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NONDESTRUCTIVE TESTING OF LASER TARGETS

R. P. Reedy

July 25, 1974

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Contents

Abstract	1
Refraction Testing Techniques	1
A General Survey	1
Illumination Distribution Study	3
Wall-Thickness Measurements	10
Photometric Techniques	12
Color Isodensity Television Display	12
Isodensitracer	12
Micro-image Scanner	15
Computer-Controlled Microdensitometer	15
Conclusions	17
Acknowledgments	18
References	19
Appendix: Calculator Program to Solve for r_3 for Transmitted Ray Segment 4	20
Microballoon Shell without Inner Coating	20
Microballoon Shell with Inner Coating	23

NONDESTRUCTIVE TESTING OF LASER TARGETS

Abstract

Very small, hollow spheres — referred to as microballoons — are commercially manufactured for various uses. They are made of several types of glass and plastics and range in size from a few to several hundred microns in diameter. Inspecting and selecting microballoons suitable for laser targets is the subject

of this report. Several testing techniques are described that make use of the optical properties of these hollow spheres. These tests can determine 1) the sphericity of the outer surface, 2) the concentricity of the inside and outside wall surfaces, 3) the wall thickness, and 4) defects in the walls.

Refraction Testing Techniques

Tests based on refraction techniques are performed with a microscope, used for making visual examinations, for photometric purposes, or for making photomicrographs.

A GENERAL SURVEY

A general survey of a large group of microballoons can be made by viewing the transilluminated spheres with a microscope focused through the spheres at a point beyond. The appearance of microballoons viewed in this manner can be seen in the photomicrograph shown as Fig. 1. The microballoons with dark symmetric circles are the most nearly perfect, while those with various asymmetric shapes to their inner light circles are correspondingly imperfect. In some of the inner light circles, darker (gray) patches can be seen; these are caused by defects that are nearly on the axis of the balloon and that refract enough light away

from its normal path to produce darkening.

By surveying a large group of microballoons in this manner, one can select only those that appear to have symmetrical figures for further tests.

Fig. 1. General survey of a group of microballoons. The more symmetrical balloons are the more nearly perfect.

The theoretical rationale for this refraction test may be understood by reference to Figs. 2 through 5.

In Fig. 2 we see 15 rays exiting from a microballoon. These rays entered the balloon evenly spaced and parallel, but they are drawn to show the exiting rays!

Fig. 2. Virtual intersections of exiting rays with the object plane.

virtual points of intersection with the object plane. The inside boundary of the black ring is formed at the greatest intersecting distance from the axis.

The angles at which rays exit a microballoon can be determined by tracing the paths of the individual rays. Figure 3

Fig. 3. Example of one ray traced through a perfect microballoon.

- θ - entrance angle
- n - refractive index of the surrounding medium
- n' - refractive index of the microballoon
- a - wall thickness
- r_1 - outside radius
- r_2 - inside radius
- $\theta_1 = \sin^{-1} \left(\frac{n \sin \theta}{n'} \right)$
- $\theta_2 = \sin^{-1} \left(\frac{n' \sin \theta_1}{n} \right)$
- $\theta_3 = \theta_1 + \alpha$

$$\theta_3 = \sin^{-1} \left(\frac{n' \sin \theta_1}{n} \right)$$

$$\theta_4 = \sin^{-1} \left(\frac{n \sin \theta_3}{n'} \right)$$

$$\theta' = \sin^{-1} \left(\frac{n' \sin \theta_4}{n} \right)$$

$$\theta_5 = \theta_4 - \alpha'$$

$$\theta_6 = \sin^{-1} \left(\frac{n' \sin \theta_5}{n} \right)$$

$$\beta = 180 - 2\theta_3$$

$$\gamma = 180 - (\theta + \theta' + \theta_6 + \beta)$$

Fig. 4. Schematic representation of the calculation of the exit angle, γ . The equations are based on Snell's law of refraction, $n \sin \theta = n' \sin \theta_1$.

