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THREE-DIMENSIONAL OBSERVATIONS ON THE PASSAGE OF SHOCK WAVES OVER A RECTANGULAR BLOCK

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This report contains the results of an investigation which is in continuation of work described in Report 53.1, Engineering Research Institute, University of Michigan, August, 1953. The work was undertaken upon the request of the Armed Forces Special Weapons Project. A rectangular block completely spanning the two inch width of the University of Michigan two inch by seven inch shock tube was exposed to shock waves of various strengths. The angles of incidence varied, and the resulting diffraction patterns were photographed and density variations recorded by means of the interferometer.

The present study proposes to utilize a three-dimensional interferometric technique devised by D. K. Weimer and described by Brickl and Bleakney.[1] Weimer's idea was to use a model made of an optically polished glass block not completely spanning the test section of the shock tube. A glass block of the same outside dimensions and identical thickness is then to be placed in the same relative position in the compensating chamber of the interferometer. In this way three-dimensional effects can be observed.

In Reference (1) it was suggested that if the glass block model were cemented to one window, longer times could be studied because the shock reflected from the opposite window would take longer to come back and interfere with the flow about the model. Following this proposal, glass blocks were cemented both to the test section window and to the compensator window, as shown in Figure 1. The techniques used will be described in detail later. With this arrangement sharp monochromatic fringes and contrasting white light fringes could be obtained simultaneously inside the block and in the outside field, and it was possible to obtain the fringe shifts both inside and outside of the block with one shot. Cementing the glass block model to the window has two additional

[1]Brickl and Bleakney, "The Diffraction of a Shock Wave Over a Three-Dimensional Object", Technical Report II-14, Department of Physics, Princeton University, April, 1953.

advantages: the model can be mounted an any angle to the incident shock wave, and the flow can be studied all about the model.

Reference (1) gives a complete explanation of the method of data reduction. At the risk of being repetitious, however, the ideas involved in the Princeton report will be explained for those who may not have ready access to that source.

Figure 2 is a drawing of the glass block model mounted on a window of the test section. Consider two rays of light, A and B; B penetrates the glass block model and is infinitesimally close to the side wall; A is infinitesimally close to the first ray but passes outside the model. Beyond the glass block the two rays go through essentiallv the same density field and therefore are shifted in phase by the same amount. Ray A, however, undergoes an additional phase shift due to the density field at the surface of the block. The fringe shift just inside the block subtracted from the fringe shift just outside the block gives the fringe shift due to the density field at the side walls of the model. If it is assumed that this density field is two-dimensional, the pressures on the side walls of the model can be calculated using the assumption of isentropic flow. It is very difficult, if not impossible, to calculate the pressures on the end of the model or in the outside field because the flow is three-dimensional.

The glass block model and its compensator were cut with a thin carborundum saw from selected plate glass 0.70 inches thick. After thoroughly cleaning both the windows and the blocks, they were placed in an oven and heated to about 160°C. A small amount of cellulose caprate* was melted onto the window and allowed to run. The glass block was then firmly pressed onto the window until all air bubbles were removed, and the window was left to cool slowly in the oven.** All residual cement was easily removed with a razor blade and acetone solvent. Since the test section windows were mounted in their frames using a bath of boiling water and Woods metal which melts at 65°C, the one test section window had to be mounted after the glass block was cemented on. Care was taken not to disturb the glass block while the Woods metal was being melted onto the space between the window and frame because the optical cement softens slightly at the temperature of boiling water.

In the first tests with a glass block model, a block one-half inch thick was used and the shock wave was fired into air at atmospheric pressure. The results were wholly unsatisfactory, the fringe shift being insufficient for accurate results. When using a block of 0.70 inches and firing the shock wave into nitrogen at 1000 mm. Hg pressure, the results were more satisfactory, but still leave much to be desired. It is suggested that future glass block model tests be done in shock tubes whose test section is at least four inches wide.

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*The cellulose caprate is an optical cement contributed by the Naval Gun Factory. Tests showed this optical cement to be very tough. It easily withstood repeated impacts of the shock wave without any sign of separation.

**In this phase of the work help is acknowledged from Alan C. Kolb.

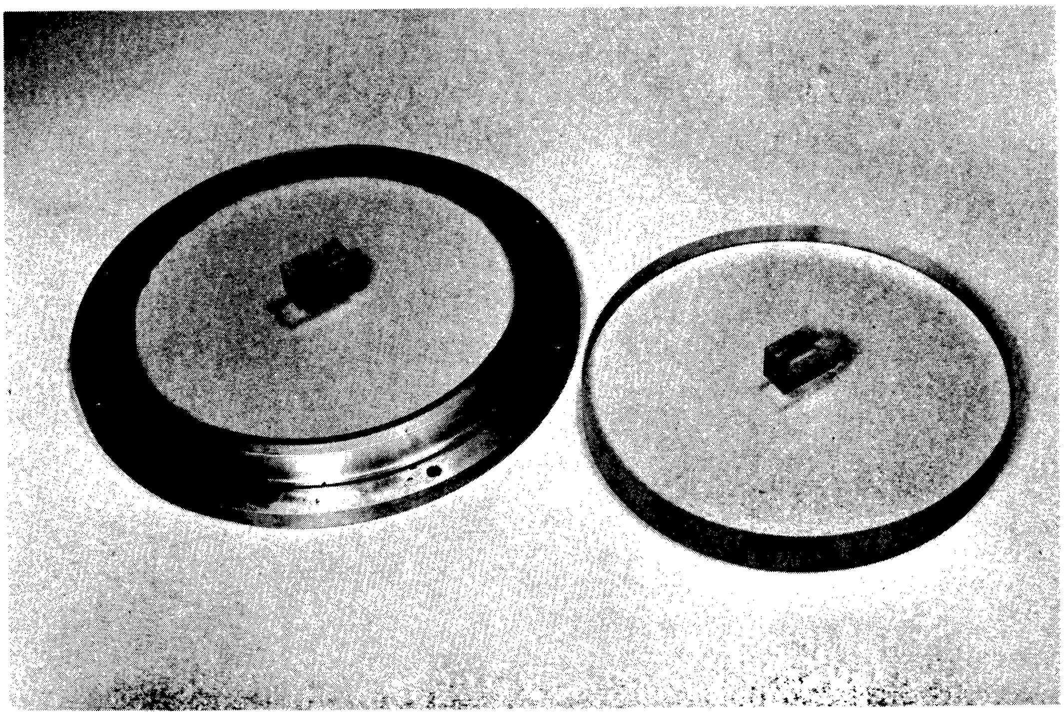


Fig. 1. Picture of glass blocks mounted on window and compensator.

