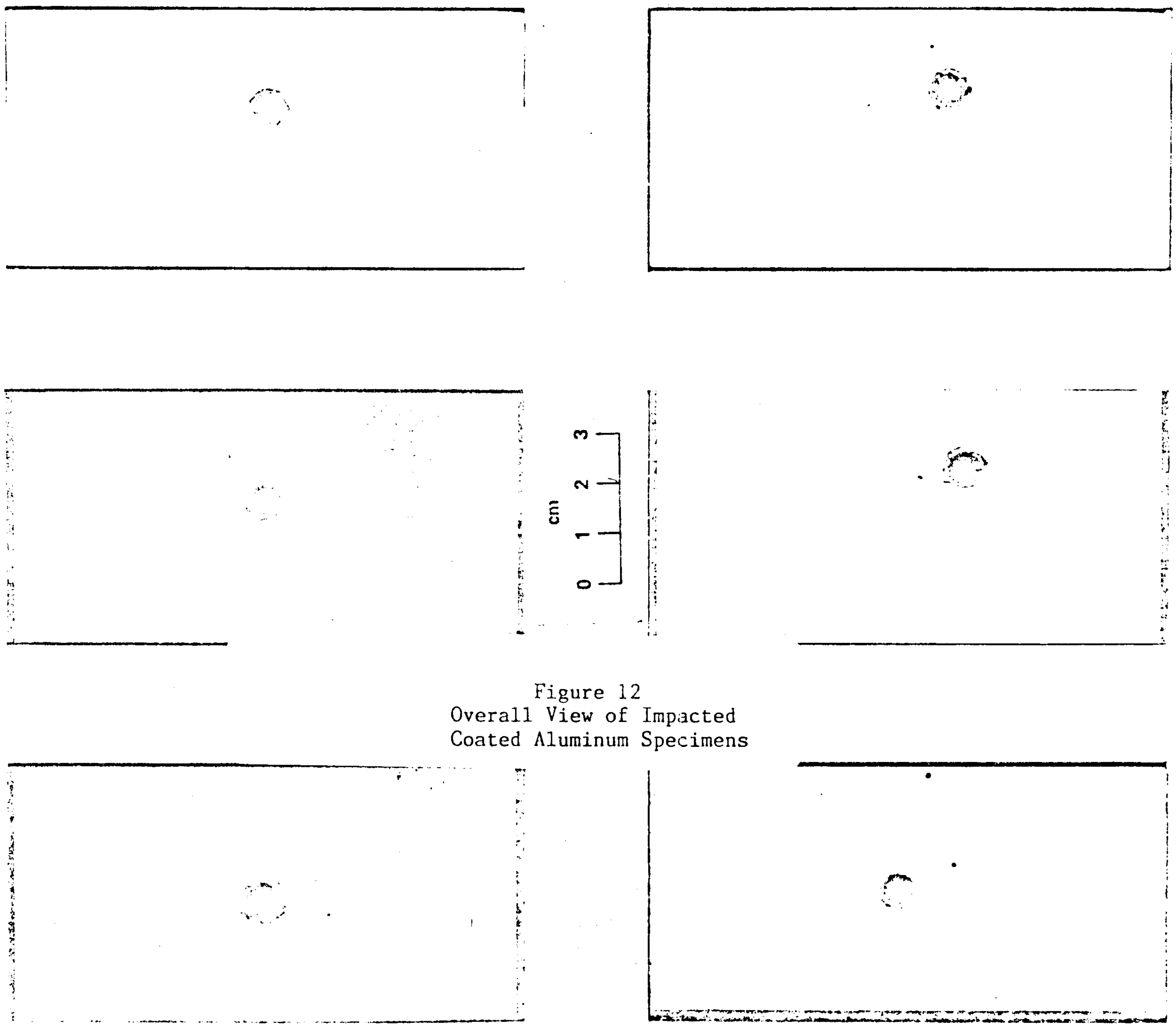


Figure 12
Overall View of Impacted
Coated Aluminum Specimens

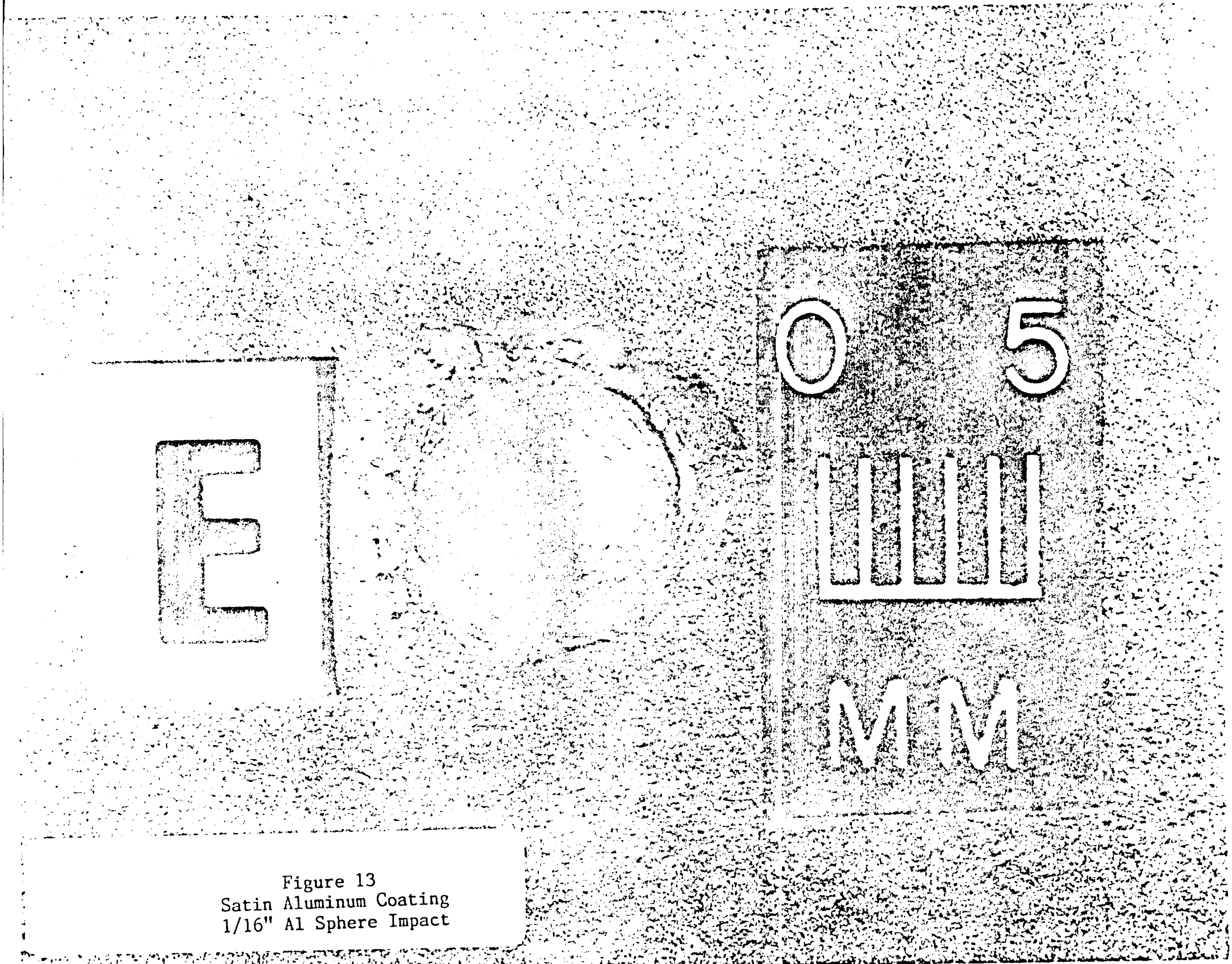


Figure 13
Satin Aluminum Coating
1/16" Al Sphere Impact

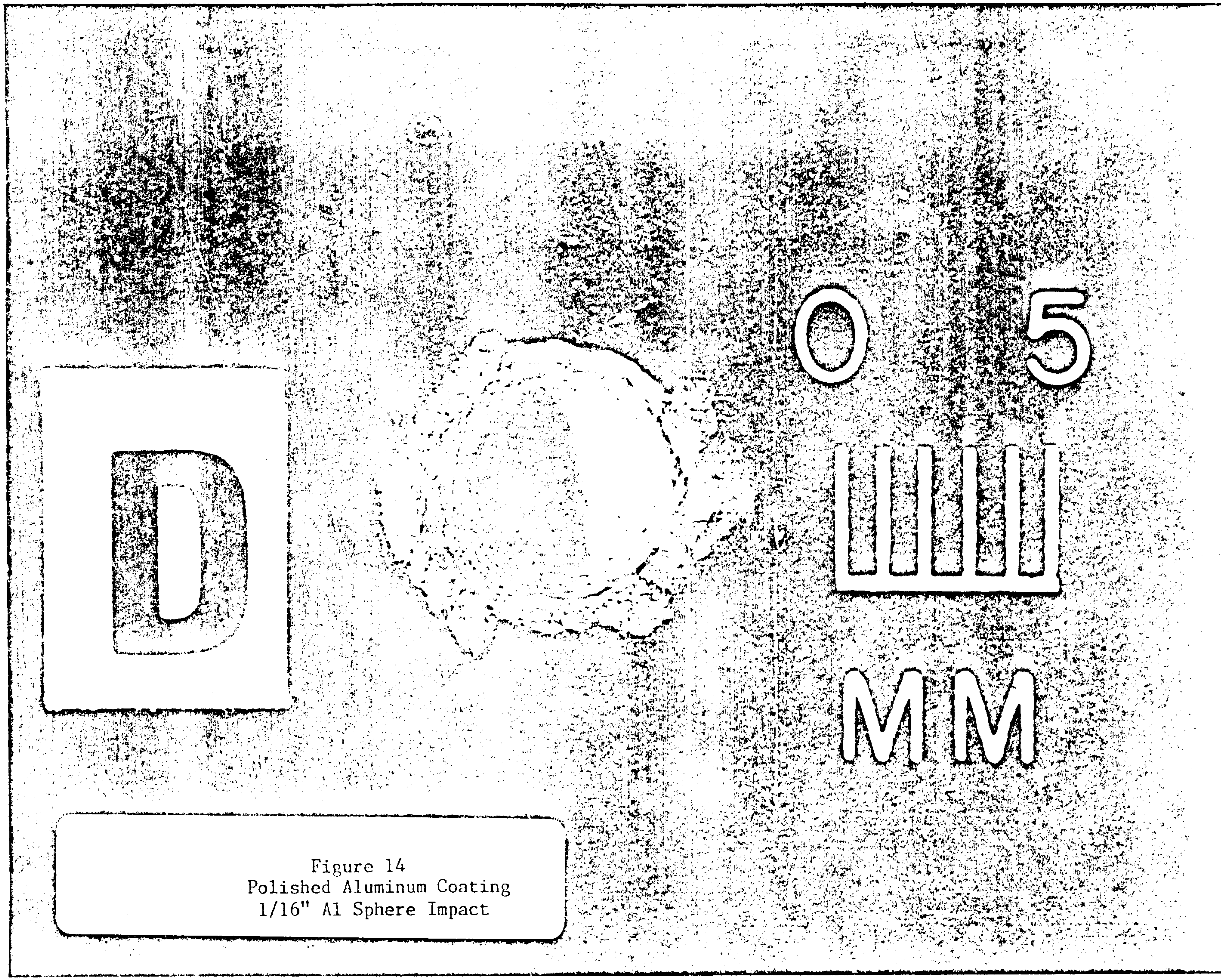


Figure 14
Polished Aluminum Coating
1/16" Al Sphere Impact

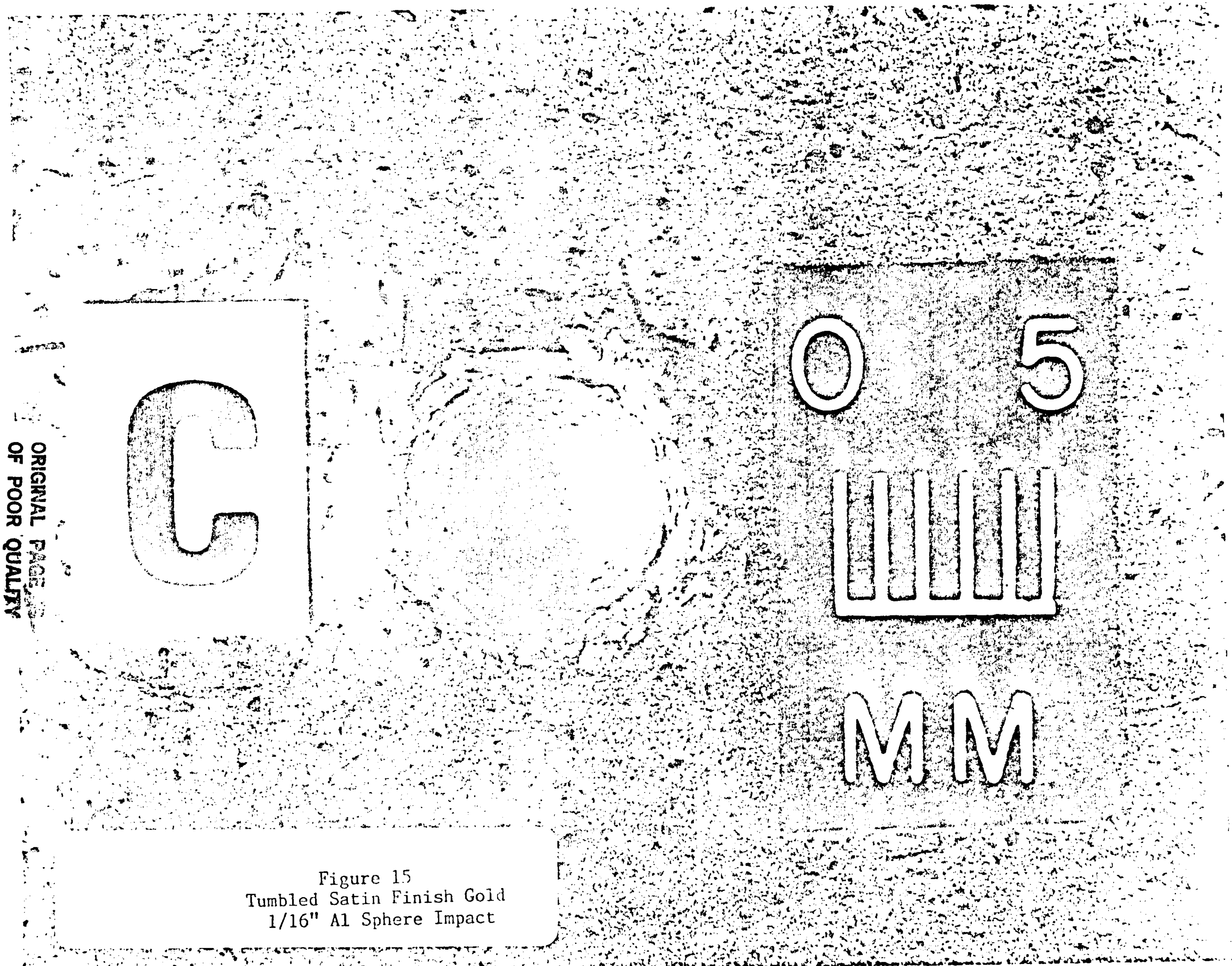


Figure 15
Tumbled Satin Finish Gold
1/16" Al Sphere Impact

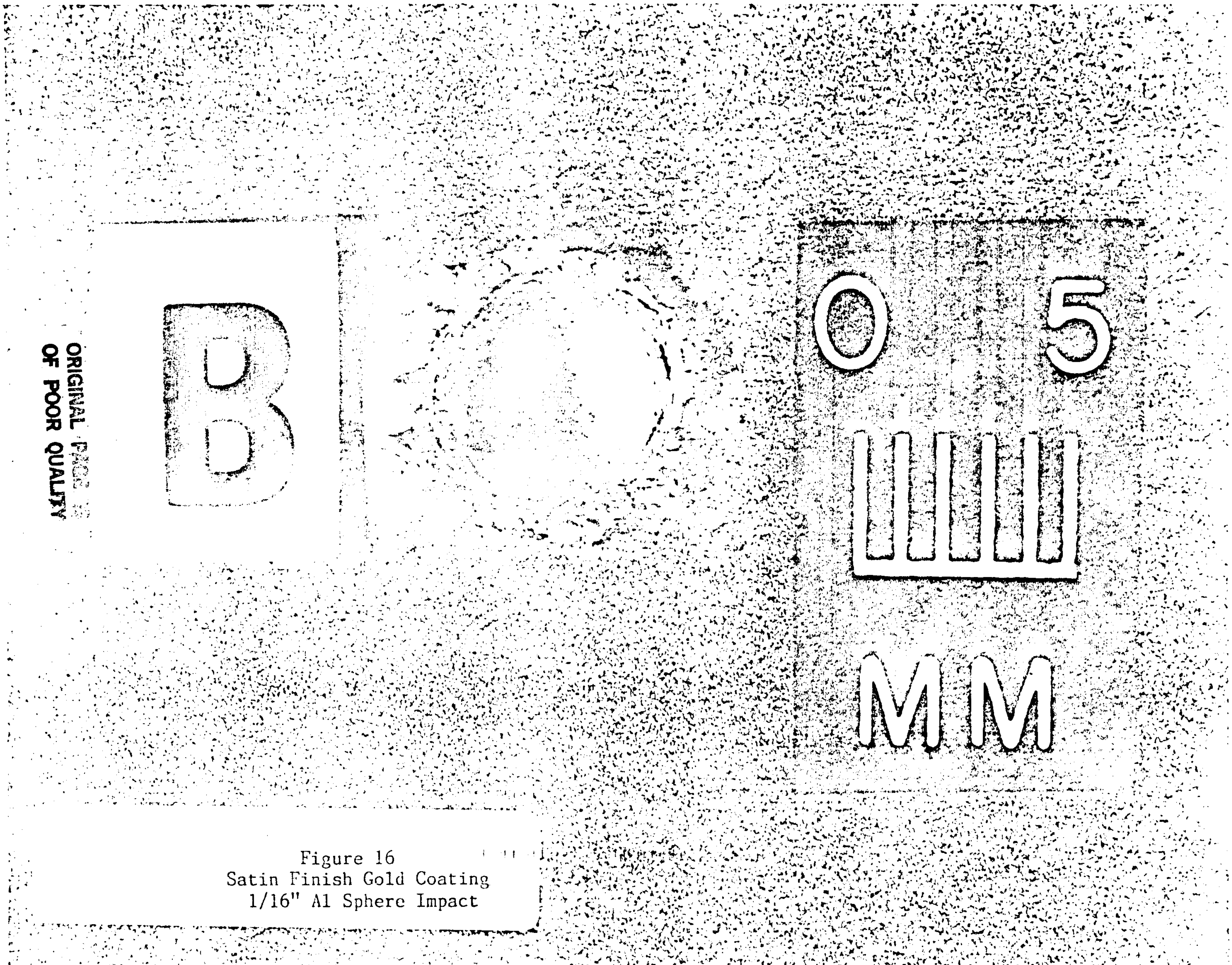


Figure 16
Satin Finish Gold Coating
1/16" Al Sphere Impact

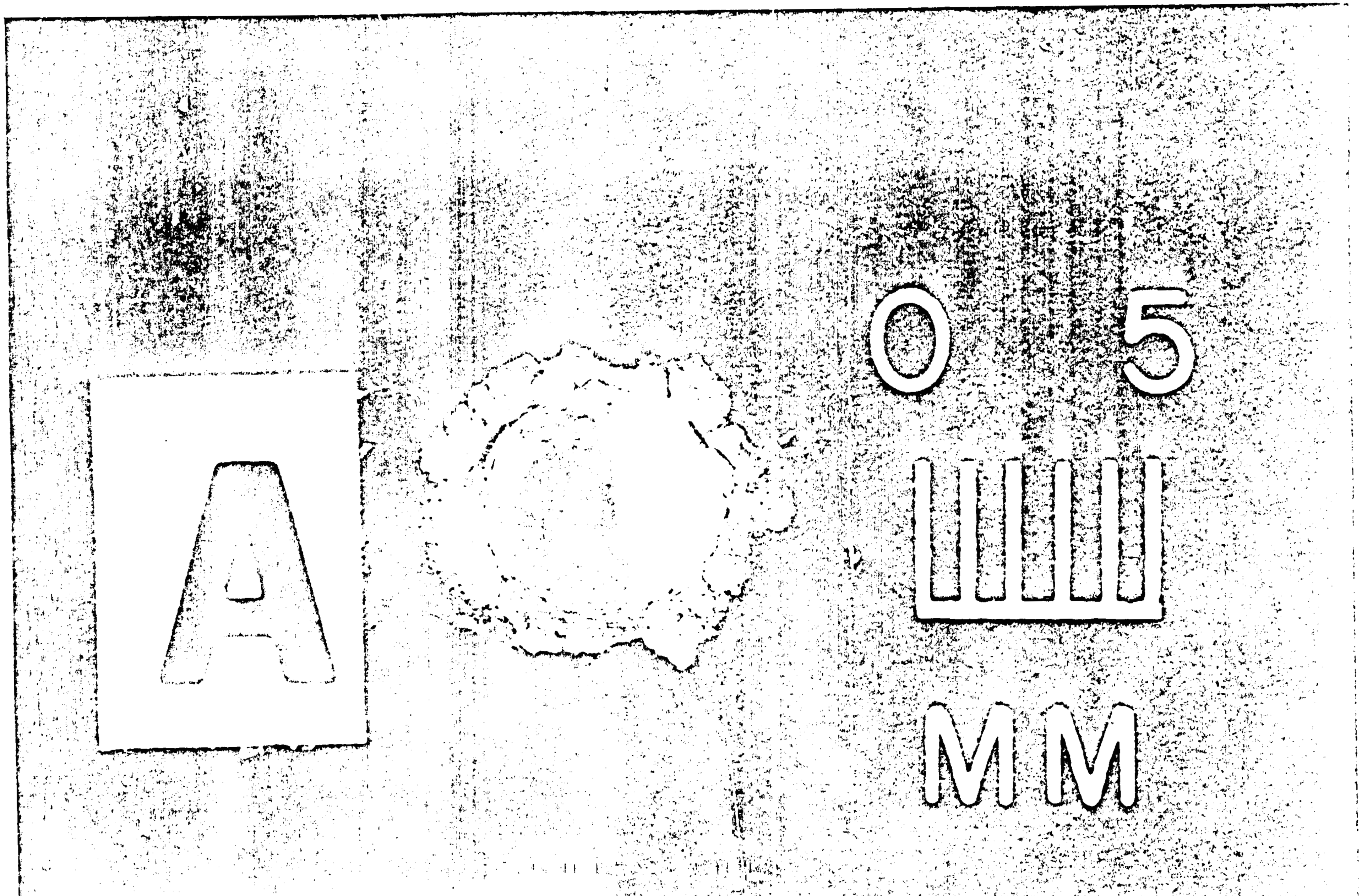


Figure 17
Polished Finish Gold Coating
1/16" Al Sphere Impact

BANGXY

```
10 'short program to calculate penetration thickness of
20 'aluminum space suits using threshold perforation formula
30 'author dick fish, nasa ames research center  1984
40 'Get the data if different from defaults:(FOR ALUM)
50 DI = .0625 : RO = 2.78 : K1 = .57