Fig. 5. Example of rays passing through an imperfect microballoon.

shows the path of one ray through a perfect microballoon. Figure 4 is a schematic representation of the calculations to determine the exit angle, γ , shown in Fig. 3; the necessary equations for computing these angles are included.

Figure 5 shows the paths of rays passing through a defective microballoon. Rays deviated from their normal course by defects such as this account for the anomalies observed in some of the images in Fig. 1.

ILLUMINATION DISTRIBUTION STUDY

Illumination Distribution Model

When photoelectric measurements of microballoon images are made, it is desirable to have a model of the illumination distribution for comparison. Before the model can be constructed, several conditions must be established.

First, the angle at which the illumination strikes the surface must be known. For our model, parallel light was chosen to meet this condition.

Second, the position of the microscope object plane must be known. This position was established as tangent to the back surface of the sphere. This plane was chosen because, being the surface upon which the sphere rests, it can easily be established experimentally.

Third, the source was assumed to be incoherent.

Fourth, all rays considered in the model were nonpolarized, or ordinary, light rays.

Fifth, the acceptance angle of the microscope must be taken into consideration. Rays with exit angle γ larger than 40° were not considered.

The first step in constructing the model requires sending rays of uniform intensity through the microballoon and finding the position of exit, the angle of exit, and the remaining intensity for each component of the ray. Six components of a ray were considered for the model (see Fig. 6):

1. The component that reflects from the external surface.
2. The component that reflects from the first inside surface and exits through the wall to the outside.
3. The component that reflects twice from the inside surface and then exits.
4. The component that traverses the balloon and exits the other side (the transmitted ray).
5. The component that traverses the balloon, passes through the wall, reflects once from the outside surface and once from the inside surface, and exits. The intensity of this component was insufficient to warrant plotting.
6. The component that traverses the balloon, reflects once from the inside

Fig. 6. Analysis of the passage of a ray through a microballoon. Circled numbers identify the six ray components enumerated in the text; numbers on the lines give the intensity of each segment of the ray components after reflection or refraction.

surface, then exits. This component was not used in the model because its intensity level is low and the ray would appear to emanate from the field surrounding the balloon.

Angles of Exit – The exit angle, γ , for each of the four components used in the model can be found as follows:

$$1: \gamma = 180^\circ - 2\theta,$$

(This is based on the law of reflection, which states that the angle of incidence equals the angle of reflection.)

$$2: \gamma = 180^\circ - (2\theta + 2\delta),$$

$$3: \gamma = 180^\circ - (2\theta + 4\delta),$$

4: The equations used for finding γ for the transmitted ray are given in Fig. 4.

Position of Exit – The position of exit, k , for each component can be found as follows (see Fig. 7):

$$1: k = r_1 \sin \theta,$$

$$2: k = r_1 \cos \epsilon,$$

$$\text{where } \epsilon = 90^\circ - (\theta + 2\delta),$$

$$3: k = r_1 \cos \epsilon,$$

$$\text{where } \epsilon = 90^\circ - (\theta + 4\delta),$$

$$4: k = r_1 \sin \epsilon,$$

$$\text{where } \epsilon = 180^\circ - (\theta + \delta + \delta' + \beta).$$

Finding the Intensity of Each Component – Each ray impinging on the surface is assigned an intensity of 1.0 light unit.

The amount of light reflected at each surface is found, and the transmitted component is reduced by this amount. Values for all components are obtained in

Fig. 7. Schematic representations of the calculation of the exit point, k .

this manner (ignoring scatter and absorption).

Two curves are then used for finding the amount reflected. The first curve is for a ray traveling from a less dense medium into a denser medium (Fig. 8A), and the second is for a ray traveling from a denser medium into a less dense medium (Fig. 8B). These curves were derived by using the equations known as Fresnel's laws of reflection (Fig. 9).

After tracing the paths of the several components of a ray entering a microballoon, and noting the angles associated with each, we can find the remaining intensity by using these reflection curves (as an example, Fig. 6).