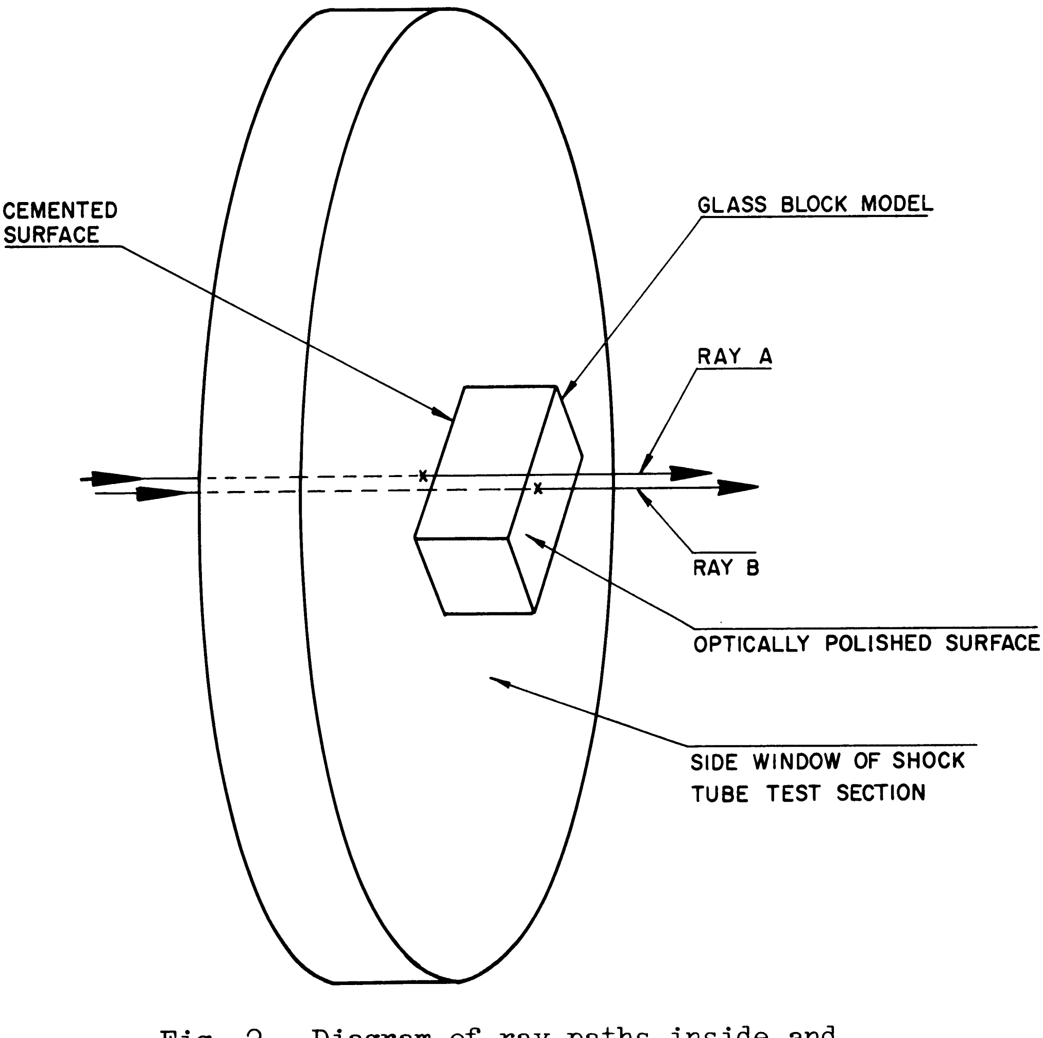


Fig. 2. Diagram of ray paths inside and outside glass block model.

Because the faces of the glass block were not exactly parallel, the fringes inside did not have the same spacing or orientation of those outside. Also a great deal of adjustment was needed to get the fringes inside and outside sharp simultaneously. For this reason, a block with opposite faces polished accurately plane-parallel would have been easier to use, although more expensive.

For most shots four pictures were made:

1. A no-flow monochromatic interferogram with the pressure in the test section adjusted so that the fringe pattern was approximately centered on the model.

2. A no-flow white light fringe picture with the pressure in the expansion chamber at the correct pressure for shooting.

3. A flow monochromatic interferogram.

4. A flow white light fringe picture.

The fringes were so adjusted that both the flow and no-flow fringes were centered approximately at the model. This technique made the best use of the limited number (about sixty) of sharp fringes which the interferometer has with the present spark source and filter.

Both the flow and no-flow monochromatic interferograms were enlarged onto eight inch by ten inch Kodalith film; in addition, a contact print was made of the no-flow monochromatic fringe picture onto a third Kodalith sheet. Superposition of the enlarged flow and no-flow pictures showed up half-integral fringe shifts as fuzzy areas which were easily traced onto a sheet of vellum placed over the superposed pictures. When the contact print of the enlarged no-flow picture was superposed on the flow pictures, the integral fringe shifts were discernible. In this manner it was possible to trace both the integral and half-integral fringe shift outside and inside the glass block model.

Since the no-flow interferogram was not made with the pressure p_o in the expansion chamber but with a higher pressure, a correction had to be made in the numbering of the fringes. For example, the so-called half-integral isopycnics had to be labelled 14.7, 15.7, etc. representing a + 0.2 fringe correction. This correction was different for each shot.

The isopycnics could be drawn accurately to $\pm$ 1/4 fringe shift, but inhomogeneities in the flow behind the shock would lead to an additional error. Therefore the accuracy of the fringe shifts may be no better than one-half unit. As in the previous report, it should be emphasized that the locations of shock fronts shown on the drawings are not accurate. Interferometer pictures do not show up shock or rarefaction fronts very well; schlieren pictures are far better for this purpose.