60 DIM X(101),Y(101)
62 COMMON X(),Y()
65 CLS
70 PRINT "This program calculates the Threshold perforation"
80 PRINT "for debris impact into structures in near earth orbit"
90 PRINT "Input will be asked for, a  N' answer will select"
100 PRINT "default values...." : PRINT : PRINT
110 INPUT "Change diameter of projectile? (dft 1/16 inch) [Y/N] ";A$
120 IF A$ ="Y" OR A$ ="y" THEN 140
130 IF A$ ="N" OR A$ ="n" THEN 150 ELSE 110
140 INPUT "Enter new diameter in decimal inches ( .XXX ) ";DI
150 INPUT "Change projectile density (dft ALUM=2.78) [Y/N] ";B$
160 IF B$ ="Y" OR B$ ="y" THEN 180
170 IF B$ ="N" OR B$ ="n" THEN 190 ELSE 150
180 INPUT "Enter new projectile density in gms/cc ( X.XX ) ";RO
185 K1$="ALUMINUM"
190 INPUT "Change target constant K1? (dft is ALUMINUM=.57) [Y/N] ";C$
200 IF C$ ="Y" OR C$ ="y" THEN 220
210 IF C$ ="N" OR C$ ="n" THEN 230 ELSE 190
220 INPUT "Enter new target constant (emperical data) (.XX) ";K1
225 LINE INPUT "What is the new material? ";K1$
230 D = DI*2.54 : M = (D^3)*(.5236)*RO : M1 = M^(.352) : D1 = RO^(.1667)
240 DEF FNA(X) = K1*M1*D1*(X^(.875))
245 print
250 PRINT "Filling array with thickness and velocity values"
260 FOR I = 0 to 100
270 X(I) = I/10
280 Y(I) = FNA(X(I))
290 NEXT I
300 CHAIN "PLOTXY",5000
999 END
```

DAMGIXY

```
10 'short program to calculate penetration thickness of
20 'aluminum space suits using threshold perforation formula
30 'author dick fish, nasa ames research center 1985
40 'Get the data if different from defaults:(FOR ALUM)
50 V = 10 : RO = 2.78 : K1 = .57 :K1$="ALUMINUM"
60 DIM X(101),Y(101)
62 COMMON X(),Y()
65 PRINT:PRINT:PRINT
70 PRINT "This program calculates the Threshold perforation"
80 PRINT "for debris impact into structures in near earth orbit"
