National Bureau of Standards

NBS Technical Note 962

Contact Deformation In Gage Block Comparisons

John S. Beers and James E. Taylor

Issued May 1978

Contact Deformation in Gage Block Comparisons

John S. Beers & James E. Taylor

National Engineering Laboratory
National Bureau of Standards
Washington, D.C. 20234

U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, Secretary

Dr. Sidney Harman, Under Secretary

Jordan J. Baruch, Assistant Secretary for Science and Technology

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

Issued May 1978

National Bureau of Standards Technical Note 962
Nat. Bur. Stand. (U.S.) Tech. Note 962, 46 pages (May 1978)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1978

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
Price Stock No. 003-003-
(Add 25 percent additional for other than U.S. mailing).

CONTENTS

CONTACT DEFORMATION IN GAGE BLOCK COMPARISONS

By John S. Beers and James E. Taylor

ABSTRACT

When calibrating gage blocks or when gaging objects with contact type comparators, local deformation occurs where the probe tip contacts the gaging surface. This deformation results in a measurement error only if the gage blocks or objects being compared are of different materials having different mechanical properties. This document presents formulas and nomographs for determining deformation magnitude, and instructions for applying deformation corrections. The formulas and nomographs are valid only for spherical probe tips. A method is given for evaluating tip geometry and it is recommended that non-spherical or flawed tips be replaced.

Key words: Calibration; comparator; deformation; gage blocks; length; metrology.

1. INTRODUCTION

This publication is intended as a practical guide to gage block deformation corrections.

Nearly all gage block length comparisons or length measurements of objects with gage blocks are made with contact type comparators where a probe tip contacts a surface under an applied force. Contact between spherical tip and plane surface results in local deformation of small but significant magnitude. If the gage blocks or objects are made of the same material, the measured length difference between them will be correct. If the materials are different, the length difference will be incorrect by the amount of deformation difference between the materials. In such cases, a deformation correction may be applied if its magnitude is significant to the measurement.

A set of nomographs is included in this publication with instructions for their use in determining deformation corrections for gage blocks and stylus tips of the most commonly used materials. The mathematical basis for the nomographs is discussed and numerical examples of deformation corrections are given.

The deformation formula and nomographs are valid only when probe tip geometry is nearly perfect (spherical). Periodic tip inspection is, therefore, recommended to maintain reliability of the deformation corrections.

2. MATHEMATICAL BASIS FOR DEFORMATION CALCULATIONS

Total deformation (probe plus object) is a function of contact force, geometry and elastic properties of the two contacting surfaces. Hertz [1] developed formulas for total uniaxial deformation based on the theory of elasticity and by assuming that the bodies are isotropic, that there is no tangential force at contact, and that the elastic limit is not exceeded in the contact area.

Many experimenters have verified the reliability of the Hertzian formulas. For example, Nichols and Oakley [2] conducted experiments on relatively soft materials with ordinary engineering surface finishes and relatively large contact forces. Bowman [3] experimented with the hard materials, optical quality surface finishes and probe forces typical of gage block comparisons and found the equations valid.

For a spherical probe tip and a flat object surface, Nichols and Oakley give the following form of the Hertz equation:

$$D = 327600 \left[\frac{P^2}{R} (A_1 + A_2)^2 \right]^{1/3} \qquad (1)$$

where D is total uniaxial deformation of the probe and object surface in microinches, P is the applied contact force in pounds, and R is the unloaded probe tip radius in inches. A is an elastic constant (subscript 1 referring to the probe tip and 2, the object) given by:

$$A = \frac{3K + 4N}{(K+N)N}$$

where K is the bulk modulus and N the modulus of rigidity. K and N are calculated from published data on Young's Modulus, Y, and Poisson's Ratio, μ [4].

$$K = \frac{Y}{3(1-2\mu)}$$

$$N = \frac{Y}{2(1+\mu)}$$

Nomographs in this publication are computed using the above formulas and data sources.

3. MEASUREMENT OF PROBE FORCE AND TIP RADIUS

Reliability of computed deformation values depends on careful measurement of probe force and, especially, of probe tip radius. Probe force is easily measured with a force gage (or a double pan balance and a set of weights), reading the force when the probe indicator meter is at midscale on the highest magnification range.

Probe tip inspection and radius measurement are critical. If the tip geometry is flawed in any way it will not follow the Hertz predictions. Tips having cracks, flat spots, chips, or ellipticity should be replaced and regular tip inspection must be made to insure reliability.

An interference microscope employing multiple beam interferometry is the inspection and measurement method used at NBS [5]. In this instrument an optical flat is brought close to the tip, normal to the probe axis, and monochromatic illumination produces a Newton Ring fringe pattern which is magnified through the microscope lens system. The multiple beam aspect of this instrument is produced by special optical components and results in very sharp interference fringes which reveal fine details in topography.

Figures 1 through 3 are multiple beam interference micrographs of diamond probe tips. The fringe patterns are a "contour map" of the tip so that all points on a given ring are equidistant from the reference optical flat. This can be expressed mathematically as

$$N\lambda = 2t \qquad (2)$$

where N is the number (order) of the fringe, counting from the center, λ is the wavelength of the light and t is the distance of the ring from the optical flat. The zero order fringe at the center is where the probe tip is in light contact with the optical flat and t is nearly zero. This relationship is used to calculate the tip radius.

Tip condition is readily observed from the micrographs. In Figure 1 a crack is seen in the tip as well as some ellipticity. Figure 2 shows a sharp edge at the tip center. An acceptable tip is shown in Figure 3.

Radius measurement of a good tip is relatively simple. Diameters of the first five rings are measured from the photograph along axes A and B, as in Figure 3. If there is a small amount of ellipticity (a large amount is unacceptable), A and B are selected as the major and minor axes. Then

$$r_n = \frac{d_n}{2\,M} \qquad (3)$$

where r_n is the actual radius of the nth Newton Ring, d_n is the ring average diameter (of A and B) measured on the micrograph, and M is the

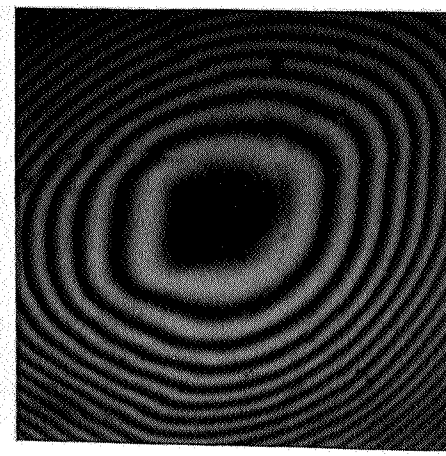


Figure 1. Interference micrograph showing a cracked tip.

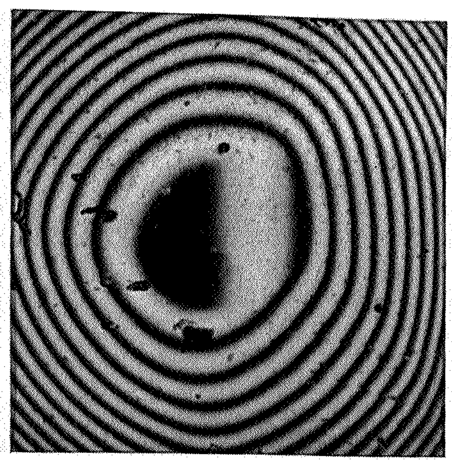


Figure 2. Interference micrograph showing lack of sphericity and a sharp edge at tip center.

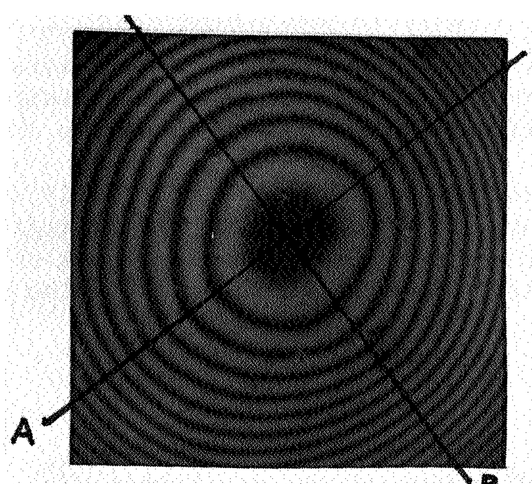


Figure 3. Interference micrograph of an acceptable tip.

microscope magnification. Substituting the ring diameter measurements in equation (3) will result in 5 radii r_1 through r_5 and from these a radius of curvature of the tip between consecutive rings is calculated:

$$R_1 = \frac{r_2^2 - r_1^2}{\lambda} \qquad (4)$$

$$R_2 = \frac{r_3^2 - r_2^2}{\lambda} \qquad (5)$$

$$R_3 = \frac{r_4^2 - r_3^2}{\lambda} \qquad (6)$$

$$R_4 = \frac{r_5^2 - r_4^2}{\lambda} \qquad (7)$$

Use the average of these four values as the tip radius.

The preceding measured and calculated values will also serve to evaluate tip sphericity. If the average difference between the five A and B ring diameters exceeds 10 percent of the average ring diameter, there is significant lack of sphericity in the tip. Also, if the total spread among the four tip radius value (R_1 through R_4) exceeds 10 percent of the average R there is significant lack of sphericity. These tests check sphericity around two axes so it is important that a tip meet both requirements or it will not follow the Hertz predictions.

4. THE COMPARATIVE PRINCIPLE

A comparator is a device for measuring differences. An electro-mechanical gage block comparator has a linear variable differential transformer as a length transducer and is capable of measuring only small length differences between gage blocks at high resolution. The length of an unknown is determined by measuring the difference between it and a reference block of the same nominal size and then calculating the length of the unknown. Let L_c equal the comparator length when its indicator reads zero (the zero may be at the left end or the center of the scale). Then, by inserting the two blocks of length L_x (unknown) and L_r (reference) and reading numerical values x and r from the comparator scale, we get

$$L_x = L_c + x$$

and

$$L_r = L_c + r$$

Solving these equations for L_x:

$$L_x = L_r + (x-r) . \tag{8}$$

Note that quantity (x-r) is the difference between the two blocks. We can now add a quantity, δ, to each comparator reading to compensate for deformation and equation (8) becomes

$$L_x = L_r + (x + \delta_x) - (r + \delta_r)$$

$$= L_r + (x - r) + (\delta_x - \delta_r).$$

The quantity $(\delta_x - \delta_r)$ in this equation is the deformation correction, C_p, therefore, the equation now becomes

$$L_x = L_r + (x-r) + C_p . \tag{9}$$

The deformation correction can be determined from the nomographs as will be explained in the next section. If the two blocks being compared are of the same material, C_p, of course, is zero.

5. USING THE NOMOGRAPHS

The nomographs are grouped in catagories according to material, force, U.S. customary units, and metric units. Use the table of contents to locate the desired graph. The 52100 steel hardened to Rockwell C65 is typical gage block material. Cervit is a trade name for a glass-ceramic having a thermal expansion coefficient near zero.

Once probe force and tip radius are known, total uniaxial deformation is found on the nomograph for the desired tip and gage block materials. Adjust a straightedge on the nomograph tip radius and probe force scales to the proper values and read the deformation scale where the straightedge intersects it.

For a single probe comparator find the total deformation for each of the two gage block materials being compared. Then the deformation correction is

$$C_p = \delta_x - \delta_r \tag{10}$$

where δ_x and δ_r are the total deformations for the test block and reference block respectively.

For a dual probe comparator the corrections for both upper and lower probes must be summed:

$$C_p = [C_p]_1 + [C_p]_2 = [\delta_x - \delta_r]_1 + [\delta_x - \delta_r]_2 \qquad (11)$$

where subscripts 1 and 2 refer to the upper and lower probes, respectively.

6. EXAMPLES

Example 1.

A single probe comparator is used to measure a 2 inch tungsten carbide gage block with a 2 inch steel reference standard gage block. From the following data find the length of the tungsten carbide block at 68 °F.

Stylus force: 4 ounces

Stylus tip material: diamond

Stylus tip radius: 0.25 inch

Length of steel reference block at 68 °F: 2.0000020 inch

Temperature of blocks: 68.05 °F

Expansion coefficients of blocks:

steel = 6.4×10^{-6}/°F

tungsten carbide = 2.5×10^{-6}/°F

Comparator reading on tungsten carbide block: 25.2 microinches

Comparator reading on reference block: 23.7 microinches

Solution: Determine the length, L_x, at 68 °F of the unknown from the relationship expressed in equation (9) modified by the addition of a temperature correction factor as follows:

$$L_x = L_r + (x-r) + C_p + C_t \qquad (12)$$

where L_r is the reference block length at 68 °F, x is the comparator reading on the reference block, r is the comparator reading on the unknown block, C_p is determined from equation (10) and C_t is the temperature correction.*

Then

$$L_x = 2.0000020 + (25.2-23.7)10^{-6} + (3.5-5.8)10^{-6}$$

$$+ (0.4)10^{-6} = 2.0000016 \text{ inches.}$$

---

*$C_t = N(t-68)K_r + N(68-t)K_x$ where N is nominal size, t is observed temperature and K_r and K_x are the thermal expansion coefficients of the reference block and unknown block respectively.

Example 2.

A dual probe comparator is used to measure a 0.5 inch steel block with a 0.5 inch chrome carbide reference block. From the following data find the length of the steel block at 68 °F.

Stylus force: 3 ounces upper, 1 ounce lower

Stylus tip material: diamond

Stylus tip radius: 0.125 inch

Length of chrome carbide reference block at 68 °F:

0.4999995 inch

Temperature of blocks: 68.25 °F

Expansion coefficients of blocks:

chrome carbide = 4.7×10^{-6}/°F

steel = 6.4×10^{-6}/°F

Comparator reading on steel block: 20.3 microinches

Comparator reading on chrome carbide block: 22.1 microinches

Solution: Using equation (12) and determining C_p from equation (11):

$$L_x = 0.4999995 + (20.3-22.1)10^{-6} + (6.0-4.6) + (2.9-2.2)\ 10^{-6}$$

$$+ (-0.2)10^{-6} = 0.49999966 \text{ inch.}$$

7. SUMMARY

Deformation corrections can be easily and accurately applied if the operative parameters of probe tip radius and probe force are known and if the probe tip is spherical and remains undamaged. It is noteworthy that with low force and large tip radius, deformation corrections become insignificant for some material combinations. Extremely low forces should be avoided, however, because poor contact is a risk. It is also important to know that thermal conditions, if ignored, can cause far greater errors than deformation, especially for long lengths.

ACKNOWLEDGEMENTS

The authors wish to thank F. Scire for making the micrographs, C. D. Tucker for supplying data and useful suggestions, and C. L. Carroll for nomograph programming assistance.

8. REFERENCES

[1] H. Hertz, J. Math (Crella's J) Vol. 92 (1881). Also H. Hertz, Gesammelte Werke, Vol. 1 pp. 155, Leipsig (1895).

[2] Nichols and Oakley, "The Influence of Measuring Force, Stylus Radius and Surface Finish on The Accuracy of Measurement of Work-Pieces by a Comparator", Proc. Instr. Mech. E., pp. 195 (1961).

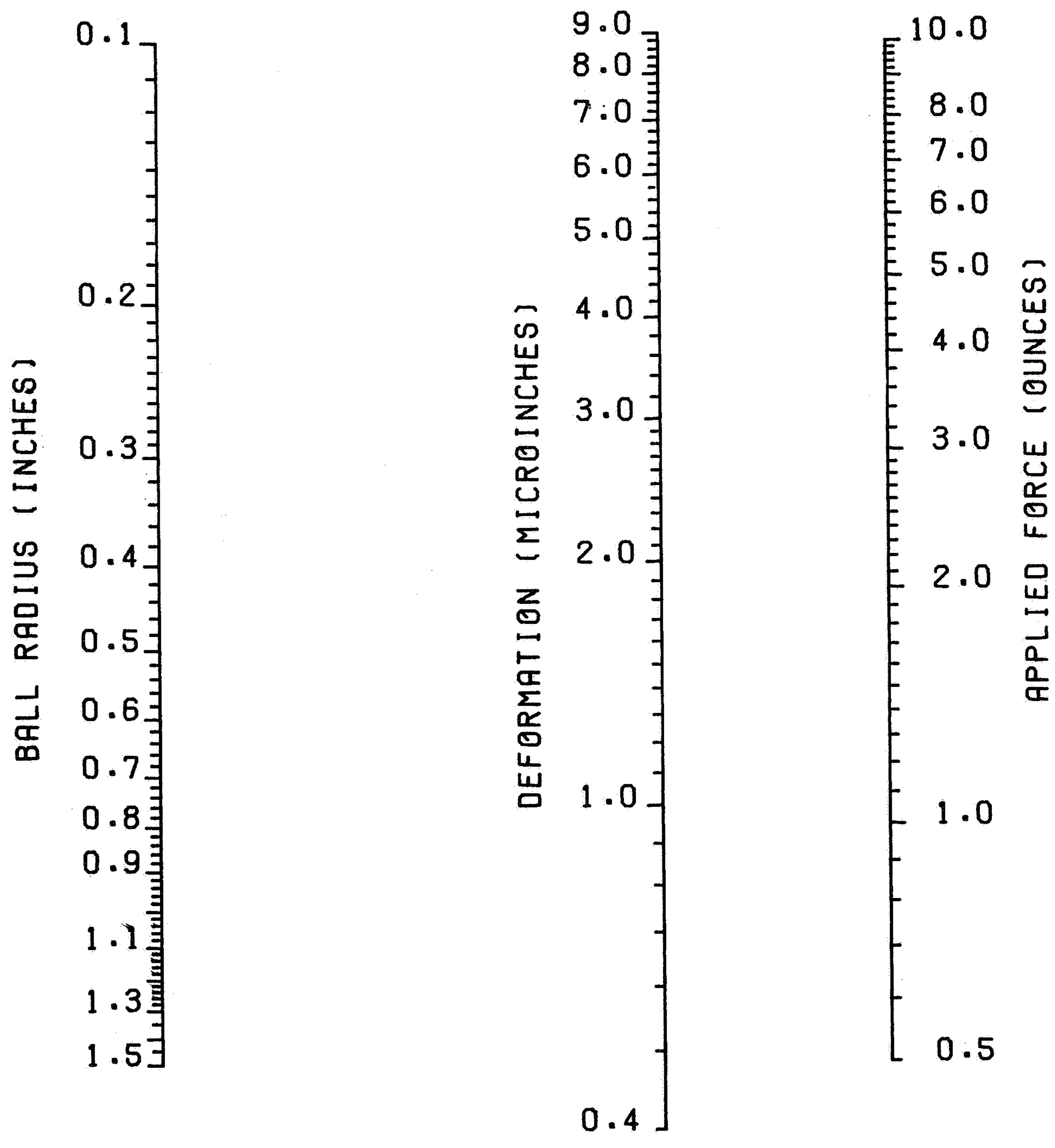
[3] Bowman, H. A., unpublished paper "Hertz Deformation Formula Applied to Gage Block Comparisons", (1975).