THEORY

The notation used in this report is as follows:

p = pressure

ρ = density

a = sound speed

n' = fringe shift inside glass block

n = fringe shift in outside field

The subscript o refers to the conditions ahead of the incident shock; the subscript 1 refers to the conditions in the region behind the incident shock which has not yet been disturbed by the model; symbols without subscripts refer to the conditions on the side walls of the model.

U = velocity of incident shock

ξ = p_o/p_1 = reciprocal of shock strength

n_1 = fringe shift across incident shock

τ = time interval between passage of incident shock over lead edge of model and instant of taking picture, in units of the time for the incident shock to travel a distance equal to one block height.

λ = wavelength of light

K = the Dale-Gladstone constant

h = thickness of the glass block model

As in the previous report, the shock strength was calculated from the measured shock velocity using the formula

$$\xi = \frac{6}{7\left(\frac{U}{a_o}\right)^2 - 1} .$$

The density ratio across the shock wave could then be calculated using the Rankine-Hugoniot equation

$$\frac{\rho_1}{\rho_o} = \frac{6 + \xi}{1 + 6\xi} ,$$

and the fringe shift across the incident shock wave is

$$n_1 = \frac{LK}{\lambda}\,\frac{273}{760}\,\frac{p_o}{T_o}\left(\frac{\rho_1}{\rho_o} - 1\right).$$

The width of the test section, L = 5.1 cm, λ is 5170Å (the magnesium triplet $3s3p\ ^3P - 3s4s\ ^3S$) and for nitrogen K = 299×10^{-6}. For all of this series $U/a_o = 1.23$, $\xi = .625$, $\rho_1/\rho_o = 1.39$ and $n_1 = 14.2$.

If we assume isentropic flow about the model, then

$$\frac{p}{\rho^\gamma} = \frac{p_1}{\rho_1^\gamma}$$

so

$$\frac{p}{p_o} = \frac{p_1}{p_o}\left(\frac{\rho_o}{\rho_1}\right)^\gamma\left(\frac{\rho}{\rho_o}\right)^\gamma.$$

Now the fringe shift due to the density just at the side walls of the model is $n - n'$.

$$n - n' = \frac{hK}{\lambda}\,\frac{273}{760}\,\frac{p_o}{T_o}\left(\frac{\rho}{\rho_o} - 1\right)$$

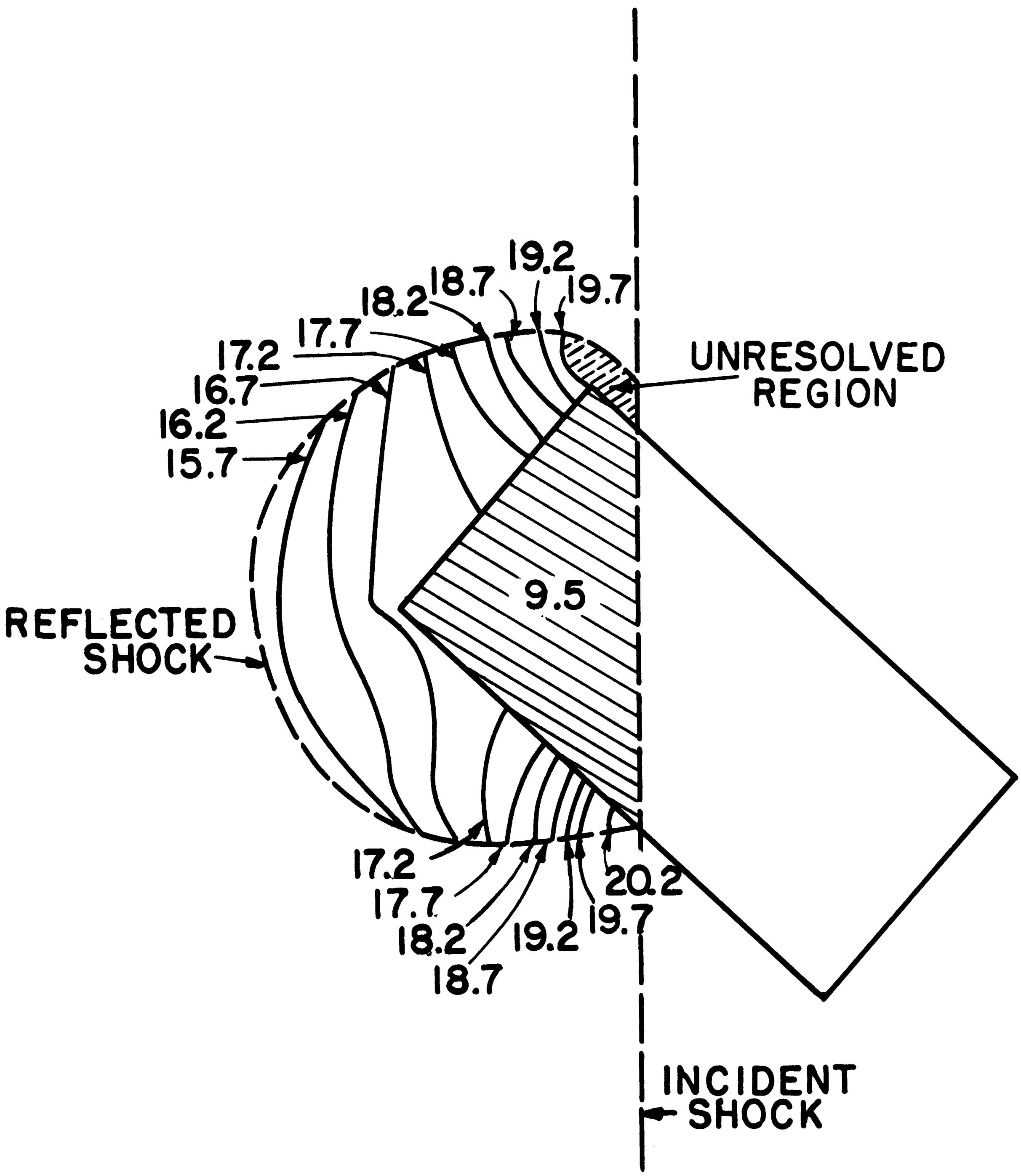
where h is the thickness of the glass block model which is 0.70 inches or 1.78 cm. Using this equation we obtain for the density ratio:

$$\frac{\rho}{\rho_o} = 1 + \frac{n - n'}{n_1}\,\frac{L}{h}\left(\frac{\rho_1}{\rho_o} - 1\right).$$