Fig. 8. Reflected intensity vs angle of incidence (θ). A: For a ray traveling from a less dense to a denser medium. B: For a ray traveling from a denser to a less dense medium. See Fig. 9 for explanation of curves.

$$\frac{R_s}{E_s} = -\frac{\sin(\phi - \phi')}{\sin(\phi + \phi')}$$

$$\frac{R_p}{E_p} = \frac{\tan(\phi - \phi')}{\tan(\phi + \phi')}$$

$$r_s = \frac{R_s^2}{E_s^2}$$

$$r_p = \frac{R_p^2}{E_p^2}$$

Fig. 9. Fresnel's laws of reflection. E and R are the amplitudes of the electric vectors in the incident and reflected light, respectively. The subscripts denote the two planes of vibration; s is perpendicular to the plane of incidence, and p is parallel to the plane of incidence. The broken curves in Fig. 8 represent the absolute magnitudes of the reflected components of the ordinary ray.

Curves relating the transmitted portion of each component to the exit angle are shown in Fig. 10.

Having located the points of exit, angles of exit, and remaining intensities for the four components of an impinging ray, we can proceed to the final steps in constructing the illumination model.

Finding the Virtual Origins of the Rays—

The next step requires determining the point in the object plane from which each component appears to be emanating

Fig. 10. Percent reflection or transmission and exit angle (γ) vs angle of incidence (θ) for components 1 through 4. For the transmitted components (2, 3, and 4) $r_1 = 36 \mu\text{m}$, $a = 1 \mu\text{m}$, and $n' = 1.51$.

(see Fig. 7). Rays exiting at the positions and angles indicated are reconstructed in the image plane at points corresponding to the virtual intersection points in the object plane, which are located at distance r_3 from the axis.

Equations for determining r_3 for the four components are (refer to Fig. 7):

$$1: r_3 = k - [(\tan \gamma)(r_1 - f)].$$

2,3: These use the same equation as for 1, with their respective values for γ and ϵ .

$$4: r_3 = k - [d + (r_1 - f) \tan \gamma],$$

where $f = r_1 - (r_1^2 - k^2)^{1/2}$.

Constructing an Intensity Profile -

Having found the positions and intensities for the four components, we can build up a family of curves like Fig. 11 by using the curves in Fig. 10.

We are now able to complete an intensity profile for a microballoon by adding the contributions from the four components for any position of r_3 . This was the procedure used in producing the intensity profiles for three different wall thicknesses shown in Fig. 12.

Comparing the Model with Experiment

The intensity profile of the model can be compared with experimental illumination distributions from microballoons like those shown in Fig. 13. These scans are from two balloons, designated 5C and 6C, and were produced with a micro-image scanner.* The object plane of the microscope used in this instrument was established tangent to the rear surface, as in the model. The Y axes of the graphs are in density units, where D_T is defined as transmission density, and

$$D_T = \log_{10} \frac{1}{T}$$

*The micro-image scanner is described under "Photometric Techniques," below.

with

$$T = \frac{\phi_1}{\phi_j},$$

where ϕ_1 is the transmitted flux (flux transmitted through the sample), and ϕ_j is the aperture flux (the flux with no sample in the aperture).² The darker the object, the larger the number. The X axes are in microns traveled by the scanning stage and are linear.

Four scans are shown for 5C, and three for 6C. The scans were made through the central regions of the balloons, and each scan was separated from the last by a few microns. These microballoons are from a group selected for their perfection. Note the changes in the profiles from one position to another. These changes in profile reflect the changing wall conditions in the microballoons.

The portions of the profiles representing the dark rings form the greatest deviation from the model. This can be accounted for by several factors; chief among these are diffraction and scatter.

The model is based on geometric ray tracing and ignores physical optics, which includes such factors as diffraction, absorption, and scatter. An example of diffraction around microballoons can be seen in Fig. 14. Obviously, the illumination distribution around these balloons would not match the model. In order to gain a better understanding of the light flux from the surface of a microsphere, an opaque sphere having surface characteristics similar to those of a microballoon was scanned. The object plane of the microscope was established in the same position as before. With the data

Fig. 11. Intensity vs r_3 for components 1 through 4. The broken line is for curve 1 before empirical modification (see text, p. 9).