[4] "Applied Elasticity", Chi-Teh Wang, McGraw-Hill, New York (1953) pp. 30-31.

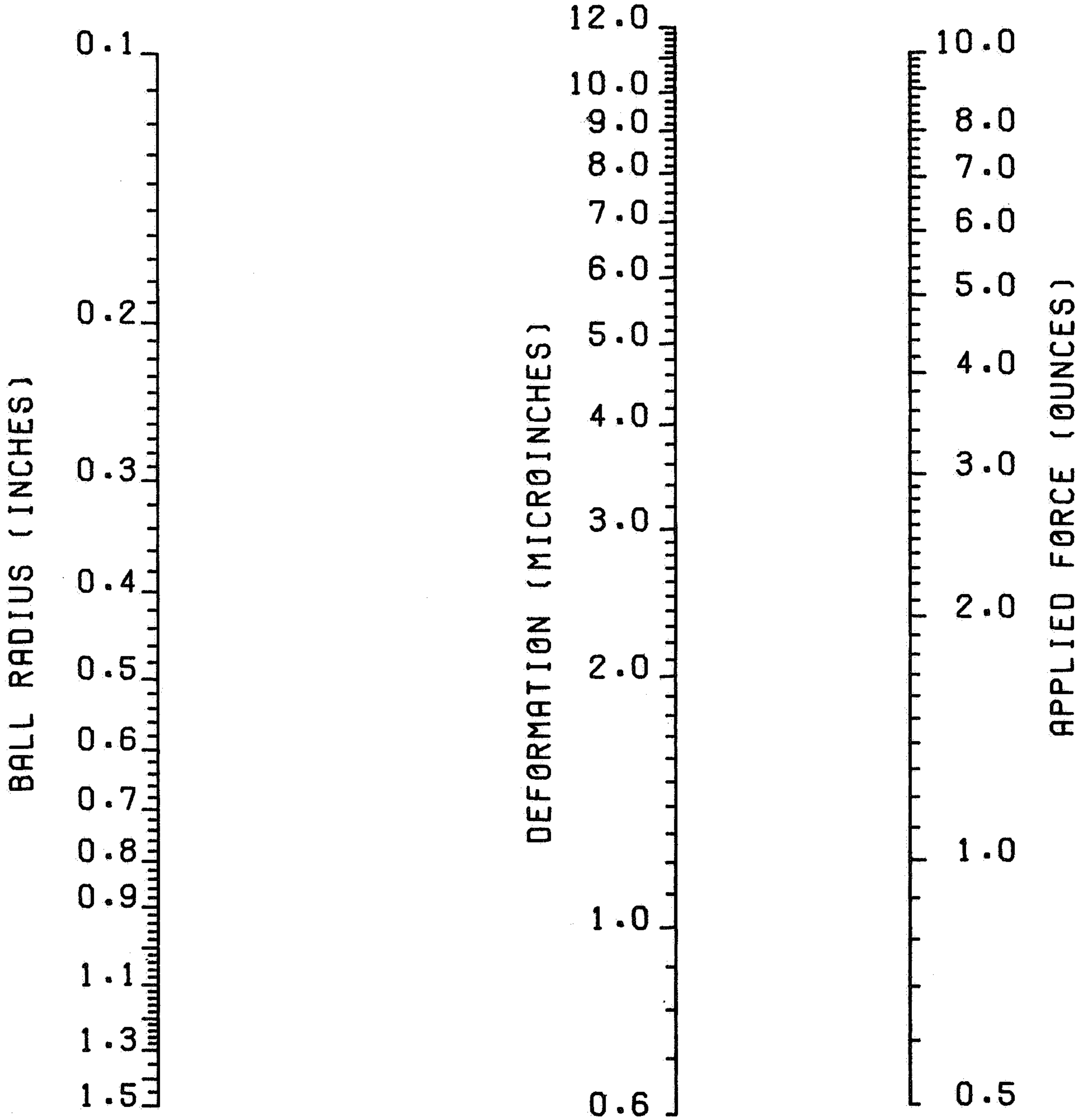
[5] "An Introduction to Interferometry", S. Tolansky, Longmans, Green and Co., London (1955).