90 PRINT "Input will be asked for, a 'N' answer will select"
100 PRINT "default values...." : PRINT : PRINT
110 INPUT "Change velocity of projectile? (dft 10 km/sec) [Y/N] ";A$
120 IF A$ ="Y" OR A$ ="y" THEN 140
130 IF A$ ="N" OR A$ ="n" THEN 150 ELSE 110
140 INPUT "Enter new velocity in decimal km/sec ( X.X ) ";V
150 INPUT "Change projectile density (dft 2.78) [Y/N] ";B$
160 IF B$ ="Y" OR B$ ="y" THEN 180
170 IF B$ ="N" OR B$ ="n" THEN 190 ELSE 150
180 INPUT "Enter new projectile density in gms/cc ( X.XX ) ";RO
190 INPUT "Change target constant K1? (dft is ALUMINUM=.57) [Y/N] ";C$
200 IF C$ ="Y" OR C$ ="y" THEN 220
210 IF C$ ="N" OR C$ ="n" THEN 230 ELSE 190
220 INPUT "Enter new target constant (emperical data) (.XX) ";K1
225 LINE INPUT "What is the new material? ";K1$
230 V1 = V^(.875) : M = (.5236)*RO : D1 = RO^(.1667)
240 DEF FNA(X) = K1*D1*V1*(X^.352)
245 PRINT:PRINT