Fig. 12. Intensity profile for microballoons of various wall thicknesses.

Fig. 13. Experimental intensity profiles for two microballoons, 5C (78- μm o.d.) and 6C (76- μm o.d.).

obtained in this manner, the illumination curve representing reflection from the outside surface (No. 1 in Fig. 11), was modified from the dotted line to the solid line.

The factor which probably dominates in causing the difference between the model and the observed data is scatter. The model is based on a smooth surface, free of defects, whereas in reality a microballoon has a very rough surface. Figure 15 is a photograph, taken with an electron microscope, of a segment from a broken microballoon. Note the surface texture.

Ray components 1, 2, and 3 (see Fig. 7) make their greatest contribution to the illumination profile at large incidence angles. Light scatter from rough surfaces would greatly reduce their contribution. This is particularly true in the area beyond which component 4 reaches its critical angle as the angle of incidence is at its greatest. If scatter were taken into account in the model, much closer agreement would result.

Fig. 14. Photomicrograph showing diffraction around two microballoons.

WALL-THICKNESS MEASUREMENTS

Component 4, the transmitted ray, causes the steep gradient seen in the illuminated profile of our model (see Fig. 11). To understand its formation, refer again to Fig. 2, which shows 15 rays exiting a microballoon. These rays entered the balloon evenly spaced and parallel, but in the figure they are drawn so as to show the exiting rays' virtual points of intersection in the object plane. For a given ray, the distance from the balloon axis to the virtual point of intersection in the object plane is denoted r_3 . Note that as the exit angles increase, r_3 also in-

Fig. 15. Electron-microscope photograph of a segment of a broken microballoon. Note the rough surface.

creases at first; but, as the angles continue to increase, a point is reached beyond which rays with greater exit angles intersect at decreasing r_3 . The boundary of the black ring is formed where r_3 is greatest.

This illustration also points out the concentration of rays causing the highly illuminated area just inside the black ring. The relationship of the position of this abrupt gradient to the outside diameter of the balloon is a function of wall thickness and can be used to make accurate wall-thickness measurements. The variations in the position of this feature with wall thickness can be seen in Fig. 12. A normalized curve relating wall thickness to the ratio of the inside diameter of the black ring to the outside diameter of the microballoon is shown in Fig. 16.

Investigations have been conducted to determine what the optical properties of a microballoon would be if a layer of solid DT were coated on the inside surface. The purpose of the investigation was to determine if the layer could be

Fig. 16. Normalized curve relating wall thickness to the ratio of the inside diameter of the black ring to the outside diameter of the microballoon.

For a microballoon lined with frozen DT, which is a transparent solid of refractive index 1.20, ray tracings were made like those shown in Fig. 17. The equations necessary for the solution of γ are included with the figure. The distance r_3 can be found by using the equations for component 4 on p. 7. The actual programs used for calculating r_3 are included in the appendix; these programs find the largest r_3 for a simple microballoon or for a microballoon having an internal layer with a different index of refraction.

The conclusion of the investigation is that frozen DT on the inside wall can easily be detected and measured. For example, if a glass microballoon of index 1.51, with a diameter of 72 μm and a wall thickness of 1 μm , had a layer of frozen DT 2 μm thick, the inside diameter of the

black ring would be 16.2% less than that of the balloon alone. If the layer were only 0.5 μm thick, it would still reduce the inside diameter of the black ring by 4.5%.

These measurements would have to be carried out in situ, since cryogenic conditions must be maintained. Measurement can be accomplished either photographically or by means of a photometric microscope.