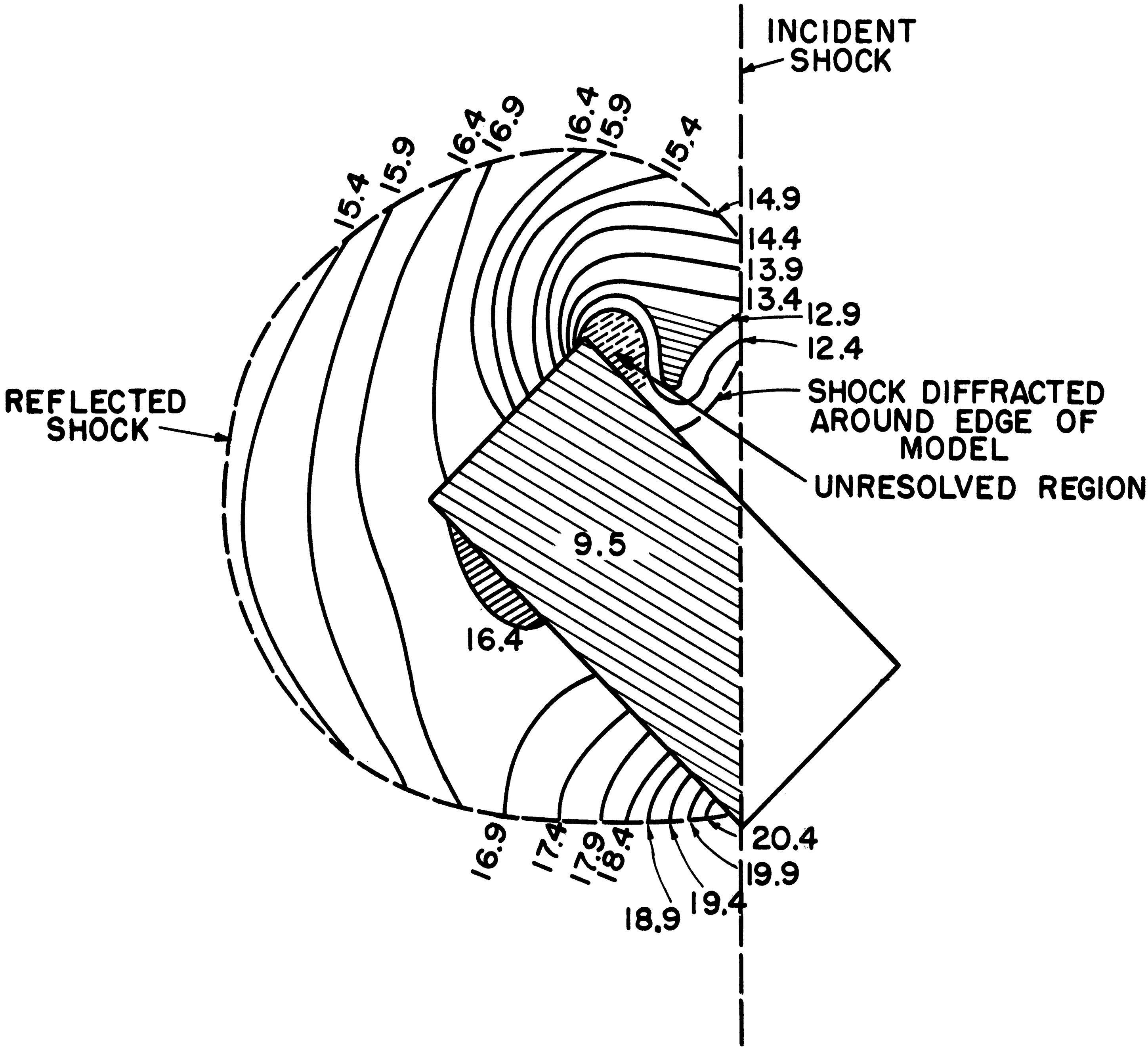
The pressure on the side walls of the model is then

$$\frac{p}{p_o} = \frac{1}{\xi}\left(\frac{\rho_o}{\rho_1}\right)^\gamma\left[1 + \frac{L}{h}\,\frac{(n - n')}{n_1}\left(\frac{\rho_1}{\rho_o} - 1\right)\right]^\gamma.$$