9. NOMOGRAPH INDEX

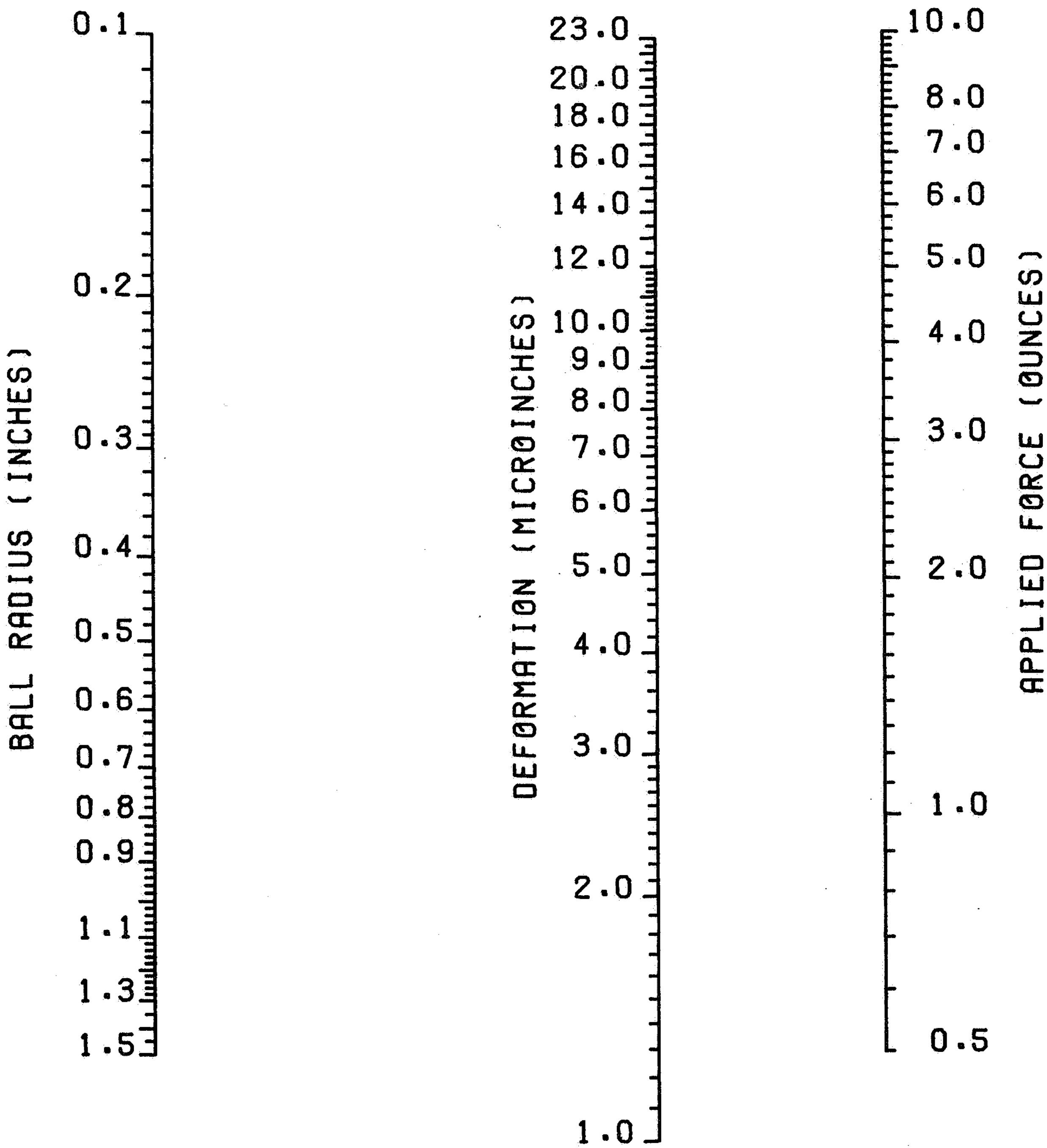
DEFØRMATIØN ØF BALL AND PLANE
DIAMØND VS. TUNGSTEN CARBIDE



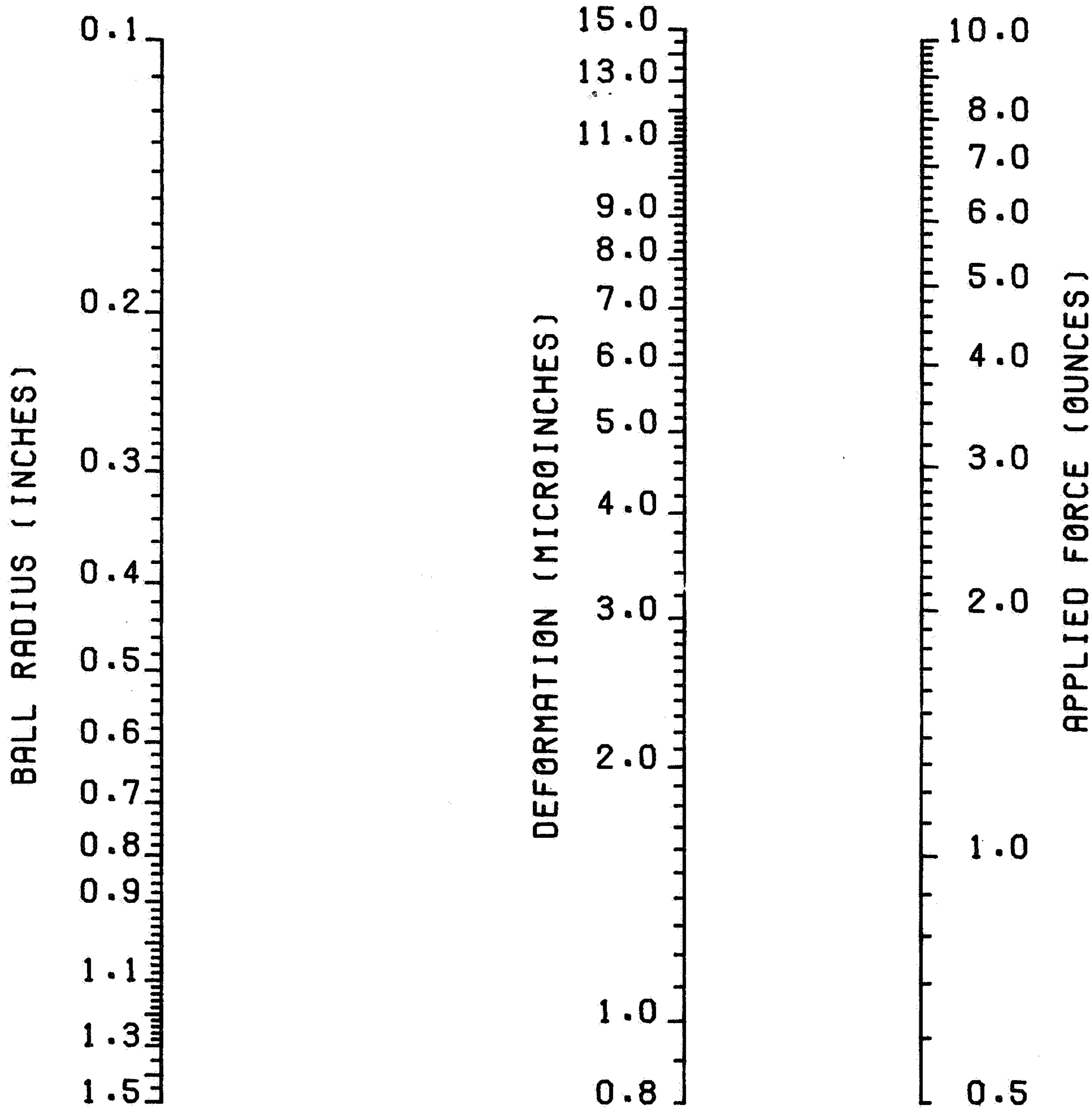
DEFORMATION OF BALL AND PLANE
DIAMOND VS. CHROME CARBIDE



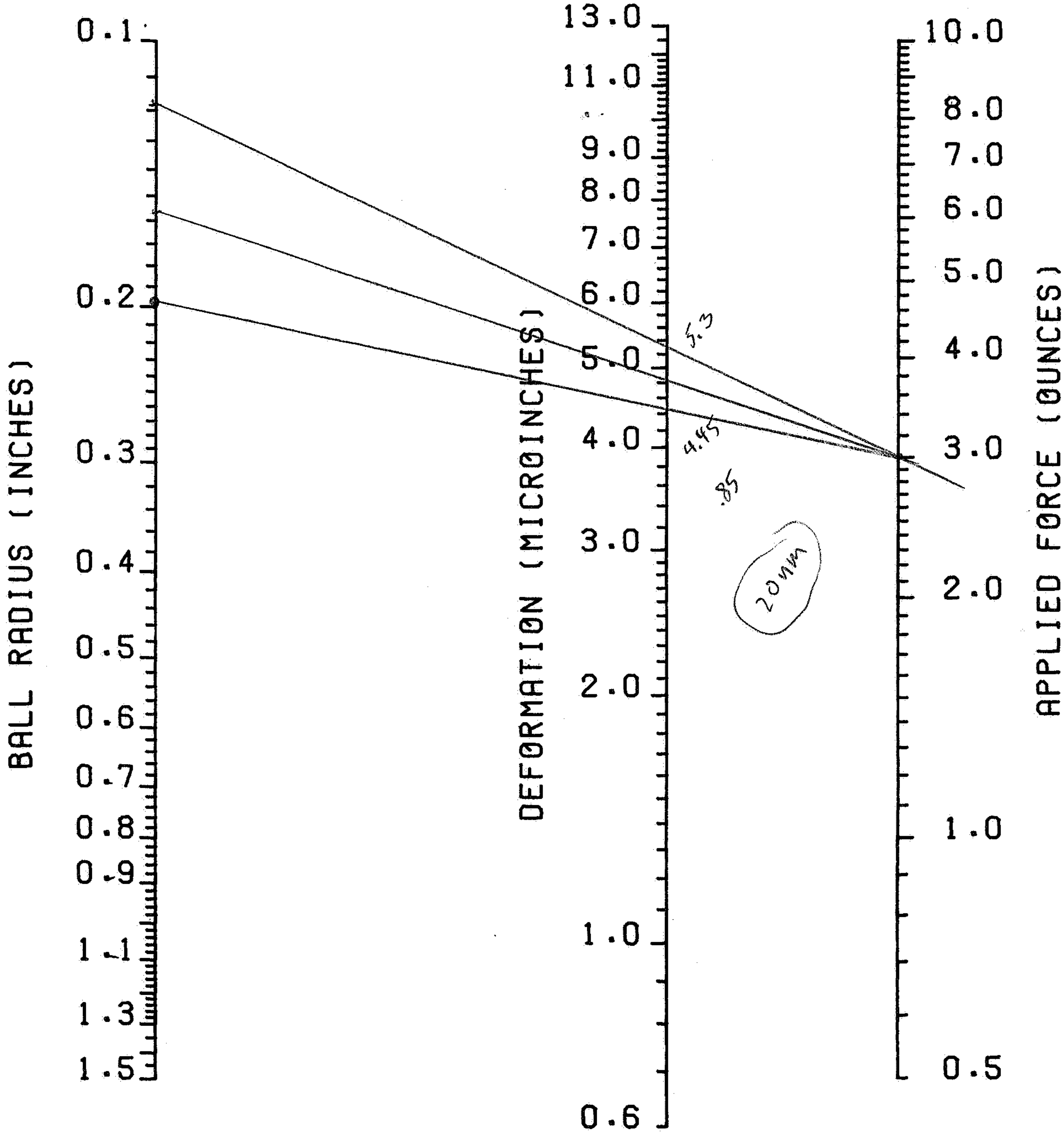
DEFØRMATIØN ØF BALL AND PLANE
DIAMØND VS. CERVIT



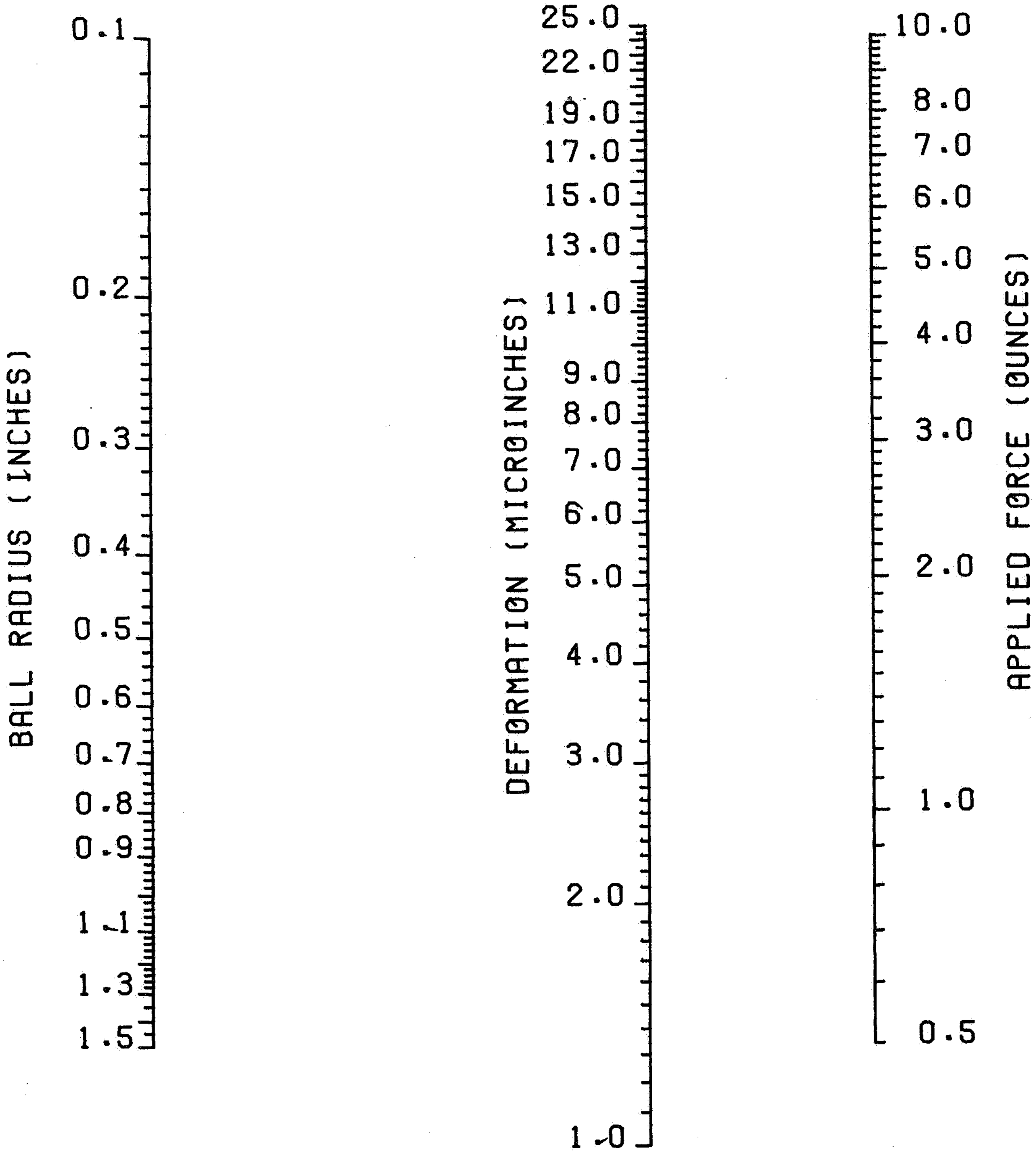
DEFORMATION OF BALL AND PLANE
DIAMOND VS. 52100 STEEL



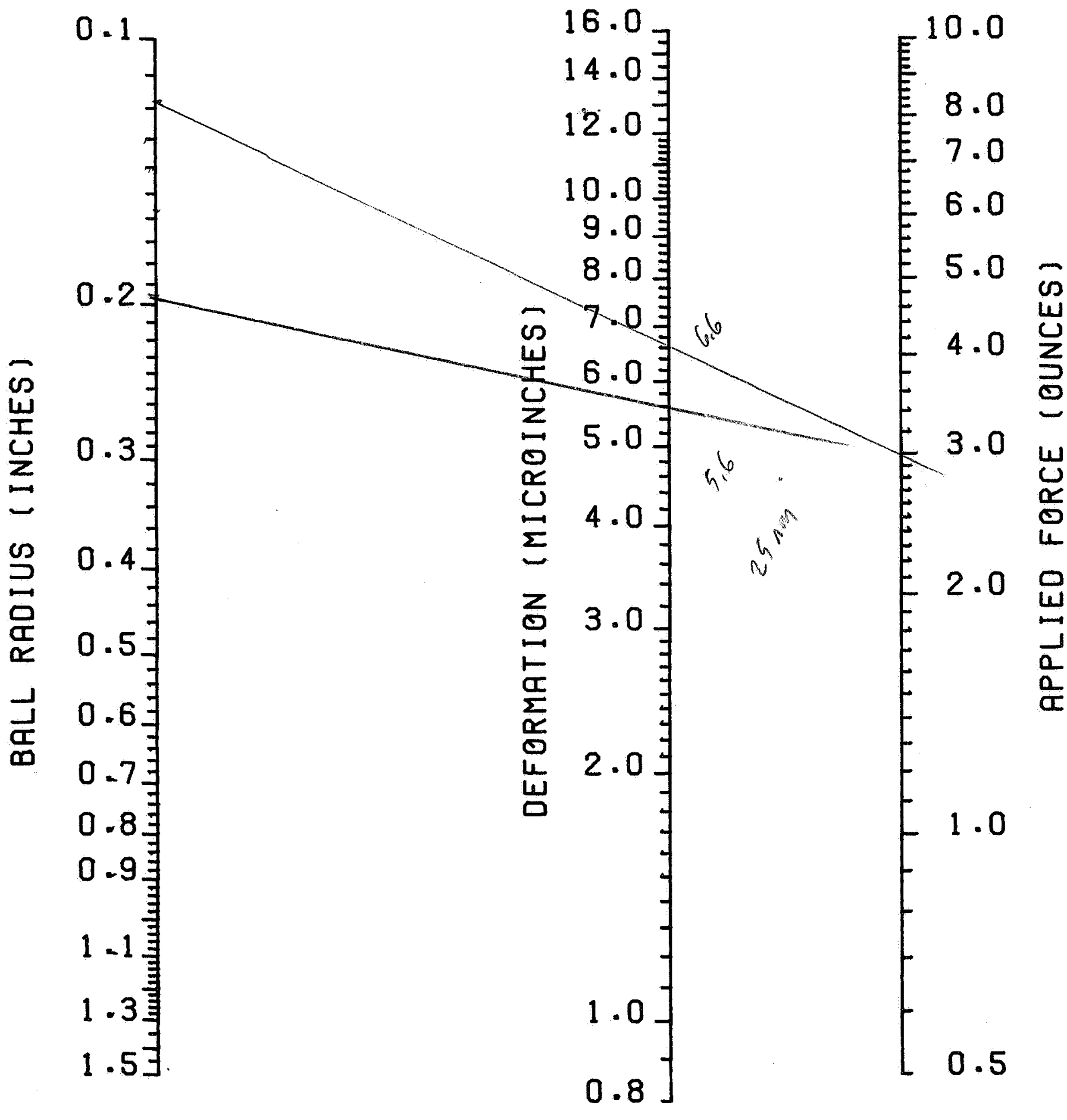
DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. CHROME CARBIDE



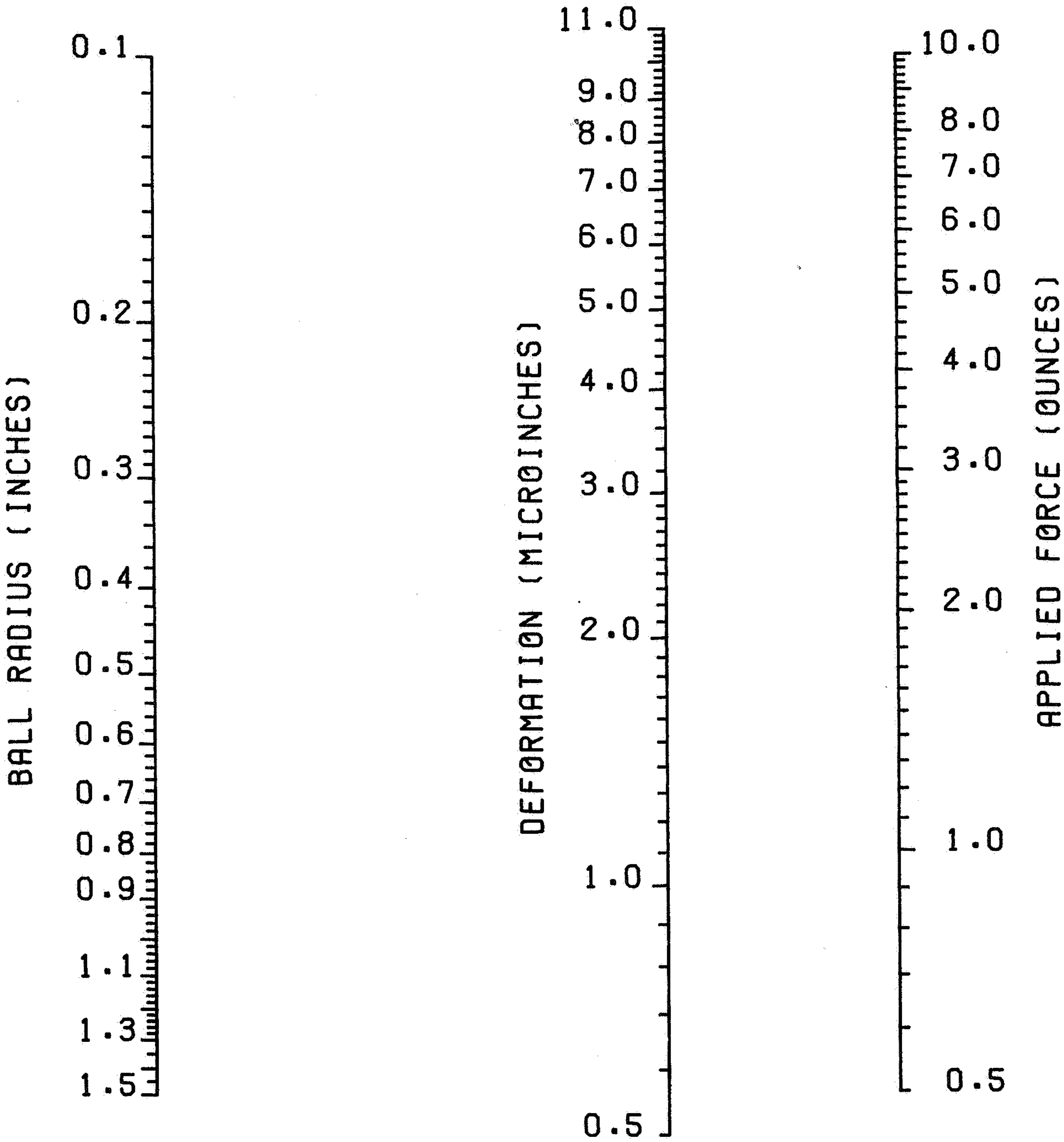
DEFØRMATIØN ØF BALL AND PLANE
TUNGSTEN CARBIDE VS. CERVIT



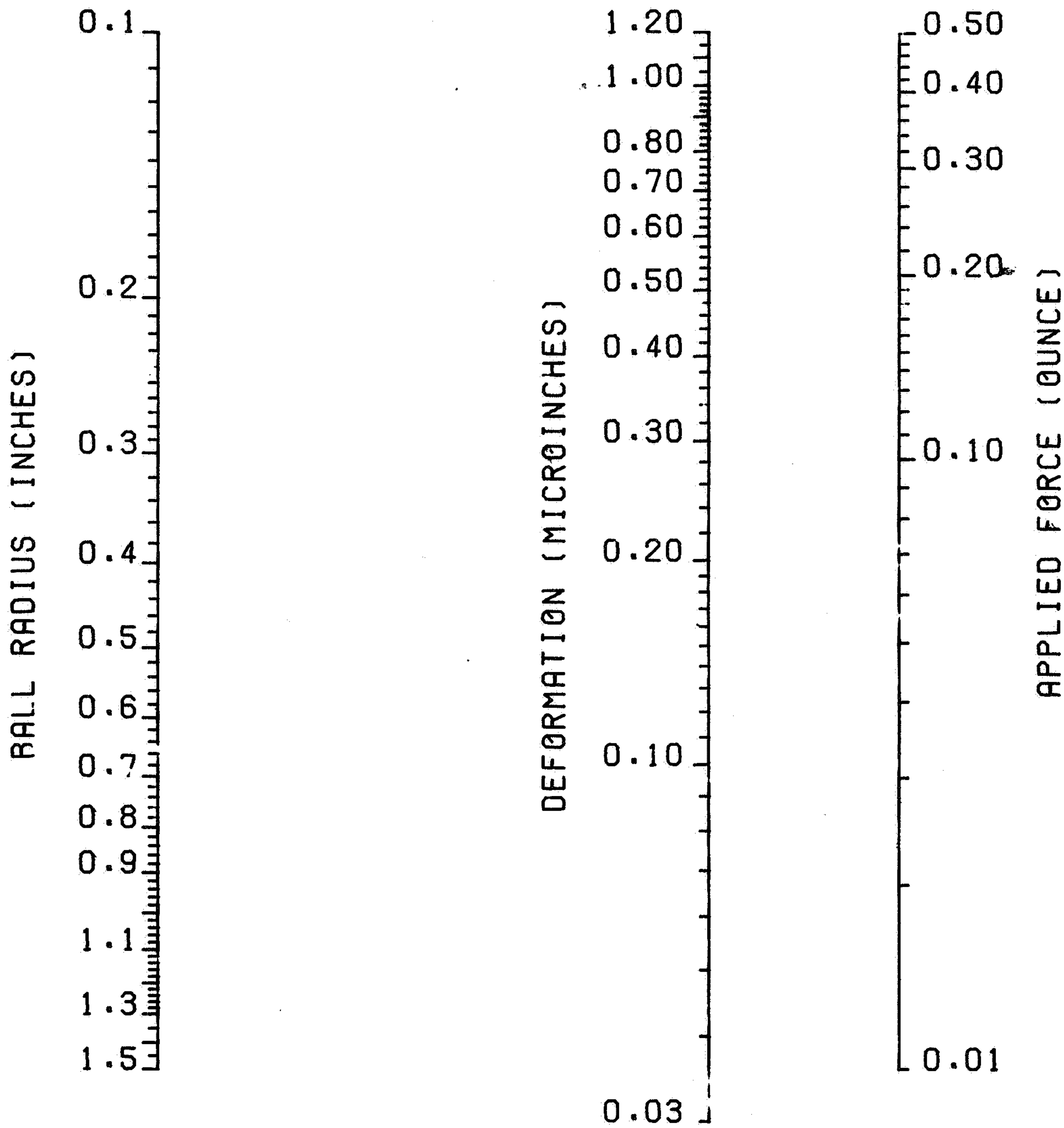
DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. 52100 STEEL