Factors involved in making accurate wall-thickness measurements based on this model are as follows:

• The object plane of the microscope must be accurately located. As can be seen in Fig. 2, the inside diameter of the black ring depends on where the object plane intersects the cone of rays. The change in r_3 caused by shifting the position of the object plane takes place slowly. As an example, shifting the object plane 4 μm changes r_3 from 29.567

$$\begin{aligned} n &= \text{entrance angle} & a &= \tan^{-1} \left(\frac{a_1 \tan \theta_1}{D} \right) \\ n &= \text{refractive index of the} & \theta_2 &= \theta_1 + \\ & \text{surrounding medium} & & \\ n' &= \text{refractive index of} & \theta_3 &= \sin^{-1} \left(\frac{n' \sin \theta_2}{n} \right) \\ & \text{the microballon} & & \\ n'' &= \text{refractive index of DT} & \theta_4 &= \sin^{-1} \left(\frac{n' \sin \theta_3}{n''} \right) \\ a &= \text{wall thickness of} & a' &= \tan^{-1} \left(\frac{a_1 \tan \theta_3}{r_0} \right) \\ & \text{the microballon} & \theta_4' &= \theta_3 - a' \\ a_1 &= \text{thickness of} & \theta_5 &= \sin^{-1} \left(\frac{n'' \sin \theta_4}{n''} \right) \\ & \text{the DT layer} & \theta_5' &= \tan^{-1} \left(\frac{a' \tan \theta_4}{a_1} \right) \\ r_1 &= \text{outside radius of} & \theta_6 &= \sin^{-1} \left(\frac{n' \sin \theta_5}{n} \right) \\ & \text{the microballon} & \theta_6' &= \tan^{-1} \left(\frac{a' \tan \theta_5}{a_1} \right) \\ r_2 &= \text{inside radius of} & \theta_7 &= \sin^{-1} \left(\frac{n' \sin \theta_6}{n} \right) \\ & \text{the microballon} & \theta_7' &= \tan^{-1} \left(\frac{a' \tan \theta_6}{a_1} \right) \\ r_0 &= \text{inside radius of} & \theta_8 &= \sin^{-1} \left(\frac{n' \sin \theta_7}{n} \right) \\ & \text{the DT layer} & \theta_8' &= \tan^{-1} \left(\frac{a' \tan \theta_7}{a_1} \right) \\ \theta_1 &= \sin^{-1} \left(\frac{n \sin \alpha}{n'} \right) & \theta_9 &= \theta_8 - \theta_7 \\ \theta &= \tan^{-1} \left(\frac{a \tan \theta_1}{r_2} \right) & \theta_9 &= \sin^{-1} \left(\frac{n' \sin \theta_8}{n} \right) \\ \theta_2 &= \theta_1 + \theta & \theta_{10} &= 180 - 2\theta_9 \\ \theta_3 &= \theta_2 + \theta & \theta_{11} &= 180 - (\theta_8 - \theta_7) + \theta_9 + \theta_8 + \theta_7 + \theta_9 \\ \theta_4 &= \sin^{-1} \left(\frac{n' \sin \theta_3}{n} \right) & & \end{aligned}$$

Fig. 17. Schematic representation of the calculation of the exit angle, γ , for a microballoon lined with a layer of frozen DT.

μm to 29.194 μm for a balloon with a diameter of 72 μm and a wall thickness of 1 μm .

- The acceptance angle of the microscope objective must be large enough to accommodate the exiting rays used in the model. An objective with a numerical aperture of 0.65 will be adequate, as its half angle in air is 40.5°.

- Light rays entering the microballoon should be reasonably parallel for accurate measurement. A divergence of 0.5° produces an error in r_3 of less than 0.02 μm when the ratio of the inside diameter of the black ring to the outside diameter of the microballoon goes from 0.66 to 0.88.

Photometric Techniques

The intensity distribution of the illumination coming from microballoons can be measured by several different photometric instruments. Either microballoons or photographs of microballoons can be analyzed with these instruments.

COLOR ISODENSITY TELEVISION DISPLAY

Photographs of microballoons can be displayed quickly and easily by using a color-television isodensity unit. An instrument is available that can display the density variations of the photograph in 32 different colors on a television picture tube. This instrument can accept a density range of 3.5. Each color represents a discrete density interval. Figure 18A shows a transparent positive black-and-white picture of a microballoon displayed by this technique.