250 PRINT"Filling array with target thickness vs projectile diameter values"
260 FOR I = 0 to 100
270 X(I) = I/200
275 M1 = (X(I)^3)*M
280 Y(I) = FNA(M1)
290 NEXT I
300 CHAIN "PLOTXY",5000
999 END
```

BANG2XY


```
10 'short program to calculate penetration thickness of
20  aluminum space suits using Bert Cour-Palais current formula
30 'author dick fish, nasa ames research center 1985
40 'Get the data if different from defaults:(FOR ALUM)
50 V = 10 : RO = 2.78 : K1 = 5.24 :K1$="ALUMINUM"
55 C = 5.1 : BH = 95. : PT = 2.78
60 DIM X(101),Y(101)
62 COMMON X(),Y()
65 PRINT:PRINT:PRINT
70 PRINT "This program calculates the Threshold perforation"
80 PRINT "for debris impact into structures in near earth orbit"
90 PRINT "Input will be asked for, a 'N' answer will select"
100 PRINT "default values...." : PRINT : PRINT
110 INPUT "Change velocity of projectile? (dft 10 km/sec) [Y/N] ";A$
120 IF A$ ="Y" OR A$ ="y" THEN 140
130 IF A$ ="N" OR A$ ="n" THEN 150 ELSE 110
140 INPUT "Enter new velocity in decimal km/sec ( X.X ) ";V
150 INPUT "Change projectile density (dft 2.78) [Y/N] ";B$
160 IF B$ ="Y" OR B$ ="y" THEN 180
170 IF B$ ="N" OR B$ ="n" THEN 190 ELSE 150
180 INPUT "Enter new projectile density in gms/cc ( X.XX ) ";RO
190 INPUT "Change target constant K1? (dft is ALUMINUM=5.24) [Y/N] ";C$
200 IF C$ ="Y" OR C$ ="y" THEN 220
210 IF C$ ="N" OR C$ ="n" THEN 230 ELSE 190
220 INPUT "Enter new target constant (emperical data) (.XX) ";K1
225 LINE INPUT "What is the new material? ";K1$
230 V1 = (V/C)^(.667) : B1 = (BH)^-(.25) : D1 = (RO/PT)^(.5)
240 DEF FNA(X) = K1*D1*V1*B1*(X^1.06)
245 PRINT:PRINT
250 PRINT"Filling array with target thickness vs projectile diameter values"
260 FOR I = 0 to 100
270 X(I) = I/200
275 M1 = X(I)
280 Y(I) = FNA(M1)
290 NEXT I
300 CHAIN "PLOTXY",5000
999 END
```