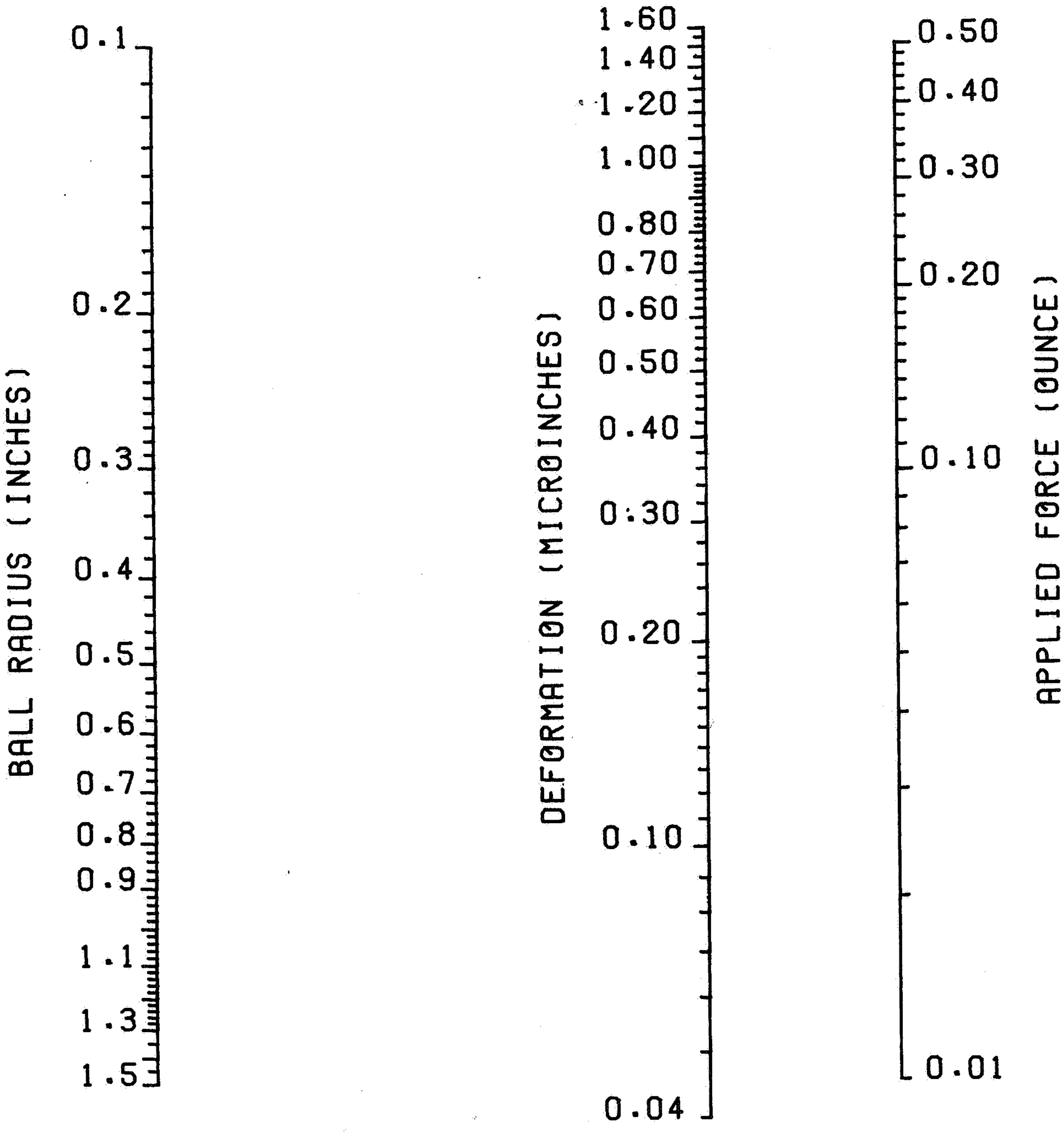
DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. TUNGSTEN CARBIDE