Another display option for this instrument presents a density profile on a black-and-white picture tube. This unit shares the same camera system with the color display. The same picture is displayed on the black-and-white tube with a line superimposed on the image. A profile of the density is displayed corresponding to the position indicated by the

reference line. The reference line can be placed anywhere on the image, yielding the density profile at that position. Such a density profile is shown in Fig. 19; this is the same image as that displayed in Fig. 18A.

Measurements can be taken from features in the image by using the video micrometer attachment. The instrument can be calibrated to a convenient scale and has a digital readout. Measurements are made by moving superimposed lines over the image by means of an X-Y joy stick. Figure 20 is a photograph of the television display system.

ISODENSITRACER

The Isodensitracer is a type of microdensitometer that can scan either microballoons or photographs of microballoons. The data can be displayed as either density contours or density profiles. If microballoons are scanned, the influx optics must be modified to provide parallel light.

An isodensitrace (density contour) made by this instrument is shown in Fig. 18B. Four colors are used, and each color appears four times in

Fig. 19. Another television isodensity display option. A density contour, from the same picture as that used for Fig. 18, is displayed on a black-and-white picture tube. The superimposed white reference line can be placed anywhere on the image, and a density profile is displayed that corresponds to the position indicated by the reference line.

covering the selected density range; this means that a change from one color to the next represents $1/16$ of the total range. In addition, each color can be displayed in four different codes consisting of dots and dashes. This combination of color and line coding allows the density range to be displayed in 64 increments. The sequence of colors indicates whether the density is increasing or decreasing; red, blue, green, black is the sequence for increasing density.

This instrument has the advantages of greater density range, finer density resolution, and greater accuracy in density measurements. The output display is on high-quality hard copy with very little distortion. The chief disadvantages are that it requires an experienced operator and that developing data by this technique is very time-consuming. Figure 21 is a photograph of this instrument.

Fig. 20. Isodensity television display system.

Fig. 21. Isodensitracer isodensitometer.

Fig. 22. Micro-image scanner.

MICRO-IMAGE SCANNER

An instrument well suited to making experimental density-profile measurements of microballoons is the micro-image scanner. It is an automatic scanning microdensitometer with no influx optics. This allows full freedom to provide the parallel light needed for measuring purposes. The density profiles in Fig. 13 were made with this instrument.

Its disadvantages are that it is not well suited to scanning photographs and that den-

sity contours cannot be made with this unit. Figure 22 is a photograph of this instrument.

COMPUTER-CONTROLLED MICRODENSITOMETER

This system has many advantages over the systems previously described. Chief among these are speed, accuracy, and flexibility. A microballoon can be scanned and the information digitized and stored on tape in approximately 30 seconds; in contrast, the isoscan shown in Fig. 18B required approximately three hours to produce, working from a photograph. The coordinates for all data points are known within 1 μm ; for the scans shown here, data points were taken every micron in both X and Y.

Data from this system can be displayed in several modes. First and most important for the inspection of microballoons is the density contour. Figure 23 displays the density contours of two microballoons. Localized defects as well as variations in wall thickness can easily be recognized, and spheroidicity and diameter can also be found.

The density profile can be displayed for any single sweep composing the

Fig. 23. Density contours of two microballoons (top view), from data digitized by the computer-controlled microdensitometer and displayed on a dd80. Data grid: 176 points by 176 lines; 1- μm increments between rasters in both X and Y. Maximum density: 1.10 density units. Contour intervals: solid lines, 1.00 density unit; dotted lines, 0.10 density unit.

density contour. Figure 24 shows one sweep. Wall-thickness measurements can be taken from the density profile. Isometric views of the density profiles can be seen in Fig. 25.

Photographs of this microdensitometer are shown in Fig. 26.

An experienced operator is required for both instrument operation and data display. The scans shown are valuable; however, the incident illumination was not parallel enough for accurate wall-thickness measurements. A modification would be required in order to render the incident light parallel.

Fig. 24. Density profile from one of the sweeps composing the density contour in Fig. 23.

Fig. 25. Isometric views of density contours. A: Front view. B: Back view. C. Front view, inverted.

Conclusions

Data on the illumination from micro-balloons taken with these photometric instruments can be evaluated on the basis of the model developed here. In order to obtain

complete information, it will be necessary to scan the balloon in several orientations.