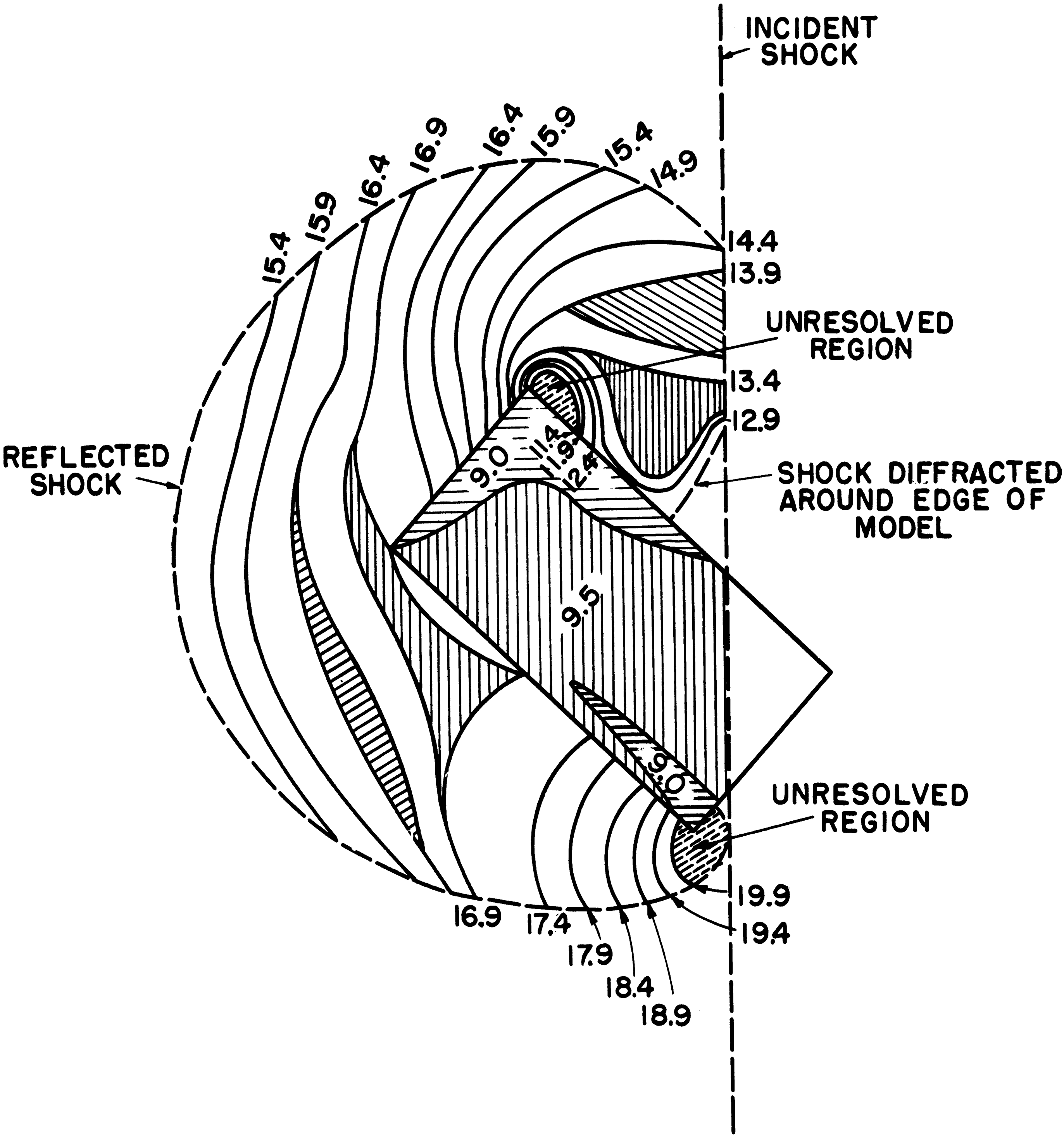
The n and n' used in the formula above should be the values of the fringe shift <u>at the surface</u> of the block.


19.2
18.2
18.7
19.7
17.7
17.2
16.7
16.2
15.7
UNRESOLVED
REGION
9.5
REFLECTED
SHOCK
17.2
17.7
18.2
18.7
19.2
19.7
20.2
INCIDENT
SHOCK

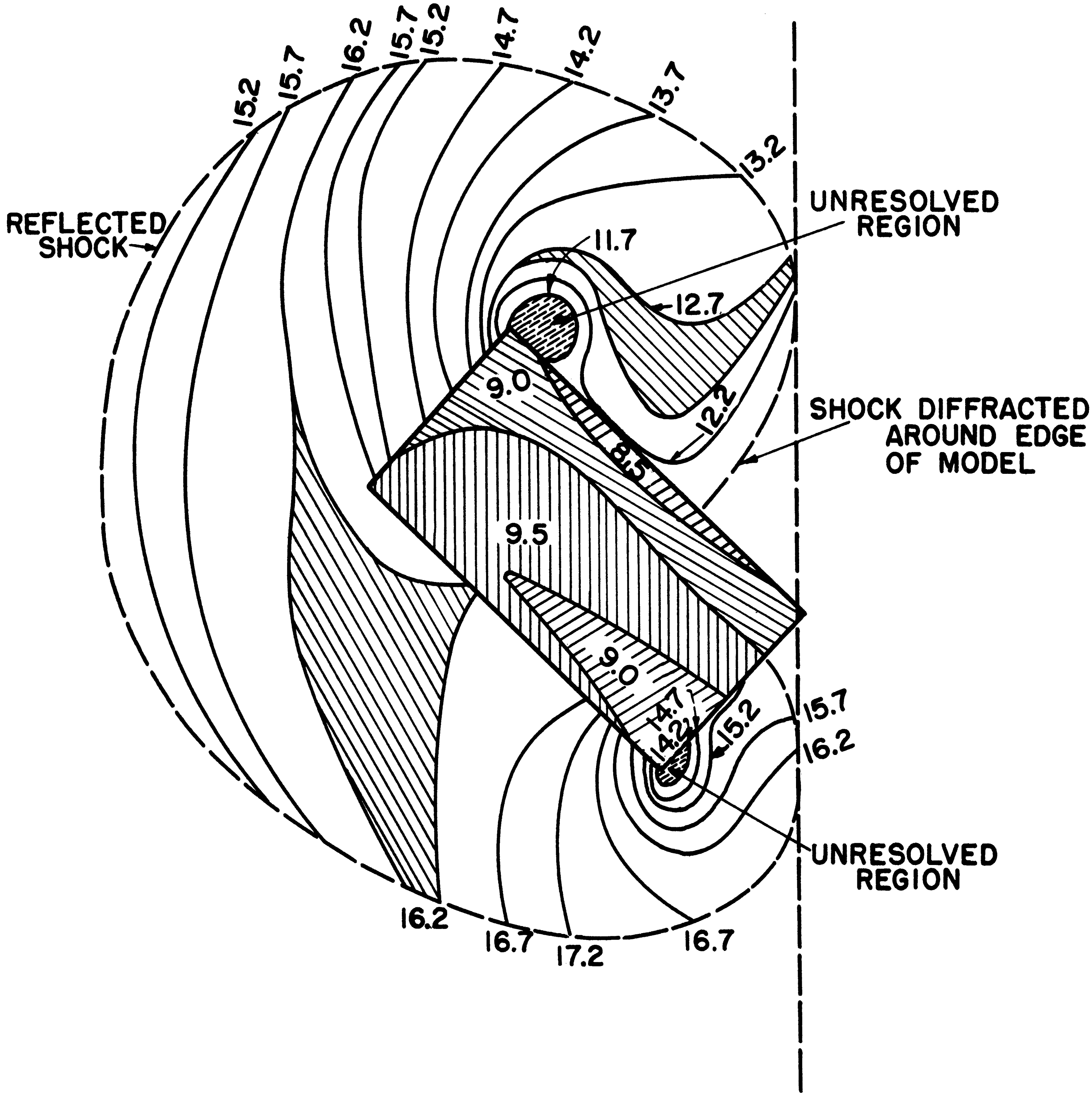
$\tau = 0.78$


INCIDENT SHOCK
REFLECTED SHOCK
SHOCK DIFFRACTED AROUND EDGE OF MODEL
UNRESOLVED REGION
15.4
15.9
16.4
16.9
16.4
15.9
15.4
14.9
14.4
13.9
13.4
12.9
12.4
9.5
16.4
16.9
17.4
17.9
18.4
18.9
19.4
19.9
20.4