```
4500 REM*********************************************************************
4520 REM*                   PLOT PROGRAM FOR Z-100 GRAPHICS                 *
4530 REM*                                BY                                 *
4540 REM*                       Dick Fish - 9/26/84                         *
4570 REM*                                                                   *
4580 REM*********************************************************************
4590 REM
4600 REM          USE THE FOLLOWING SPACE TO CALCULATE A 101 BY 101
4610 REM          DATA ARRAY IN X(I) AND Y(I).
4620 REM          ENTER PROGRAM BELOW THIS SECTION IF ARRAY EXISTS.
4630 REM
4640 REM          SAMPLE ARRAY->     CONCENTRIC ELLIPSES
4650 REM
4660 DIM Y(101),X(101):REM      MOV DIM TO CALLING PROGRAM
4670 REM
4680    FOR I=0 TO 50
4690    Y(I)=SIN(I*6.282/50):X(I)=COS(I*6.282/50)
4700    NEXT I
4710 REM
4720    FOR I=51 TO 100
4730    J=I-50
4740    Y(I)=.5*SIN(J*6.282/50):X(I)=.5*COS(J*6.282/50)
4750    NEXT I
4760 REM
4770 REM   *** CALLING PROGRAM MUST DIM X() & Y() & COMMON ***
4780 REM*********************************************************************
4790 REM*           ENTER TITLE OF PLOT AND AXIS LEGENDS                    *
4800 REM*********************************************************************
4810 REM   VVV ENTER PLOT HERE AS SUB TO MAIN MATH PROGRAM VVV
4820 REM
5000    XTITLE$=SPACE$(50):YTITLE$=SPACE$(20):PTITLE$=SPACE$(50)
5010    LINE INPUT "ENTER TITLE OF PLOT (50 CHARACTERS OR LESS) ";P$
5020    LINE INPUT "ENTER Y-AXIS TITLE (20 CHARACTERS OR LESS) ";Y$
5030    LINE INPUT "ENTER X-AXIS TITLE (50 CHARACTERS OR LESS) ";X$
5040    MID$(YTITLE$,(LEN(YTITLE$)-LEN(Y$))/2)=Y$:REM ; THIS SECTION
5050    MID$(XTITLE$,(LEN(XTITLE$)-LEN(X$))/2)=X$:REM ;  SCALES THE
5060    MID$(PTITLE$,(LEN(PTITLE$)-LEN(P$))/2)=P$:REM ; TITLE SPACE
5070    INPUT "DO YOU WANT A(UTO) OR M(ANUAL) SCALING ";N$
5080    IF N$="M" OR N$="m" THEN 5110
5090    IF N$="A" OR N$="a" THEN GOSUB 6330 ELSE 5070
5100    GOTO 5205
5110    INPUT "ENTER MAXIMUM VALUE OF Y-AXIS";YMAX
5120    INPUT "ENTER MINIMUM VALUE OF Y-AXIS";YMIN
5130    INPUT "ENTER MAXIMUM VALUE OF X-AXIS";XMAX
5140    INPUT "ENTER MINIMUM VALUE OF X-AXIS";XMIN
5150 REM
5160 REM*********************************************************************
5170 REM*                MAIN BODY OF PROGRAM STARTS HERE                   *
5180 REM*********************************************************************
5190 REM
5200 REM
5205    CLS:LOCATE 1,19
5210    PRINT PTITLE$:REM                    PRINT TITLE OF PLOT
5260    FOR LNNO=0 TO 180 STEP 18
5270    YN=YMIN+(((YMAX-YMIN)/180)*(180-LNNO)):  REM NORMALIZE Y
5280    YD=ABS((YMAX-YMIN)/180):REM              VALUE OF EACH LINE
5290    GOSUB 5930:REM                           PRINT VERTICAL SCALE
5300    NEXT LNNO
5305    GOSUB 6040:REM                           PRINT Y TITLE
5310    GOSUB 5010:REM                           PLOT DATA
```

```
5370     GOSUB 6140:REM                                PRINT X SCALE, TITLE
5450     FOR J=1 TO 20:FOR K=1 TO 1500:NEXT K:NEXT J
5456     SYSTEM
5460 REM
5470 REM**************************************************************
5480 REM*          END OF MAIN BODY-- SUBROUTINES START HERE           *
5490 REM**************************************************************
5500 REM
5770 REM**************************************************************
5780 REM*                     PLOT DATA SUBROUTINE                     *
5790 REM**************************************************************
5800 REM
5810     YS=13+180-FIX((Y(0)-YMIN)*100/(YMAX-YMIN))
5820     XS=60+FIX((X(0)-XMIN)*560/(XMAX-XMIN))
5830     PSET (XS,YS),7
5832     FOR I=1 TO 100
5834     YP=13+180-FIX((Y(I)-YMIN)*180/(YMAX-YMIN))
5836     XP=60+FIX((X(I)-XMIN)*560/(XMAX-XMIN))
5837     IF YP<13 OR XP>620 THEN 5870
5850     LINE -(XP,YP)
5860     NEXT I
5870     LINE (60,13)-(620,193),,B
5875     RETURN
5880 REM
5890 REM**************************************************************
5900 REM*                        PLOT Y SCALE                          *
5910 REM**************************************************************
5920 REM
5930     R$="R20":L$="L20"
5940     LOCATE LNNO/10*2+2,2
5950     PRINT USING "###.##";YN
5960     PSET(60,LNNO+13),7:DRAW R$
5970     PSET(620,LNNO+13),7:DRAW L$
5980     RETURN
5990 REM
6000 REM**************************************************************