Large defects, such as slowly changing wall thickness and deviation from

Fig. 26. The computer-controlled microdensitometer. Left: Scanner. Right: Controller and data processor.

sphericity, can easily be detected and measured. Small defects, such as bubbles in the walls and bumps and depressions, are more difficult to detect and interpret; however, of all of the microballoons evaluated, none was found to be free from detectable defects by any of the microdensitometers described. Thus a threshold of detection for small defects has not yet been established for these photometric devices.

Attempts to correlate wall-thickness measurements based on the model presented here with values obtained by several other techniques are in progress. A report on this work is available.³

Of the instruments described, the computer-controlled microdensitometer would lend itself best to the semiautomatic inspection of microballoons. We are investigating the possibilities of programming the apparatus to recognize specific structural characteristics in microballoons.

Acknowledgments

This work was undertaken at the suggestion of R. Stone. I would like to thank G. Michael for suggestions offered for the improvement of this report.

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Appendix

Calculator Program to Solve for r_3 for Transmitted Ray Segment 4*

MICROBALLOON SHELL
WITHOUT INNER COATING

Required Input

Register

R01 = n' index of refraction of shell
R02 = r_1 outside radius
R03 = r_2 inside radius
R04 = a wall thickness
K2 = θ entrance angle
K3 = Δ the increment which, when
added to θ , forms the new
 θ .

(All angles are in degrees.)

Storage

Register

R05 = θ_1
R06 = δ
R07 = θ_2
R08 = θ_3
R09 = θ_4
R10 = δ'
R11 = θ_5
R12 = γ
R13 = β
R14 = k

Equations for Solution of r_3

$$\theta_1 = \sin^{-1} \left(\frac{n \sin \theta}{n'} \right)$$

$$\delta = \tan^{-1} \left(\frac{a \tan \theta_1}{r_2} \right)$$

$$\theta_2 = \theta_1 + \delta$$

$$\theta_3 = \sin^{-1} \left(\frac{n' \sin \theta_2}{n} \right)$$

$$\theta_4 = \sin^{-1} \left(\frac{n \sin \theta_3}{n'} \right)$$

$$\delta' = \tan^{-1} \left(\frac{a \tan \theta_4}{r_1} \right)$$

$$\theta_5 = \theta_4 - \delta'$$

$$\theta_6 = \sin^{-1} \left(\frac{n' \sin \theta_5}{n} \right)$$

$$\beta = 180^\circ - 2\theta_3$$

$$\gamma = 180^\circ - (\theta + \delta + \beta + \delta' + \theta_6)$$

$$\epsilon = 180^\circ - (\theta + \delta + \delta' + \beta)$$

$$k = \sin \epsilon(n)$$

$$f = r_1 - (r_1^2 - k^2)^{1/2}$$

$$r_3 = k - \tan \gamma [d + (n - f)]$$

Program Steps

0000	R
0001	
0002	3
0003	
0004	F
0005	O
0006	R
0007	
0008	T
0009	R
0010	A
0011	N
0012	S
0013	
0014	.
0015	
0016	R
0017	A
0018	Y
0019	
0020	
0021	PAPR
0022	E
0023	N

* This program is designed for use on the Tektronix Model #31 desk calculator.

Fig. A1. Flow chart of the calculator program for solving for r_3 of transmitted ray component 4.

```

0024      T
0025      E
0026      R
0027
0028      D
0029      A
0030      T
0031      A
0032      STOP
0033      K_
0034      2
0035      PRNT
0036      R_
0037      0
  
```

```

0038      1
0039      PRNT
0040      R_
0041      0
0042      2
0043      PRNT
0044      R_
0045      0
0046      4
0047      PRNT
0048      CONT
0049      K_
0050      2
0051      SIN
0052      /
0053      R_
0054      0
0055      1
0056      =
0057      ARC
0058      SIN
0059      =
0060      R_
0061      0
0062      5
0063      TAN
0064      *
0065      R_
0066      0
0067      4
0068      =
0069      /
0070      R_
0071      0
0072      3
0073      =
0074      ARC
0075      TAN
0076      =
0077      R_
0078      0
0079      6
0080      +
0081      R_
0082      0
0083      5
0084      =
0085      R_
0086      0
0087      7
0088      SIN
0089      *
0090      R_
0091      0
0092      1
0093      =
0094      ARC
0095      SIN
0096      =
0097      R_
0098      0
0099      8
  