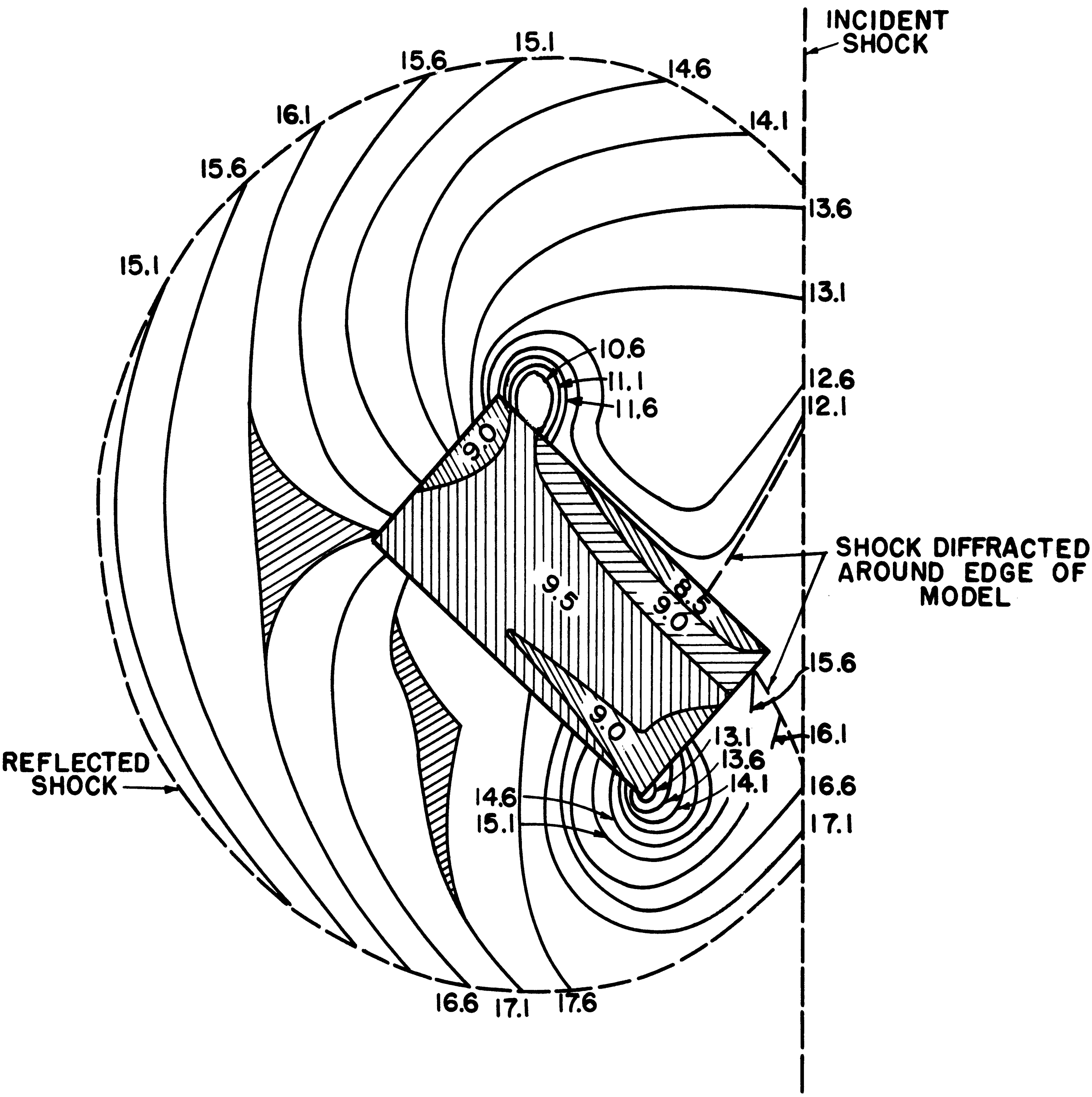
$\tau = 1.38$


INCIDENT SHOCK
15.4
15.9
16.4
16.9
16.4
15.9
15.4
14.9
14.4
13.9
UNRESOLVED REGION
13.4
12.9
REFLECTED SHOCK
9.0
11.4
11.9
12.4
SHOCK DIFFRACTED AROUND EDGE OF MODEL
9.5
9.0
UNRESOLVED REGION
19.9
19.4
16.9
17.4
17.9
18.4
18.9