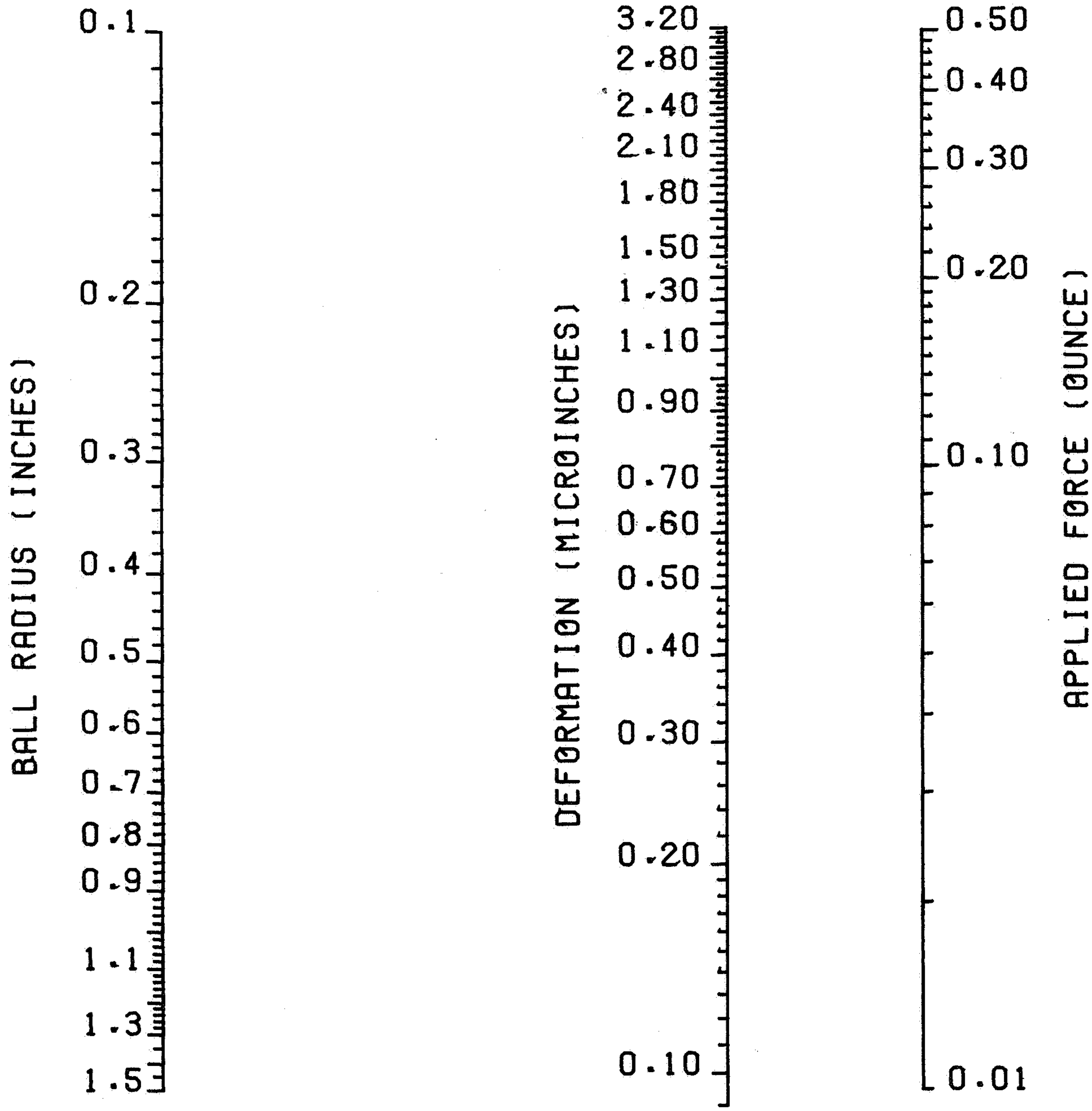
DEFØRMATIØN ØF BALL AND PLANE
DIAMØND VS. TUNGSTEN CARBIDE



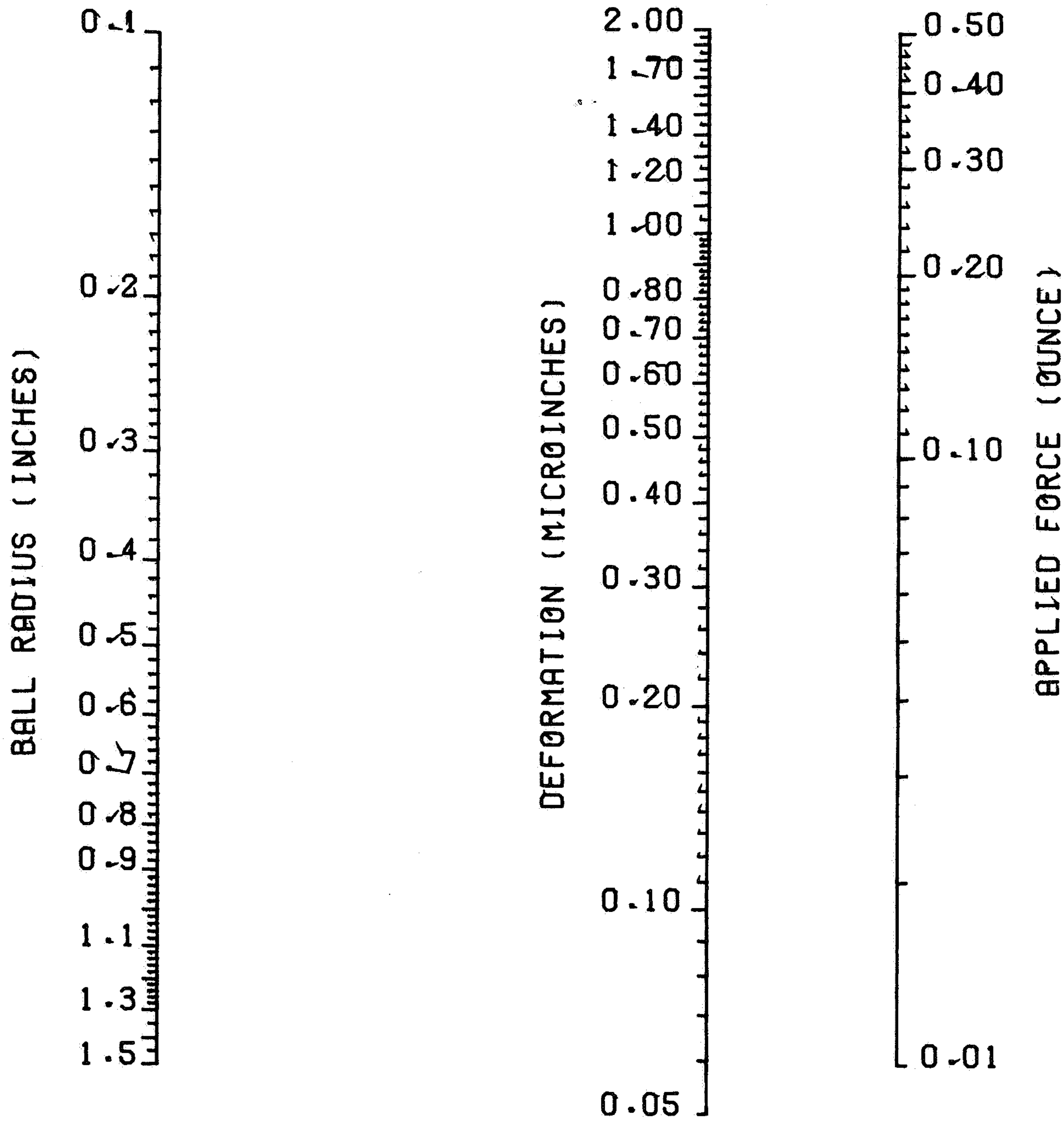
DEFORMATION OF BALL AND PLANE
DIAMOND VS. CHROME CARBIDE



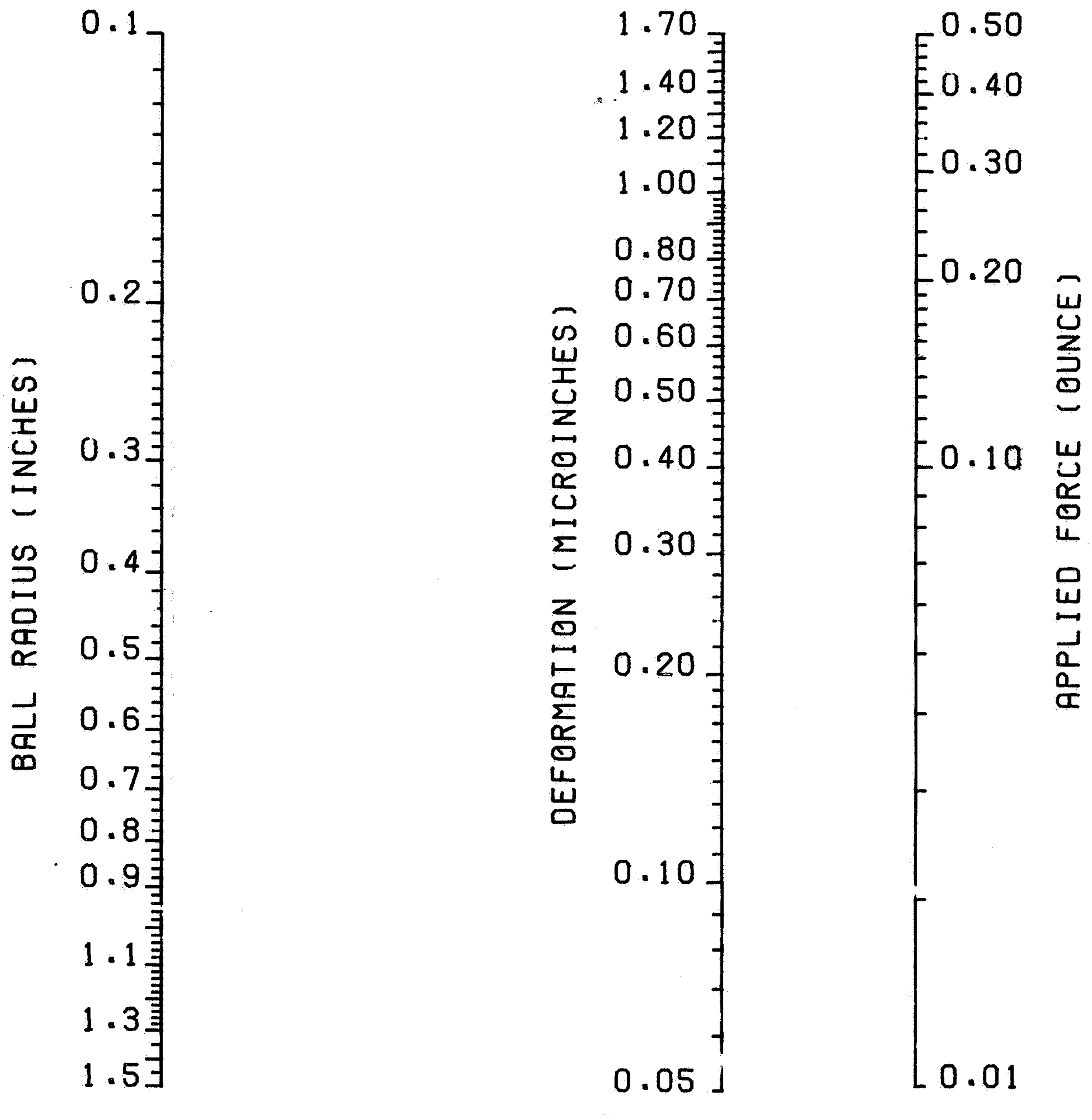
DEFØRMATIØN ØF BALL AND PLANE
DIAMØND VS. CERVIT



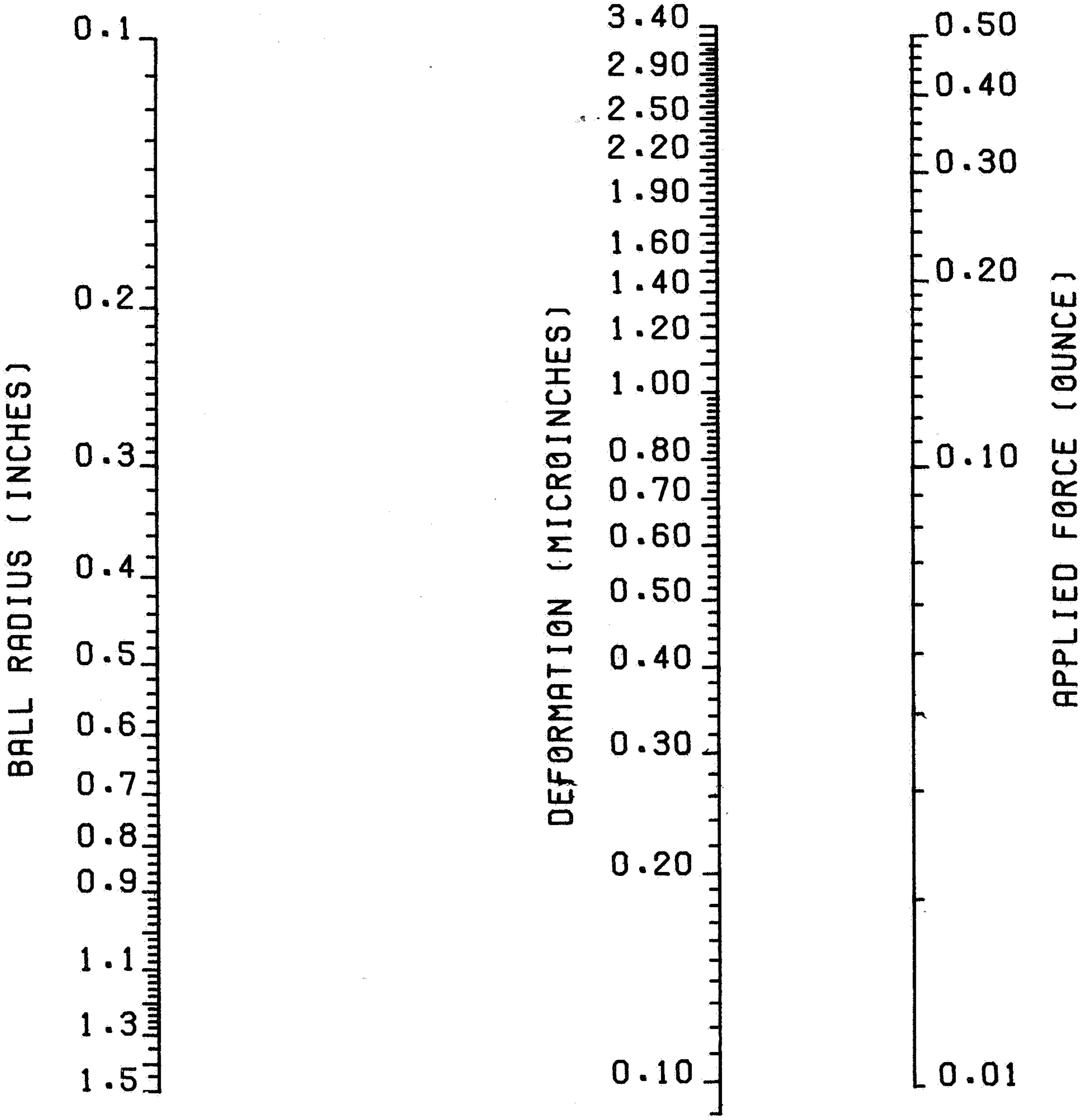
DEFORMATION OF BALL AND PLANE
DIAMOND VS. 52100 STEEL



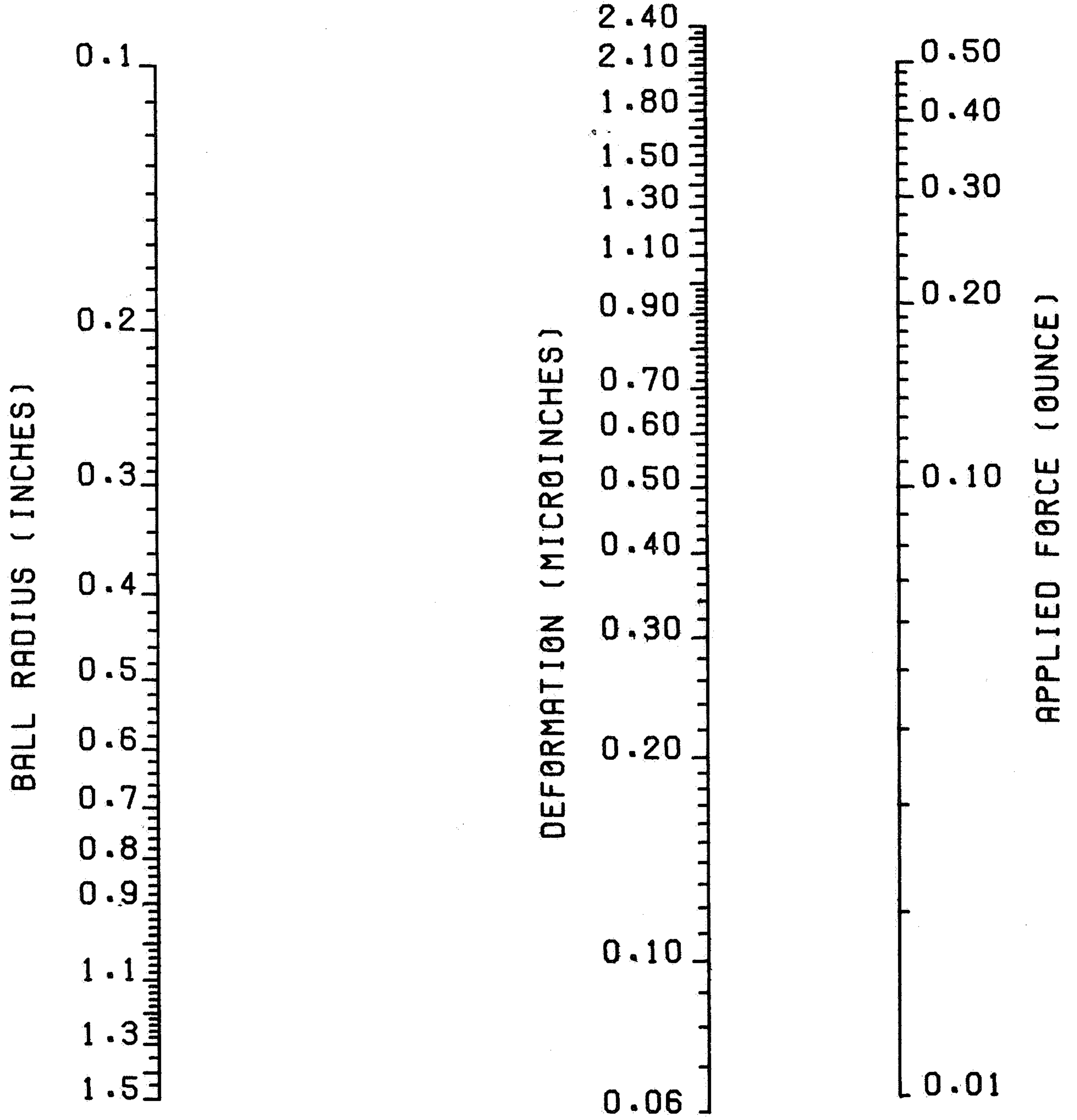
DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. CHROME CARBIDE



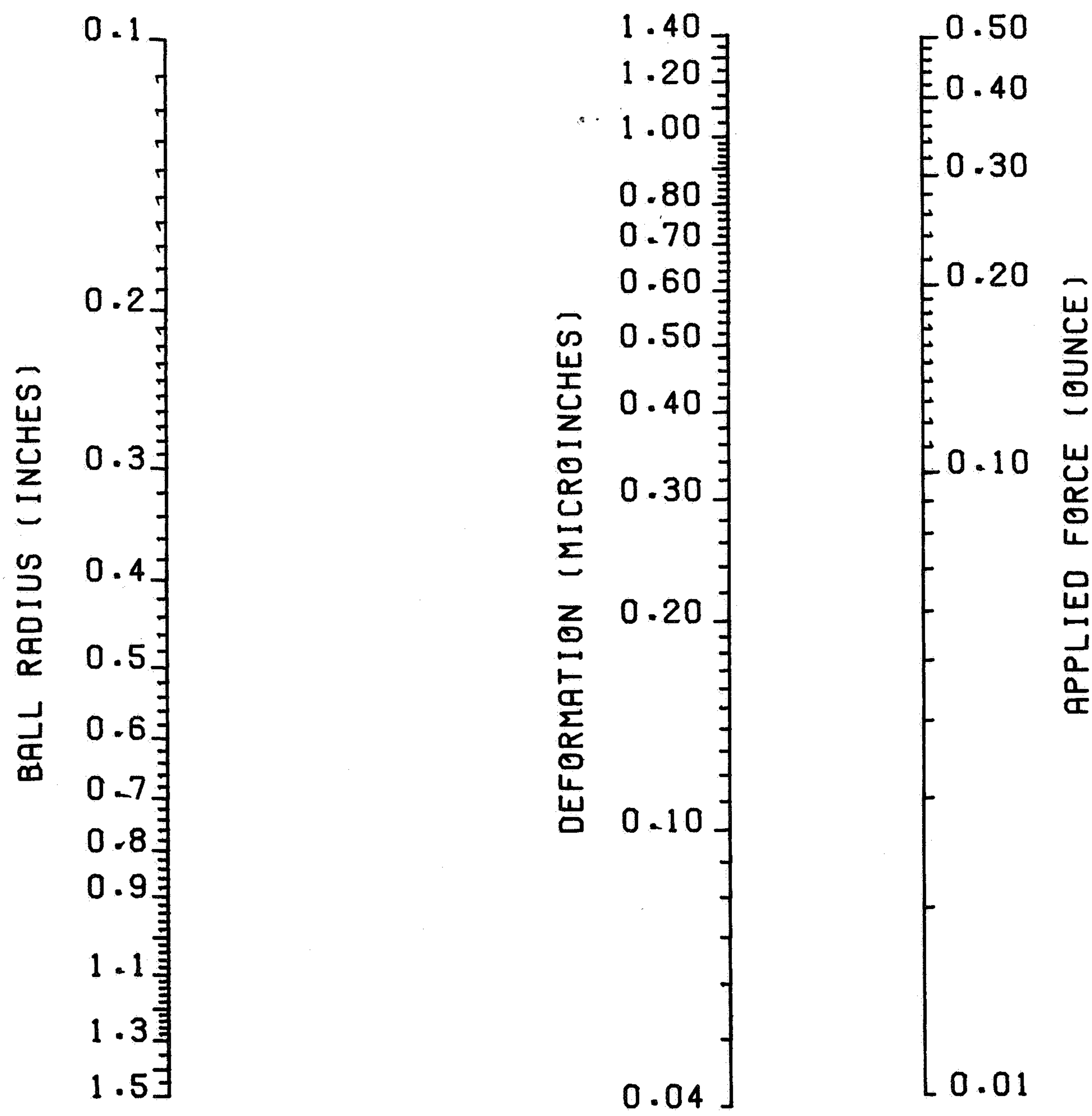
DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. CERVIT



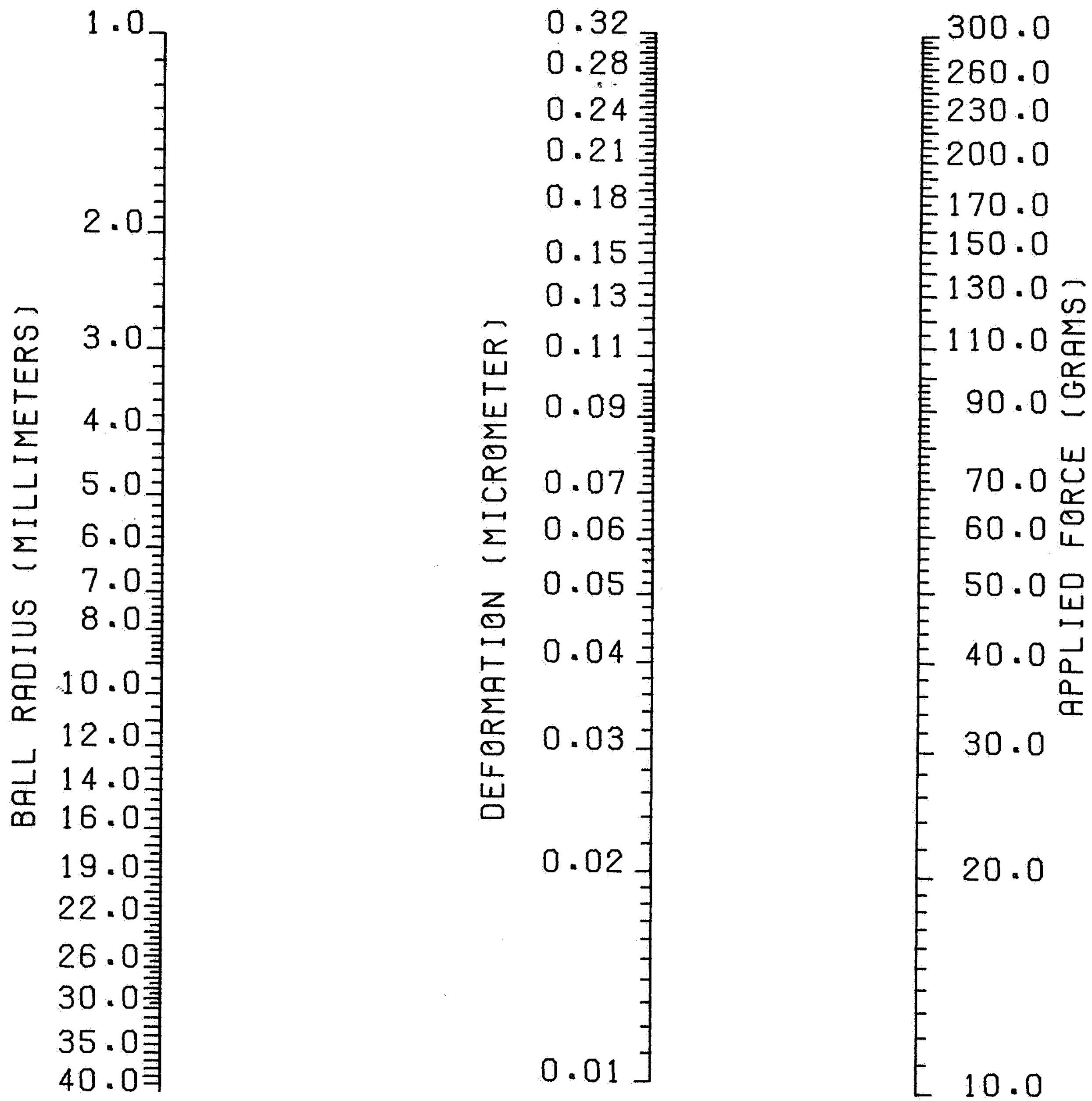
DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. 52100 STEEL



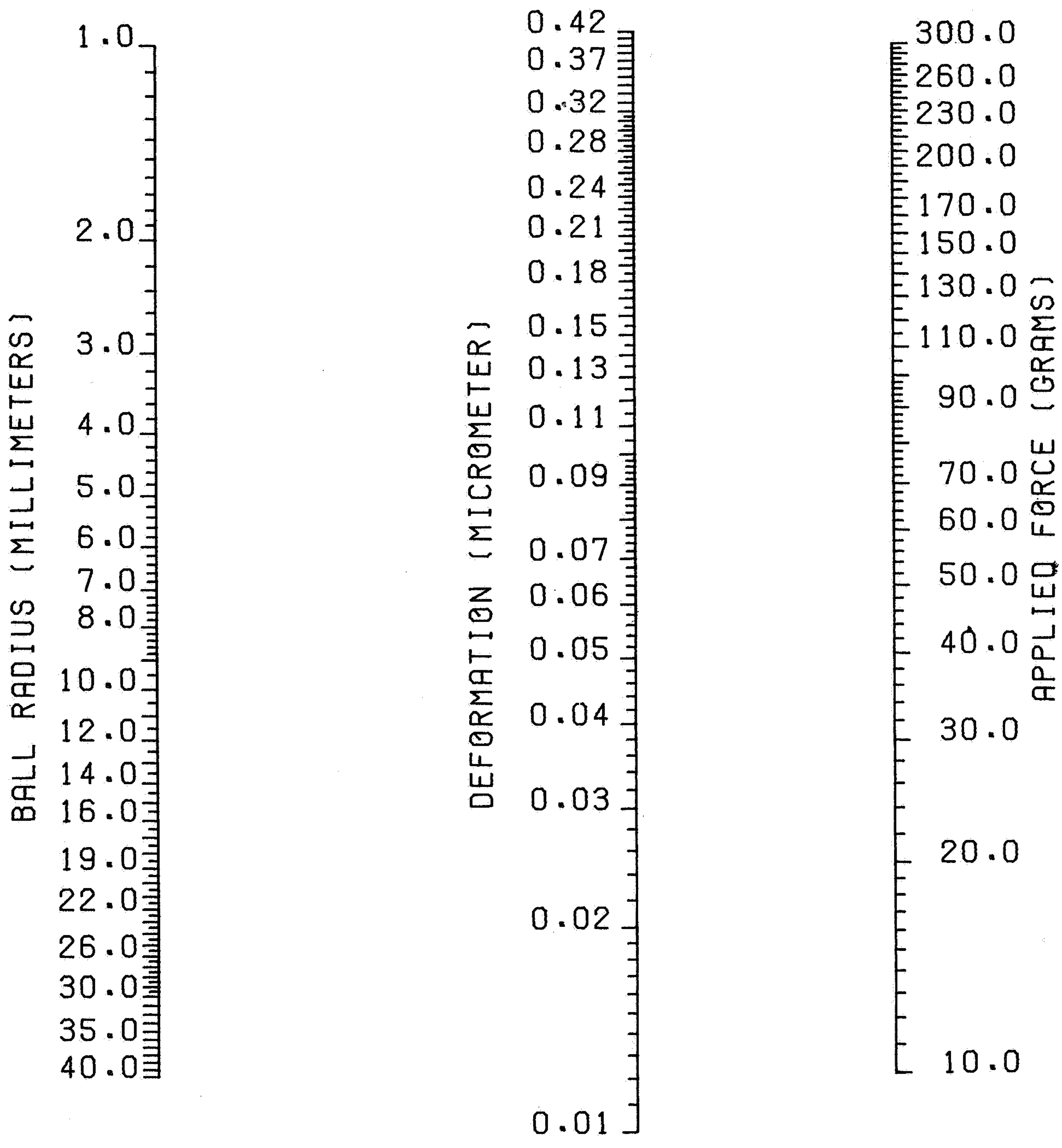
DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. TUNGSTEN CARBIDE