6010 REM*                    PRINT Y-AXIS TITLE                        *
6020 REM**************************************************************
6030 REM
6040     LOCATE 3,1
6050     FOR I=1 TO LEN(YTITLE$)
6060     CHAR$=MID$(YTITLE$,I,1)
6065     PRINT CHAR$
6070     NEXT I
6080     RETURN
6090 REM
6100 REM**************************************************************
6110 REM*                 PRINT X SCALE SUBROUTINE                     *
6120 REM**************************************************************
6130 REM
6140     U$="U10":D$="D10"
6150     LOCATE 23,4
6160     FOR I=0 TO 10
6170     PRINT USING "###.###";(XMAX-XMIN)*I/10+XMIN;
6172     NEXT I
6174     FOR I=1 TO 10
6175     PSET(56*I+4,193),7:DRAW U$
6176     PSET(56*I+4,13),7:DRAW D$
6180     NEXT I
6200 REM
```

```
6210 REM****************************************************************
6220 REM*                          PRINT X AXIS TITLE                  *
6230 REM****************************************************************
6240 REM
6250     LOCATE 24,19
6260     PRINT XTITLE$;
6265     LOCATE 1,1
6270     RETURN
6280 REM
6290 REM****************************************************************
6300 REM*                    AUTO SCALING  SUBROUTINES                 *
6310 REM****************************************************************
6320 REM
6330     YMAX=Y(0):XMAX=X(0):YMIN=Y(0):XMIN=X(0)
6340     FOR I=1 TO 100:REM                       FIND XMAX & YMAX
6350     IF Y(I)>YMAX THEN YMAX=Y(I)
6360     IF Y(I)<YMIN THEN YMIN=Y(I)
6370     IF X(I)>XMAX THEN XMAX=X(I)
6380     IF X(I)<XMIN THEN XMIN=X(I)
6390     NEXT I
6400     RESTORE 6610:REM----------------------------------------------
6410     MSD=(YMAX-YMIN)/10:REM                  SCALE THE Y-AXIS
6420     FOR I=-2 TO 4
6430     FOR K=1 TO 3:READ J
6440     IF MSD<=J*10^(I) THEN MSD=J*10^(I):GOTO 6460
6450     NEXT K:RESTORE 6610:NEXT I
6460     FOR I=10 TO -10 STEP -1
6470     IF (YMAX<=I*MSD)*(YMAX>I*MSD-.99999*MSD) THEN YMAX=I*MSD
6480     NEXT I
6490     YMIN=YMAX-10*MSD
6500     RESTORE 6610:REM----------------------------------------------
6510     MSD=(XMAX-XMIN)/10:REM                  SCALE THE X-AXIS
6520     FOR I=-2 TO 4
6530     FOR K=1 TO 3:READ J
6540     IF MSD<=J*10^I THEN MSD=J*10^I:GOTO 6560
6550     NEXT K:RESTORE 6610:NEXT I
6560     FOR I=10 TO -10 STEP -1
6570     IF (XMAX<=I*MSD)*(XMAX>I*MSD-.99999*MSD) THEN XMAX=I*MSD
6580     NEXT I
6590     XMIN=XMAX-10*MSD
6600     RETURN
6610     DATA 1,2,5:REM                     CHANGE THIS DATA LINE IF
6750 REM
6760 REM****************************************************************
6770 REM*          LIST OF VARIABLE NAMES USED IN THE PROGRAM          *
6780 REM****************************************************************
6790 REM
6800 REM          Y(I)                     Y AXIS DATA ARRAY
6810 REM          X(I)                     X AXIS DATA ARRAY
6820 REM          YMAX                     MAXIMUM VALUE OF Y AXIS
6830 REM          YMIN                     MINIMUM VALUE OF Y AXIS
6840 REM          XMAX                     MAXIMUM VALUE OF X AXIS
6850 REM          XMIN                     MINIMUM VALUE OF X AXIS
6860 REM          LNNO                     Y AXIS LINE NUMBER
6870 REM          RSTOP                    CHARACTER TAB STOP
6880 REM          LSPACE                   PRINTER LINEFEED IN N/72 INCH
6890 REM          YN                       NORMALIZED Y AXIS VALUE
6900 REM          YD                       DELTA VALUE EACH Y AXIS LINE
6910 REM          MSD                      MINIMUM SCALE DELTA
6920 REM          J                        SCALE DELTA
```

```
6930 REM          K                        INDEX COUNTER
6940 REM          I                        INDEX COUNTER
6950 REM          P$                       PLOT TITLE
6960 REM          PTITLE$                  CENTERED PLOT TITLE STRING
6970 REM          Y$                       Y AXIS TITLE
6980 REM          YTITLE$                  CENTERED Y-AXIS TITLE STRING
6990 REM          X$                       X AXIS TITLE
7000 REM          XTITLE$                  CENTERED X-AXIS TITLE STRING
7010 REM          CHAR$                    CHARACTER PRINTED AT RSTOP
7030 REM          N$                       INPUT VARIABLE FOR SCALING
7060 REM          I,J,K,L,&M               ;       PLOT OF DATA
9510 REM*                                                              *
```