$\tau = 1.61$

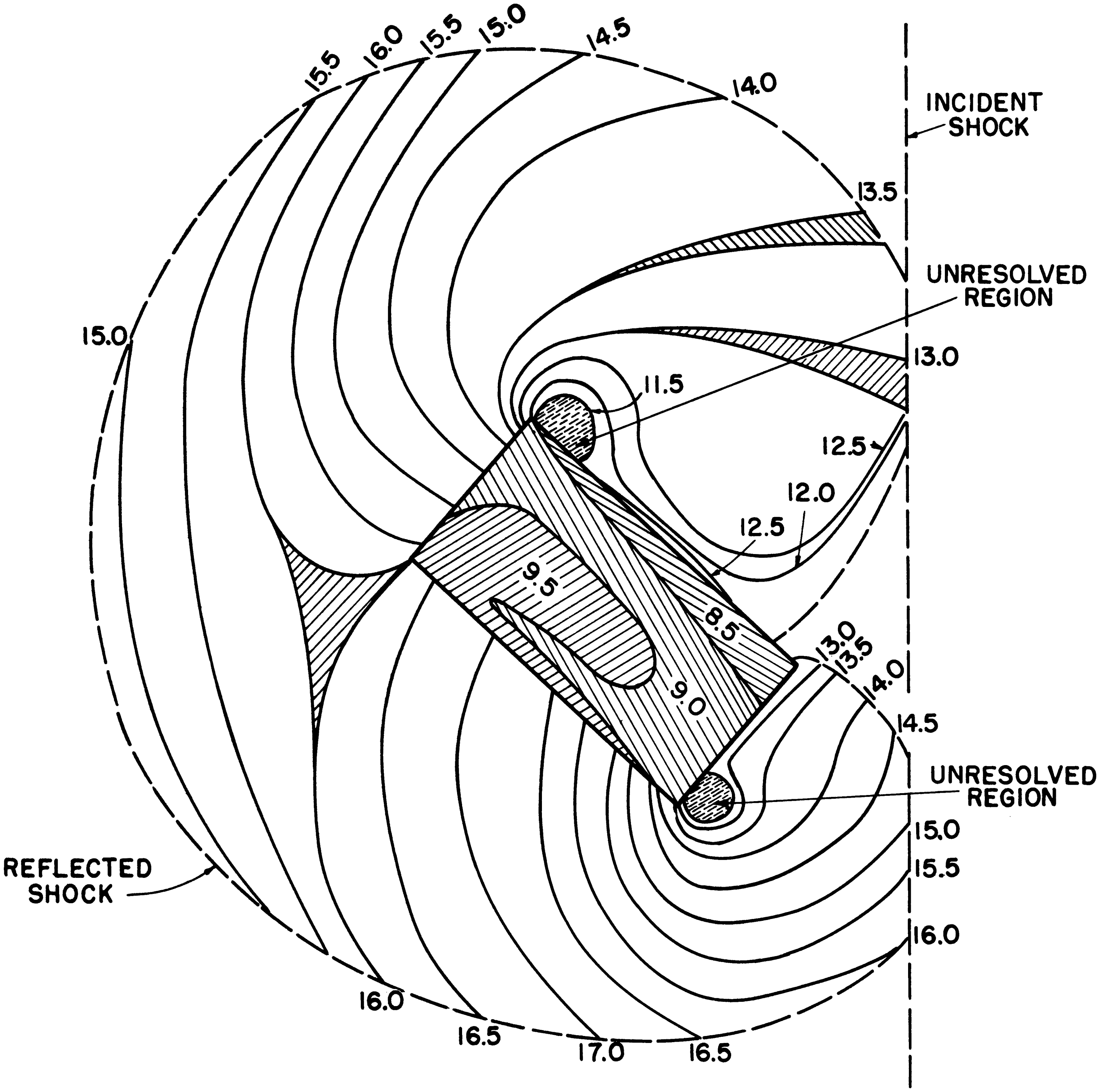

15.2
15.7
16.2
15.7
15.2
14.7
14.2
13.7
13.2
REFLECTED SHOCK
UNRESOLVED REGION
11.7
12.7
9.0
12.2
8.5
SHOCK DIFFRACTED AROUND EDGE OF MODEL
9.5
9.0
4.7
14.2
15.2
15.7
16.2
UNRESOLVED REGION
16.2
16.7
17.2
16.7