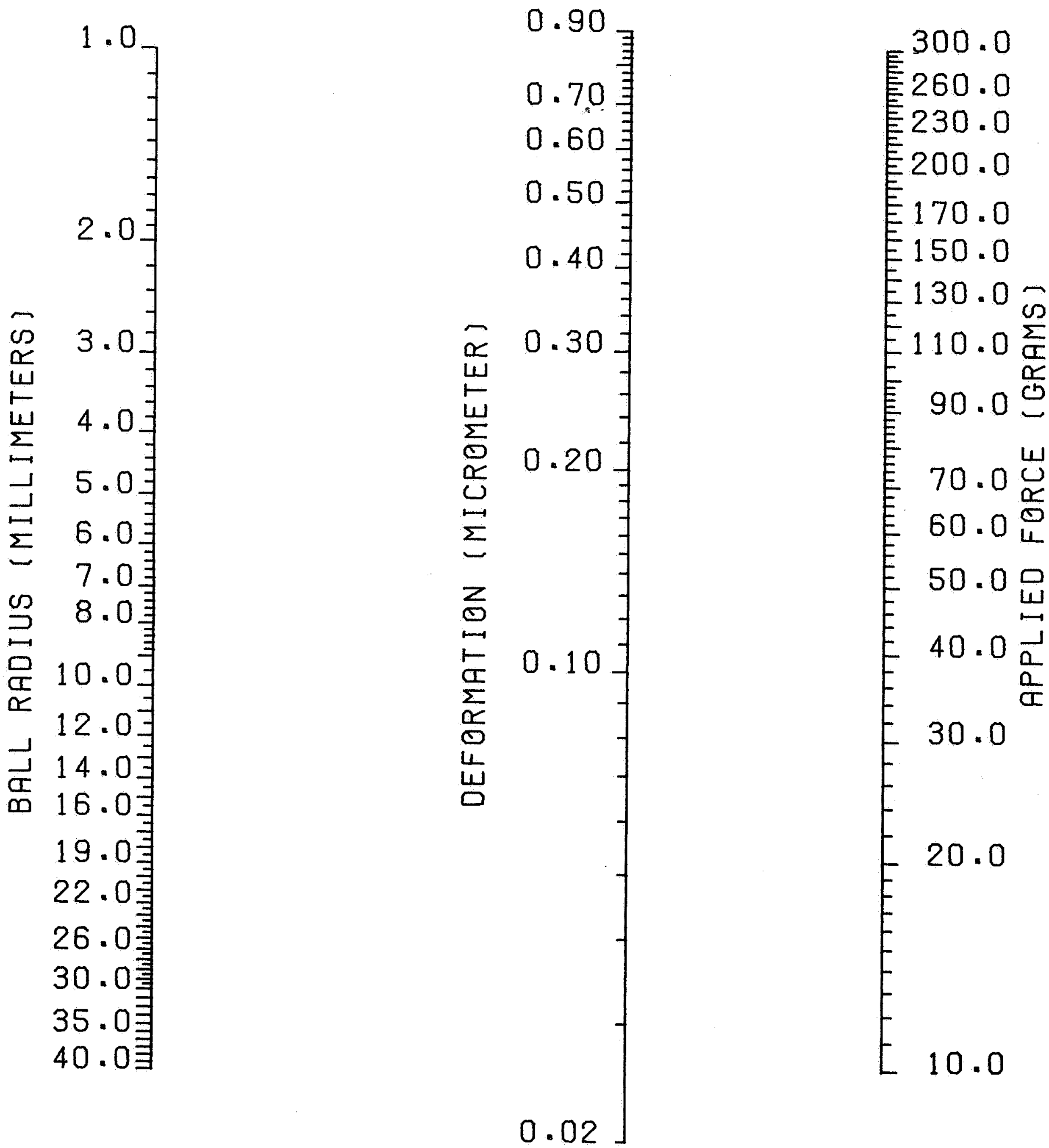
DEFORMATION OF BALL AND PLANE
DIAMOND VS. TUNGSTEN CARBIDE



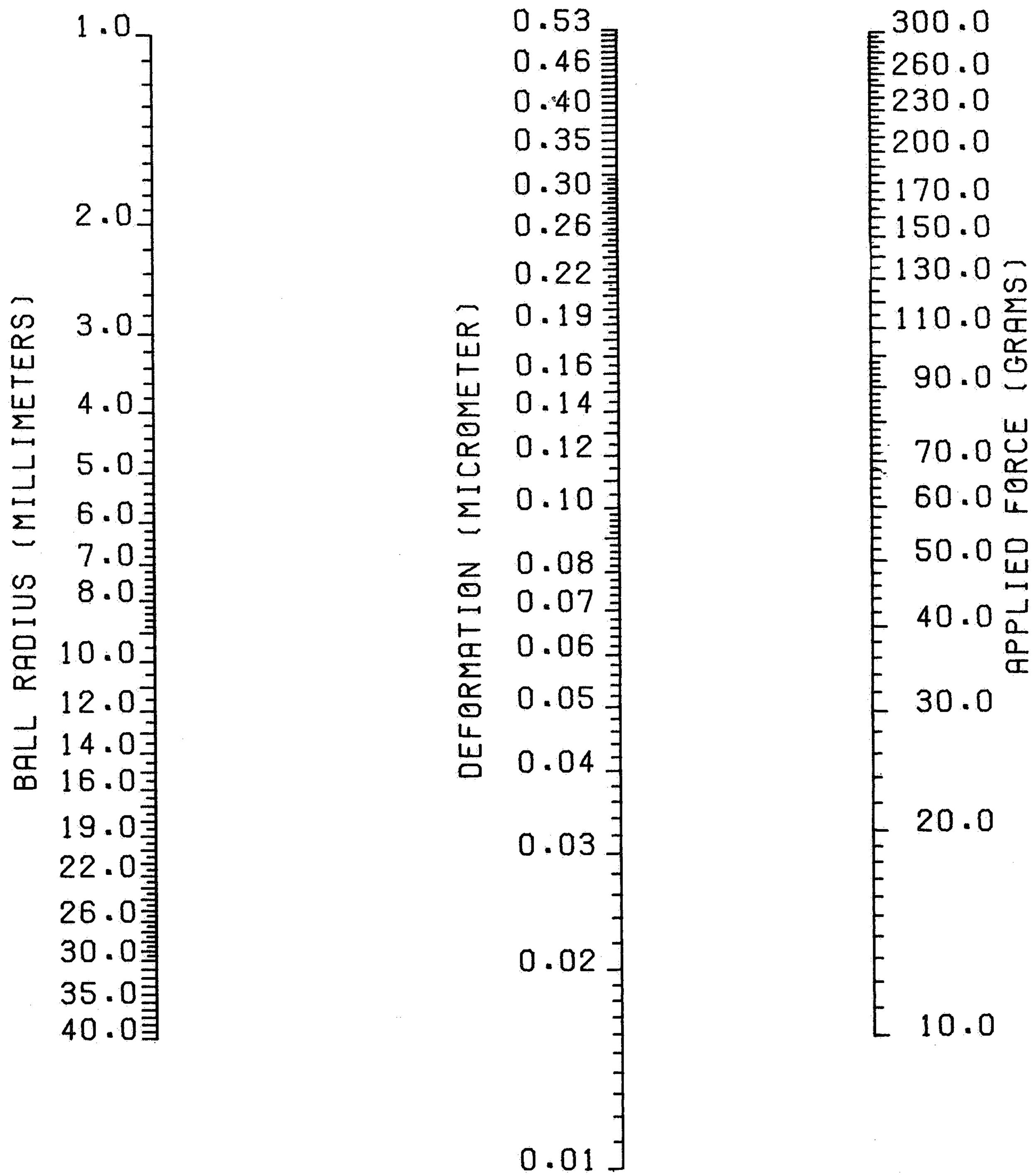
DEFØRMATIØN ØF BALL AND PLANE
DIAMØND VS. CHRØME CARBIDE



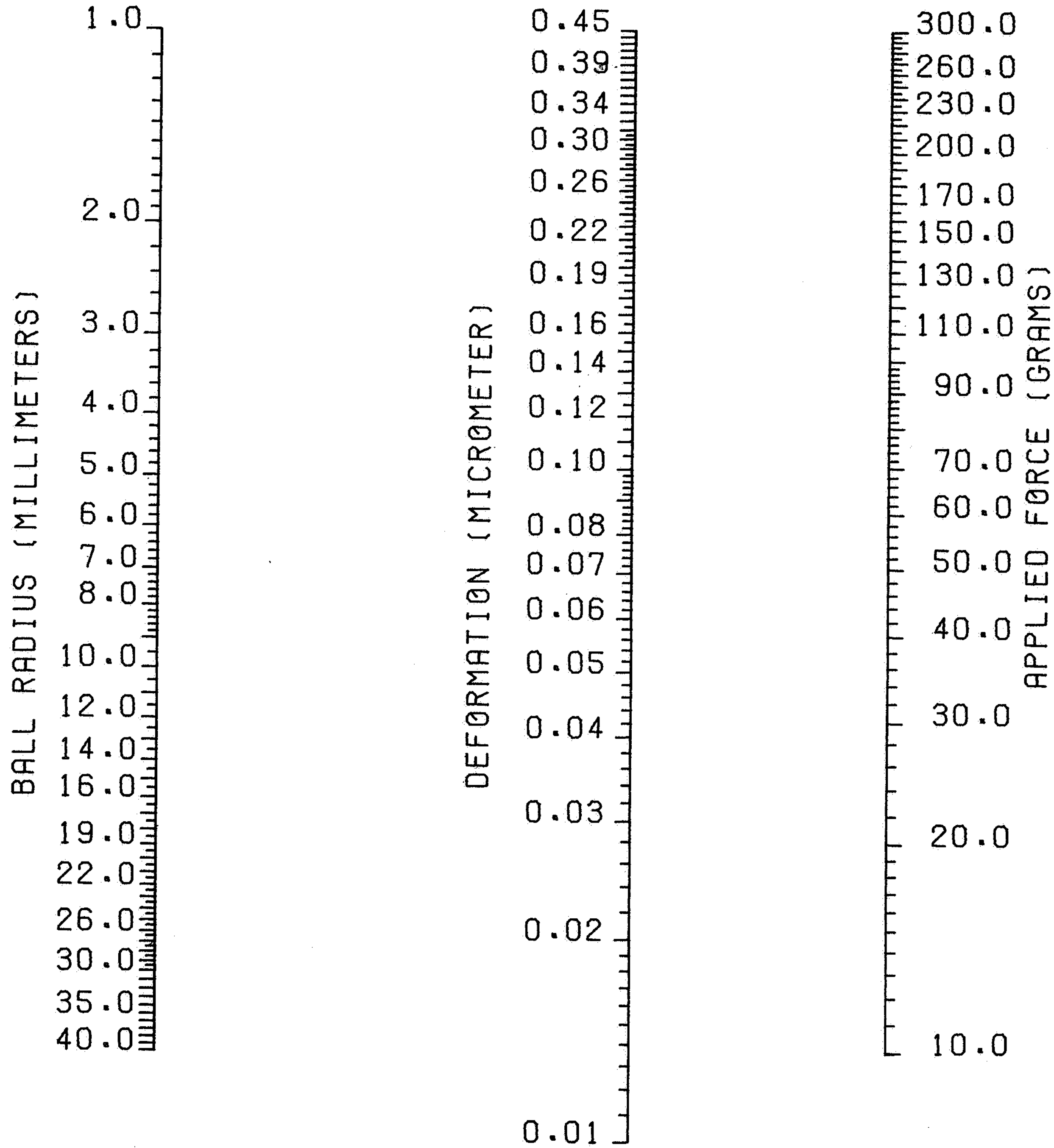
DEFORMATION OF BALL AND PLANE
DIAMOND VS. CERVIT



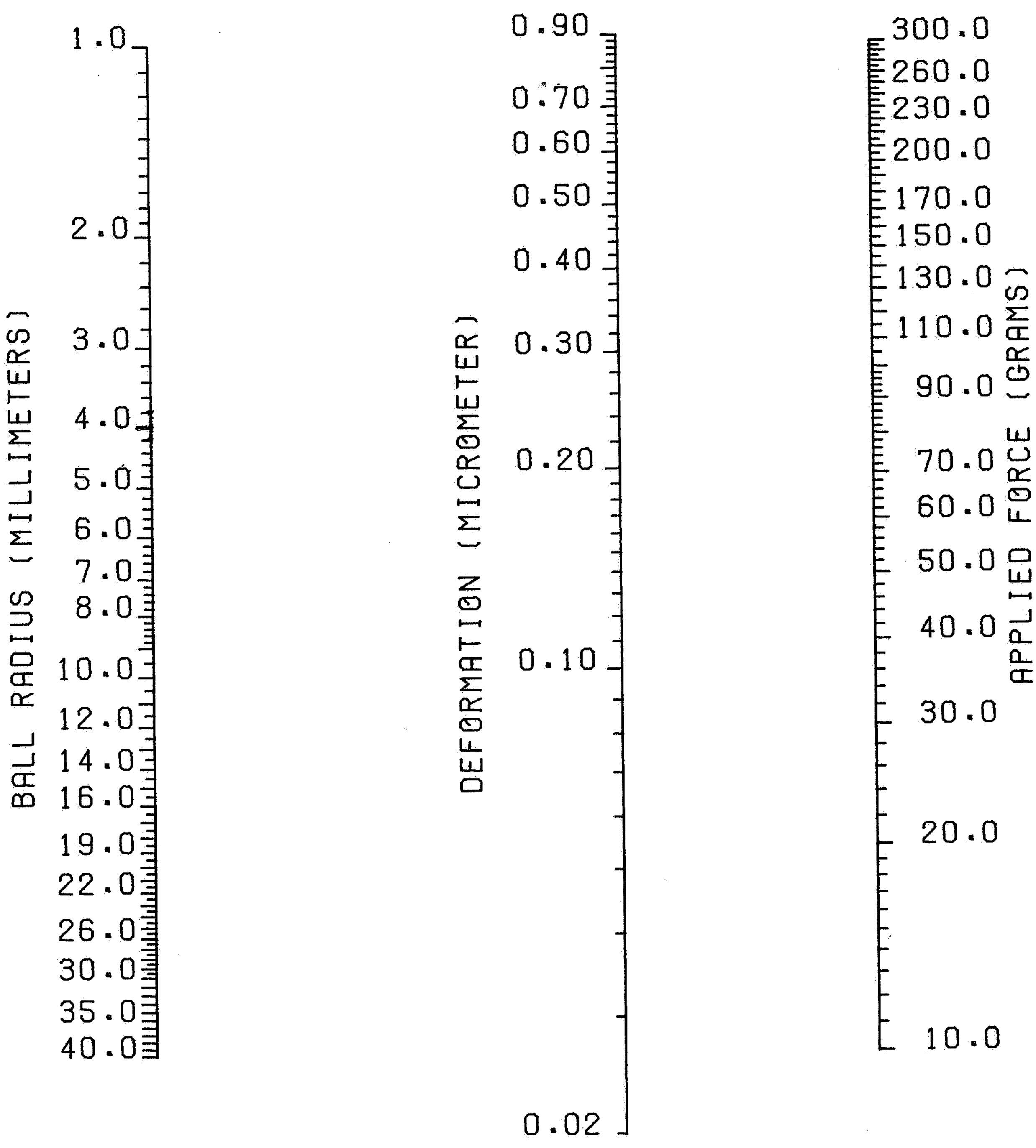
DEFØRMATIØN ØF BALL AND PLANE
DIAMØND VS. 52100 STEEL

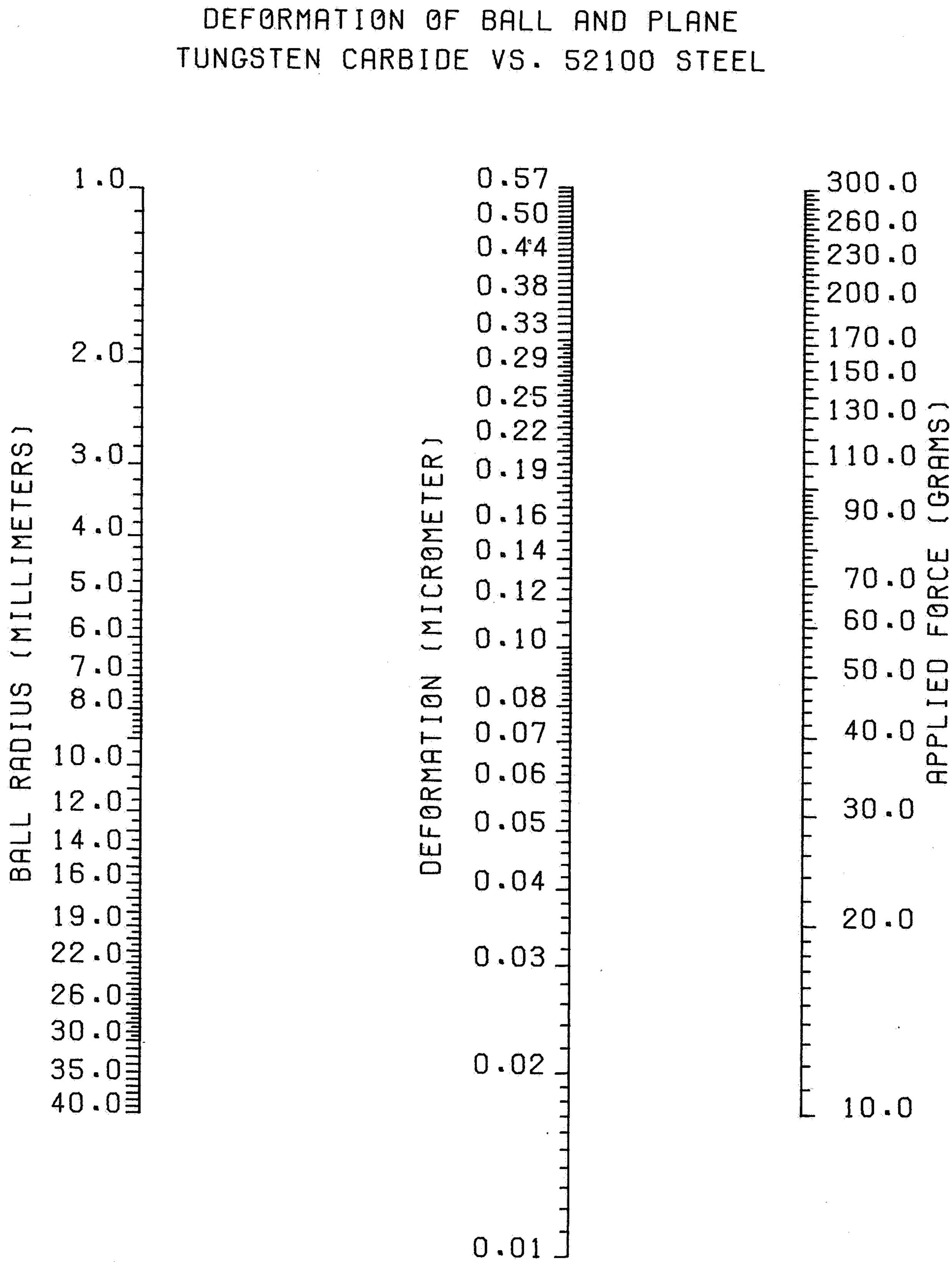


DEFØRMATIØN ØF BALL AND PLANE
TUNGSTEN CARBIDE VS. CHRØME CARBIDE

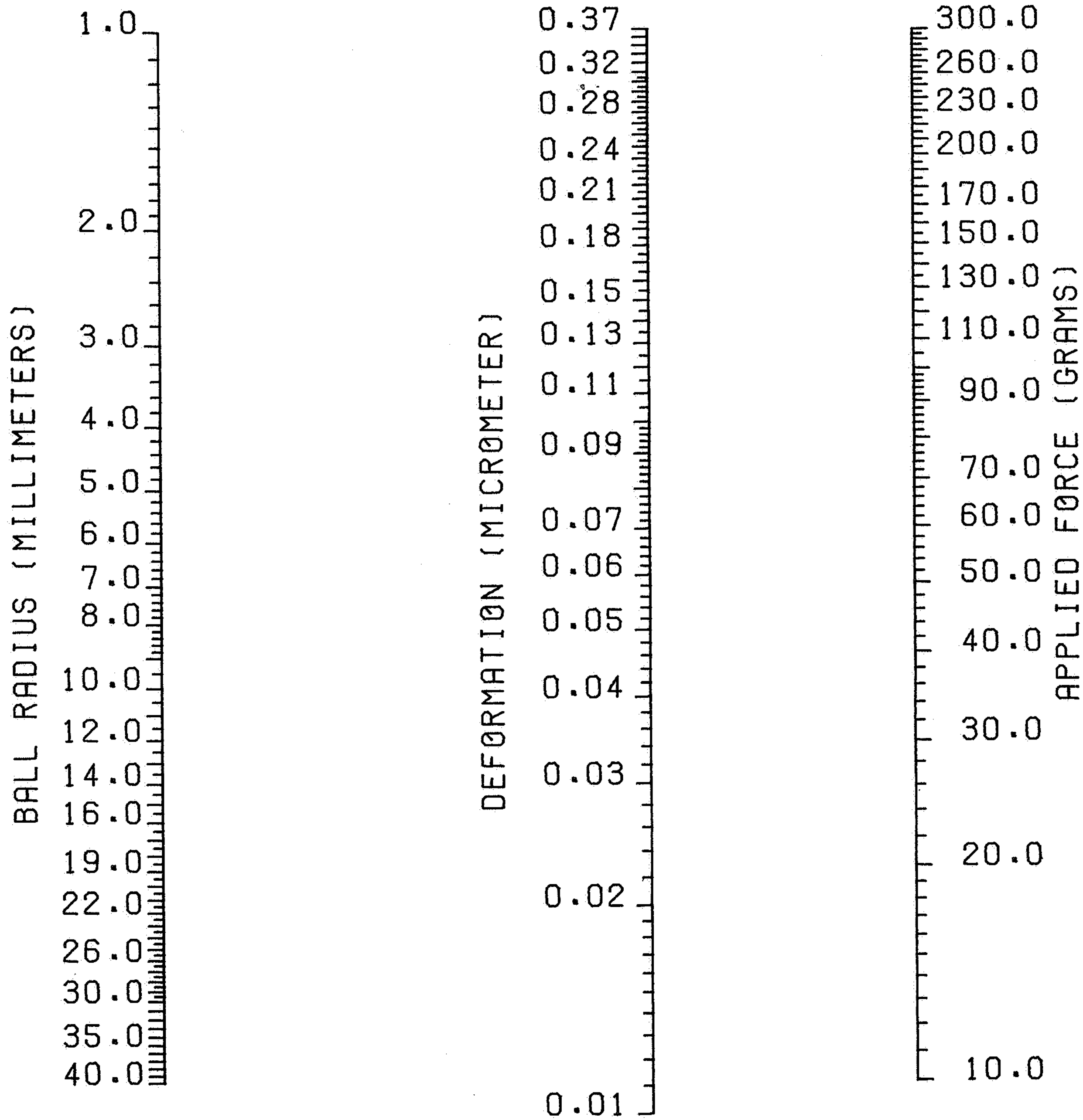


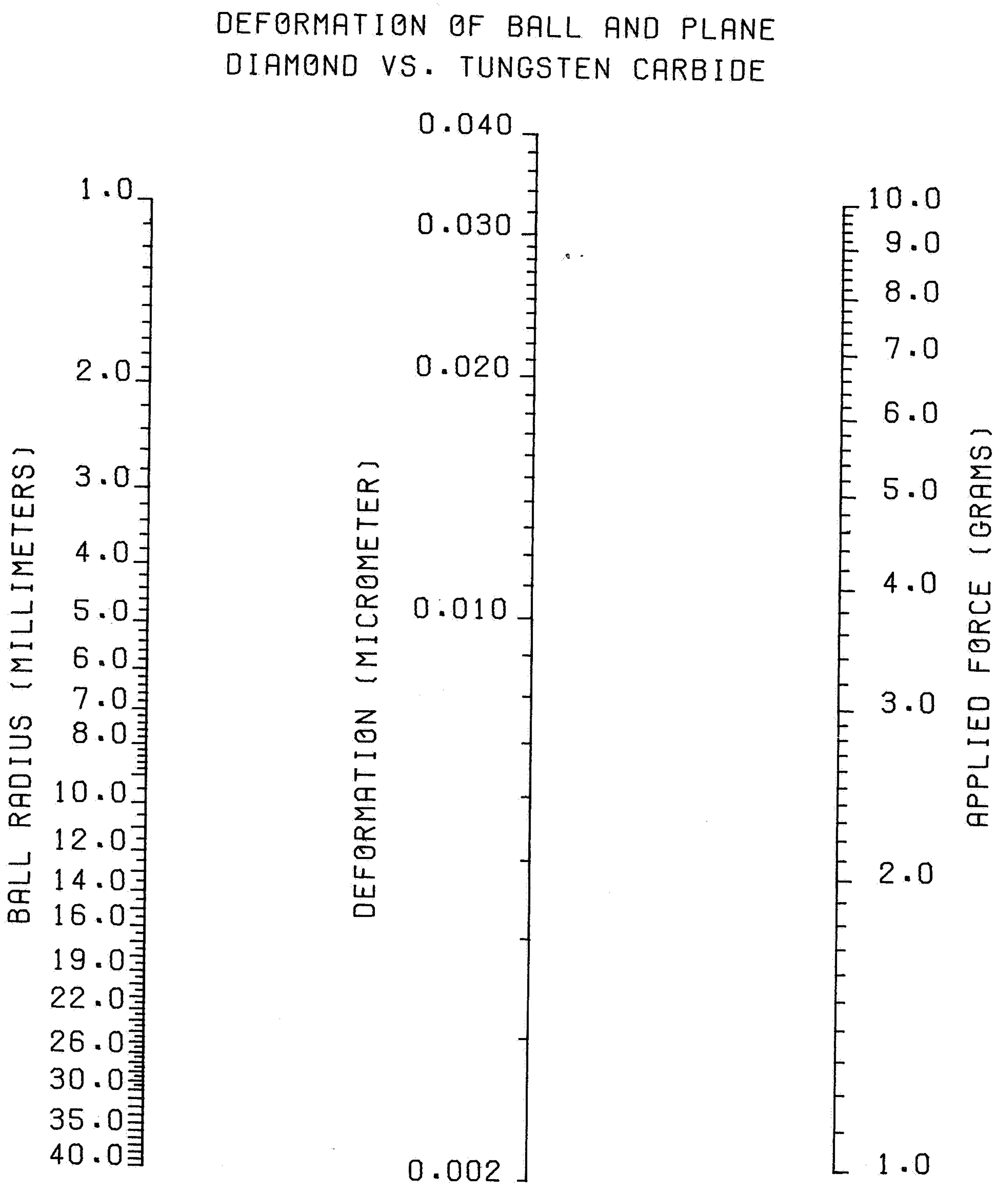
DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. CERVIT



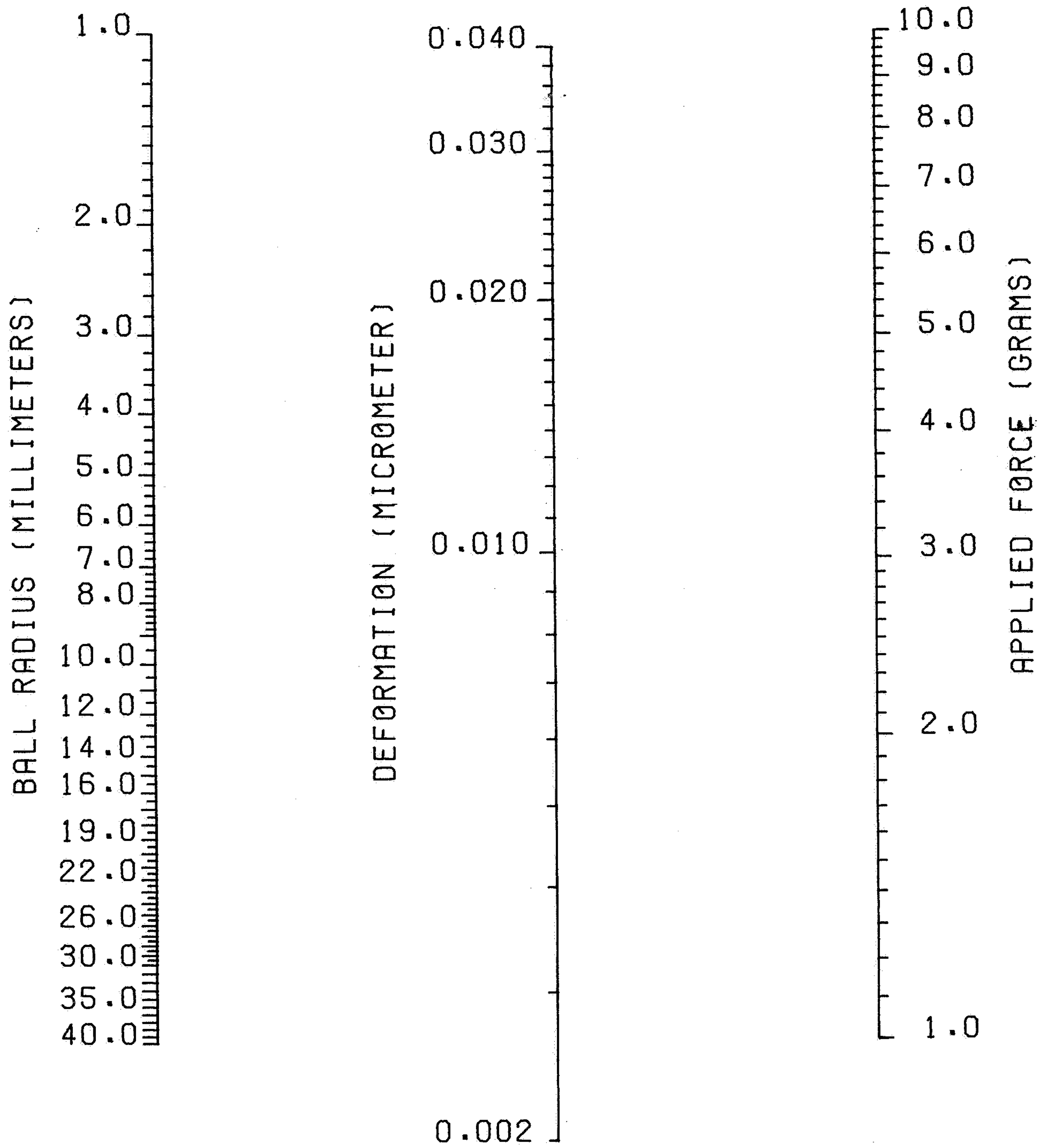

DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. 52100 STEEL
BALL RADIUS (MILLIMETERS)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
10.0
12.0
14.0
16.0
19.0
22.0
26.0
30.0
35.0
40.0
DEFORMATION (MICROMETER)
0.57
0.50
0.44
0.38
0.33
0.29
0.25
0.22
0.19
0.16
0.14
0.12
0.10
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
APPLIED FORCE (GRAMS)
300.0
260.0
230.0
200.0
170.0
150.0
130.0
110.0
90.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0

DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. TUNGSTEN CARBIDE

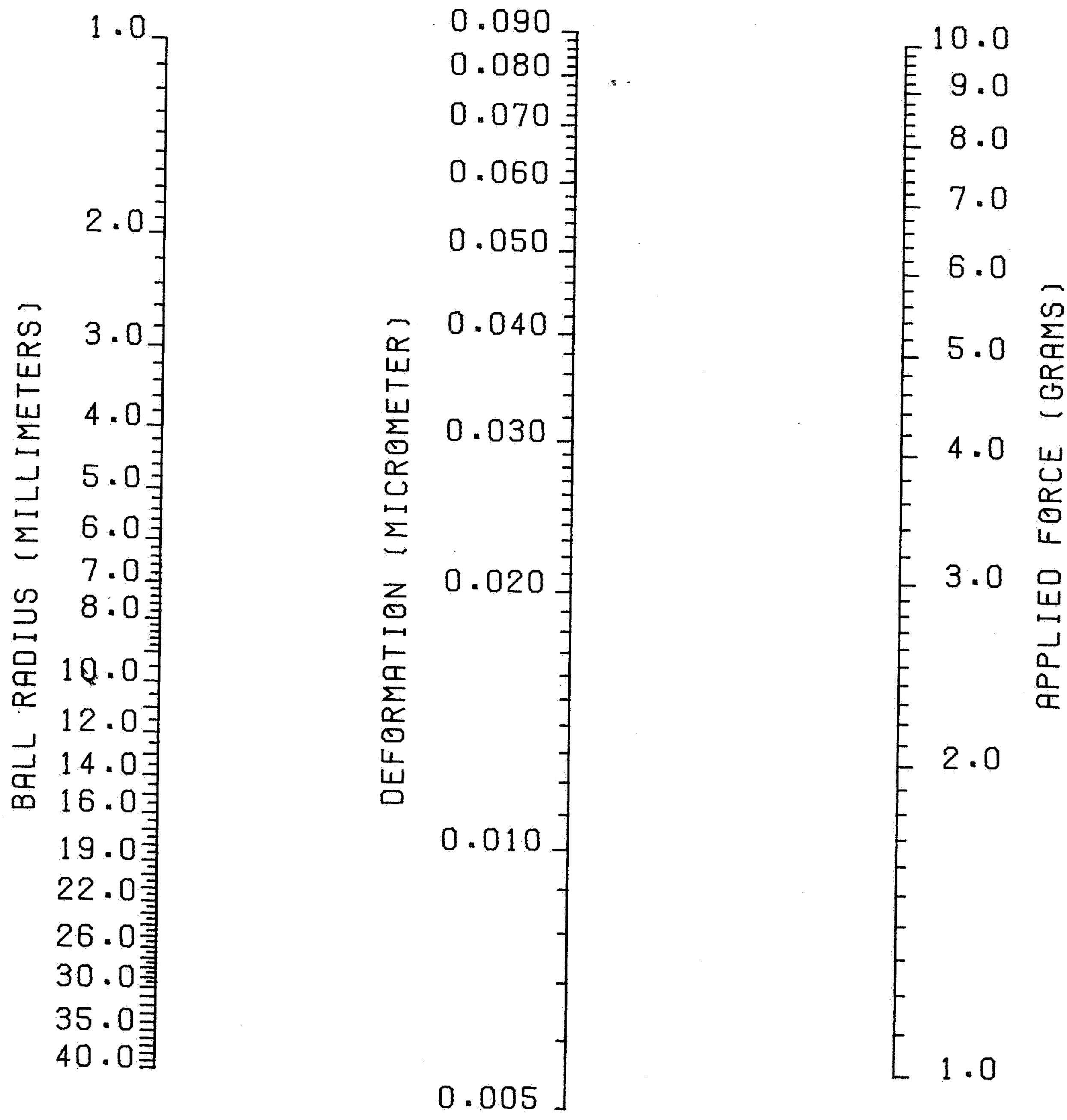


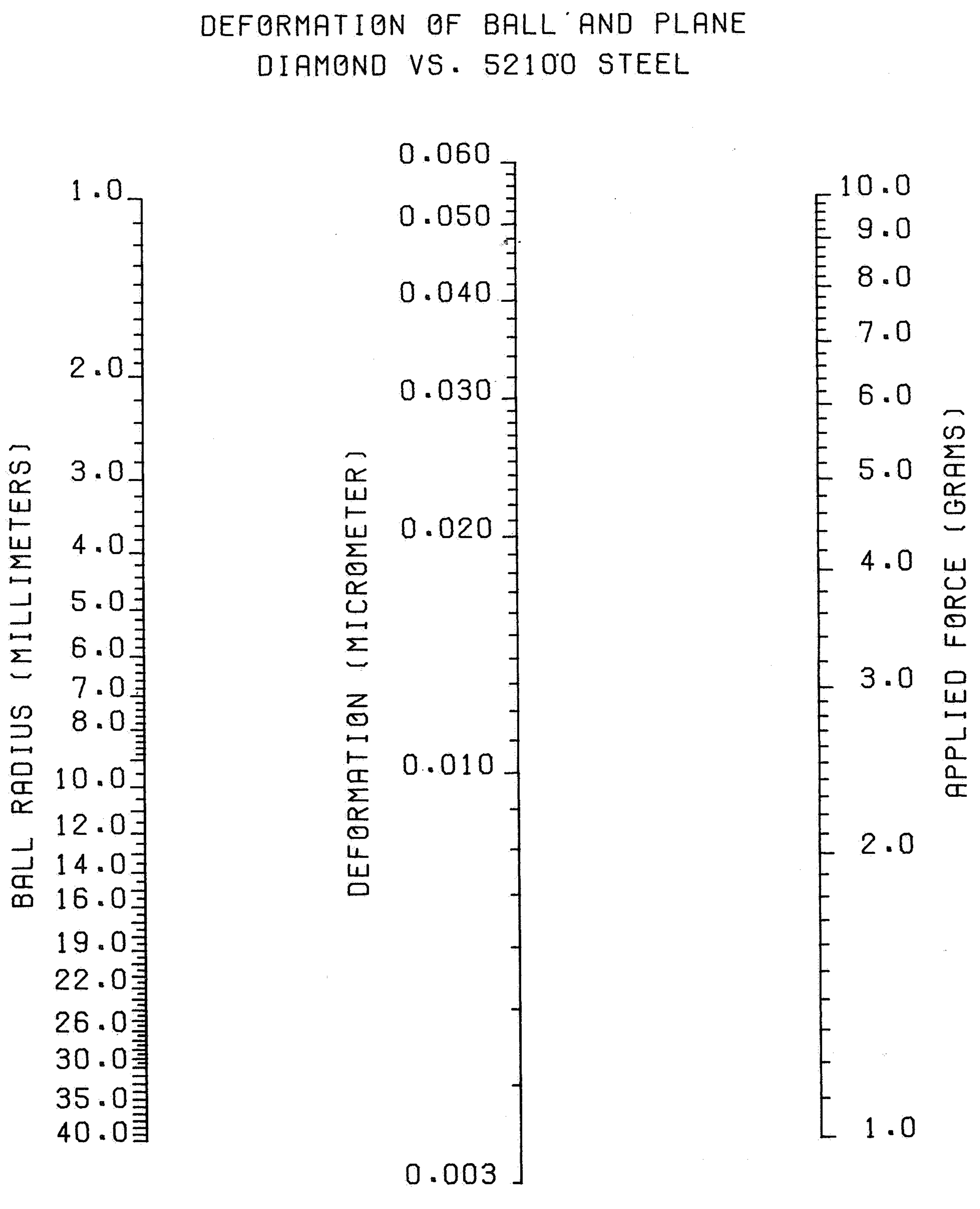

DEFØRMATIØN ØF BALL AND PLANE
DIAMØND VS. TUNGSTEN CARBIDE
BALL RADIUS (MILLIMETERS)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
10.0
12.0
14.0
16.0
19.0
22.0
26.0
30.0
35.0
40.0
DEFØRMATIØN (MICRØMETER)
0.040
0.030
0.020
0.010
0.002
APPLIED FØRCE (GRAMS)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0

DEFORMATION OF BALL AND PLANE
DIAMOND VS. CHROME CARBIDE

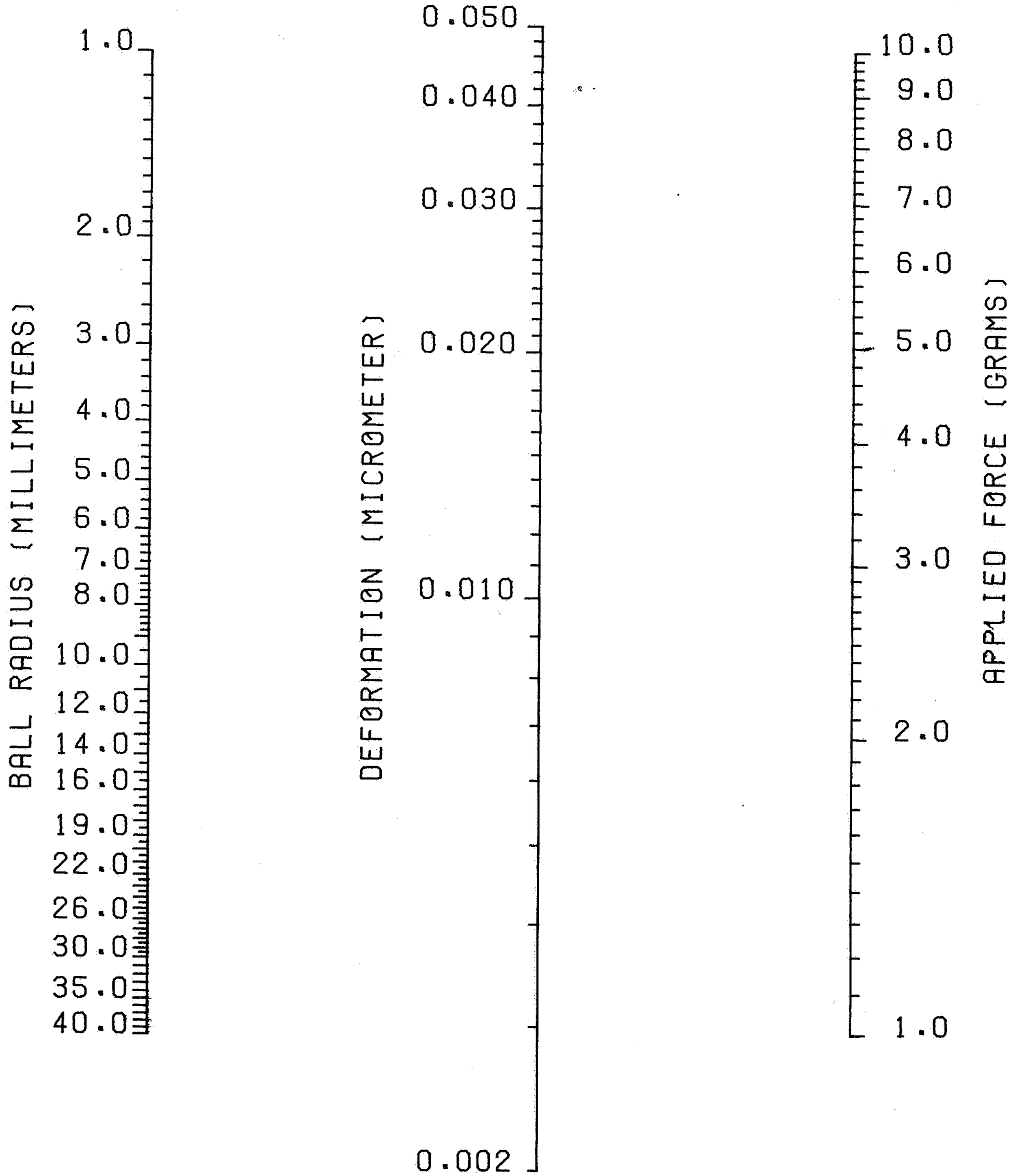


DEFORMATION OF BALL AND PLANE
DIAMOND VS. CERVIT

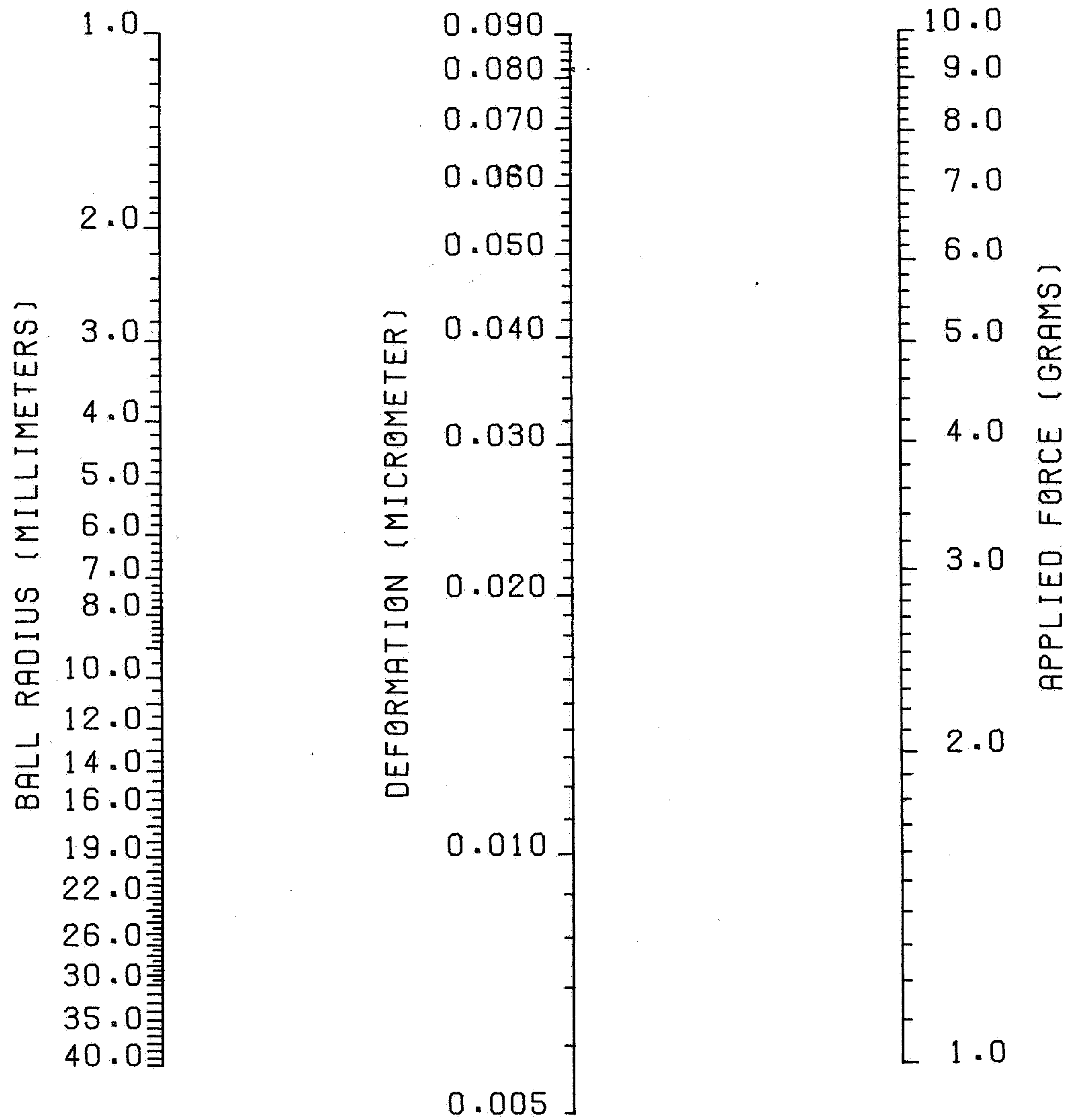



DEFORMATION OF BALL AND PLANE
DIAMOND VS. 52100 STEEL
BALL RADIUS (MILLIMETERS)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
10.0
12.0
14.0
16.0
19.0
22.0
26.0
30.0
35.0
40.0
DEFORMATION (MICROMETER)
0.060
0.050
0.040
0.030
0.020
0.010
0.003
APPLIED FORCE (GRAMS)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0

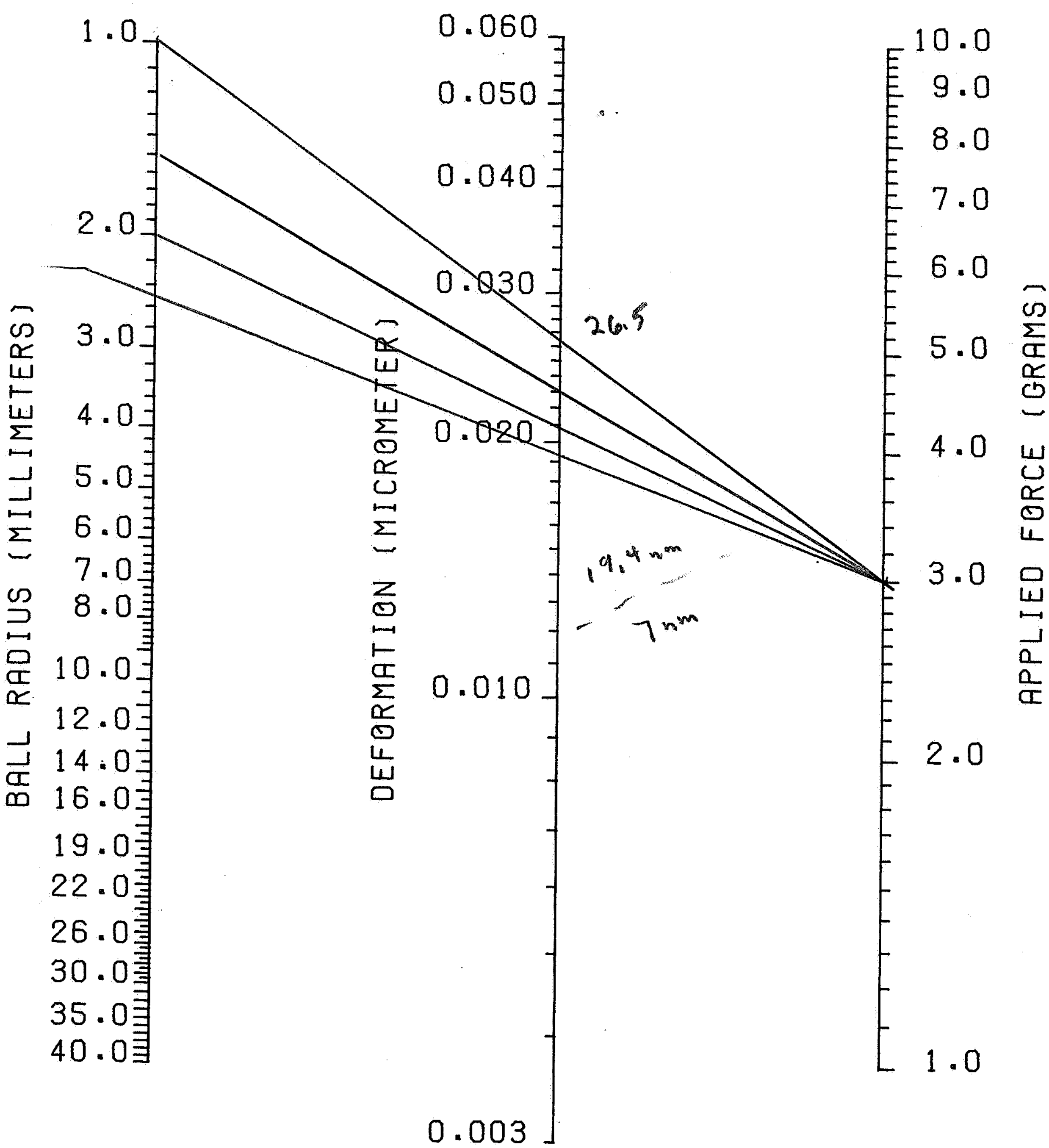
DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. CHROME CARBIDE



DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. CERVIT



DEFØRMATIØN ØF BALL AND PLANE
TUNGSTEN CARBIDE VS. 52100 STEEL



DEFORMATION OF BALL AND PLANE
TUNGSTEN CARBIDE VS. TUNGSTEN CARBIDE