$\tau = 2.08$

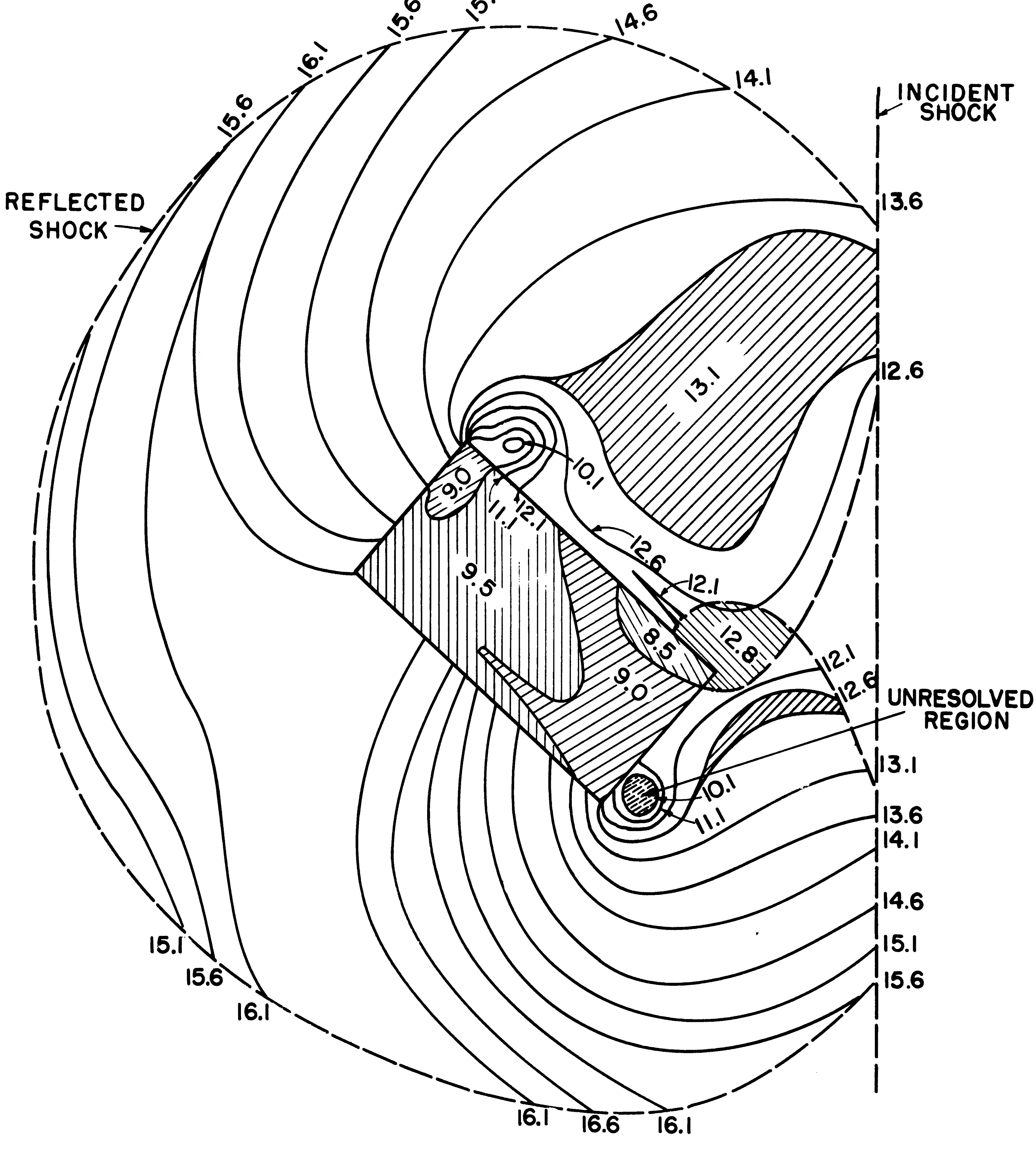


INCIDENT SHOCK
15.1
15.6
14.6
16.1
14.1
15.6
13.6
15.1
13.1
10.6
11.1
12.6
11.6
12.1
9.0
SHOCK DIFFRACTED AROUND EDGE OF MODEL
9.5
8.5
9.0
15.6
9.0
13.1
16.1
REFLECTED SHOCK
13.6
14.1
14.6
16.6
15.1
17.1
16.6
17.1
17.6

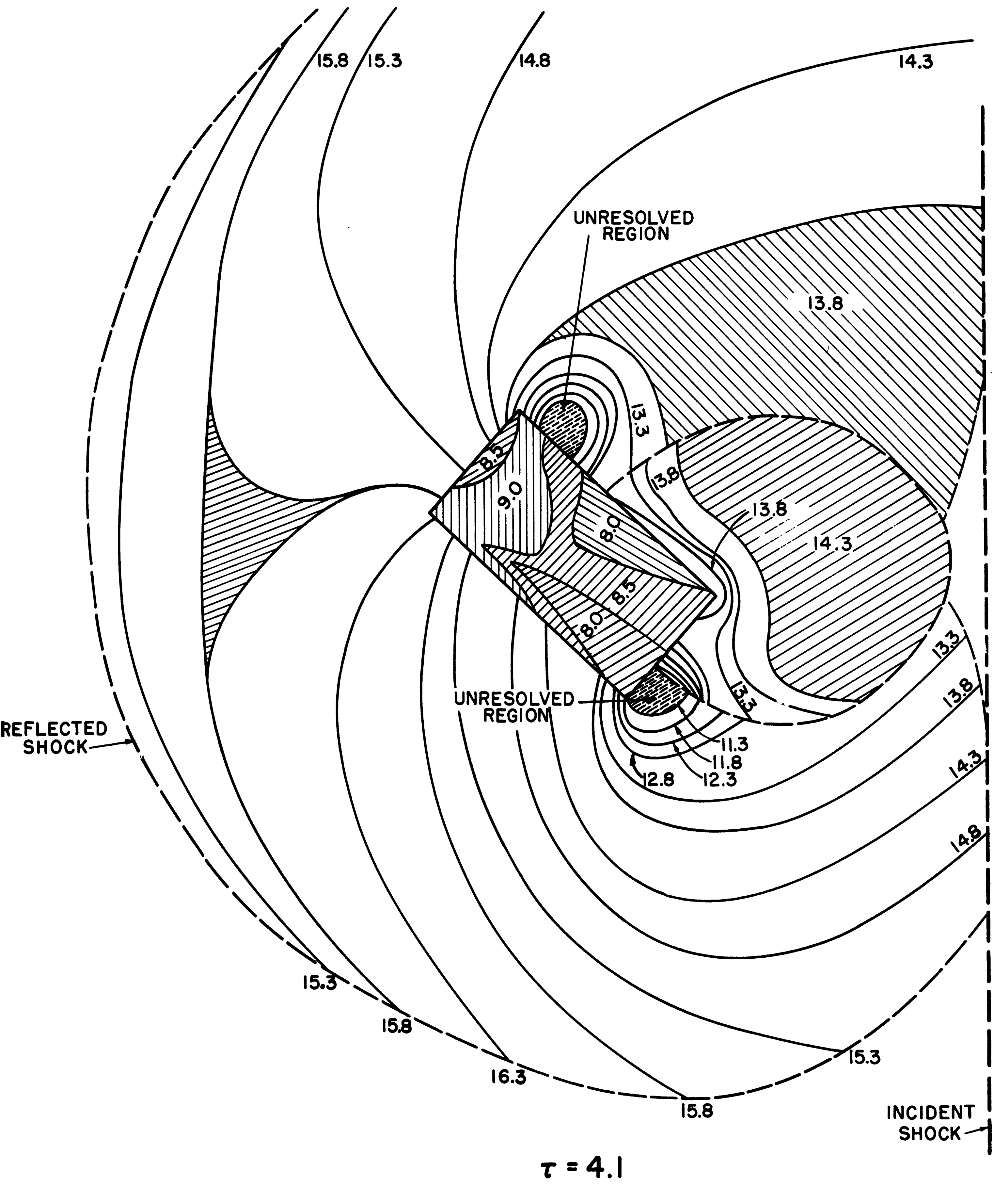
τ = 2.33


15.5
16.0
15.5
15.0
14.5
14.0
INCIDENT SHOCK
13.5
UNRESOLVED REGION
15.0
13.0
11.5
12.5
12.0
12.5
9.5
8.5
9.0
13.0
13.5
14.0
14.5
UNRESOLVED REGION
15.0
15.5
REFLECTED SHOCK
16.0
16.0
16.5
17.0
16.5

$\tau = 2.71$


INCIDENT SHOCK
REFLECTED SHOCK
UNRESOLVED REGION
15.6
16.1
15.6
15.1
14.6
14.1
13.6
12.6
13.1
10.1
9.0
11.1
12.1
9.5
12.6
12.1
8.5
12.8
9.0
12.1
12.6
13.1
10.1
11.1
13.6
14.1
14.6
15.1
15.6
15.1
15.6
16.1
16.1
16.6
16.1

$\tau = 3.0$


15.8
15.3
14.8
14.3
UNRESOLVED REGION
13.8
13.3
8.5
9.0
13.8
13.8
8.0
14.3
8.5
8.0
13.3
13.8
UNRESOLVED REGION
13.3
REFLECTED SHOCK
11.3
11.8
12.8
12.3
14.3
14.8
15.3
15.8
16.3
15.8
15.3
INCIDENT SHOCK

$\tau = 4.1$

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