```

$\left. \begin{array}{l} \theta_1 \\ \theta_2 \\ \theta_3 \end{array} \right\}$

0100	SIN		0162	+/-	
0101	/		0163	=	
0102	R--		0164	R--	} β
0103	0		0165	1	
0104	1		0166	3	
0105	=		0167	+	
0106	ARC		0168	R--	
0107	SIN		0169	.	
0108	=		0170	1	
0109	R--	} θ_4	0171	=	
0110	0		0172	+	
0111	9		0173	R--	
0112	TAN		0174	1	
0113	*		0175	0	
0114	R--		0176	=	
0115	0		0177	+	
0116	4		0178	R--	
0117	=		0179	0	
0118	/		0180	6	
0119	R--		0181	=	
0120	0		0182	+	
0121	2		0183	K-	
0122	=		0184	2	
0123	ARC		0185	.	
0124	TAN		0186	-	
0125	=		0187	1	
0126	R--	} δ'	0188	8	
0127	1		0189	0	
0128	0		0190	=	
0129	CLDP		0191	+/-	
0130	R--		0192	IF<0	
0131	0		0193	STOP	
0132	9		0194	CONT	
0133	-		0195	PRNT $\rightarrow \gamma$	
0134	R--		0196	R--	
0135	1		0197	1	
0136	0		0198	2	
0137	=		0199	CLDP	
0138	SIN		0200	R--	
0139	*		0201	0	
0140	R--		0202	6	
0141	0		0203	*	
0142	1		0204	2	
0143	=		0205	=	
0144	ARC		0206	+	
0145	SIN		0207	K-	
0146	=		0208	2	
0147	R--	} θ_6	0209	=	
0148	1		0210	+	
0149	1		0211	R--	
0150	CLDP		0212	1	
0151	R--		0213	3	
0152	0		0214	=	
0153	8		0215	-	
0154	*		0216	1	
0155	2		0217	8	
0156	=		0218	0	
0157	-		0219	=	$\rightarrow \epsilon$
0158	1		0220	+/-	
0159	8		0221	SIN	
0160	0		0222	*	
0161	-		0223	R--	

```

0224 0
0225 2
0226 =
0227 R-- } k
0228 1
0229 4
0230 X12
0231 =
0232 K-
0233 1
0234 CLDP
0235 R--
0236 0
0237 2
0238 X12
0239 -
0240 K-
0241 1
0242 =
0243 SQRT
0244 -
0245 R--
0246 0
0247 2
0248 = → f
0249 +/-
0250 -
0251 R--
0252 0
0253 2
0254 =
0255 +/-
0256 +
0257 R--
0258 0
0259 2
0260 =
0261 K-
0262 1
0263 CLDP
0264 R--
0265 1
0266 2
0267 TAN
0268 *
0269 K-
0270 1
0271 =
0272 -
0273 R--
0274 1
0275 4
0276 =
0277 +/-
0278 PRNT → r3
0279 CLDP
0280 3SM2
0281 K-
0282 2
0283 PRNT
0284 CLDP
0285 GOTO

```

```

0286 0
0287 0
0288 4
0289 9

```

Printout

R 3 FOR TRANS:

RAY

ENTER DATA

```

50. 0
1.51 n'
36. r3
1. a
2.04713796 γ
26.30442147 r3
52.5 new θ
2.342489059
27.1072263
55.
2.693032151
27.82318041
57.5
3.114077137
28.44192516
60.
3.62722289
28.94984683
62.5
4.264245841
29.32808009
65.
5.074540073
29.54873965
67.5
6.14091344
29.56704148 largest r3
70.
7.618564923
29.30219274
72.5
9.857714828
28.57840786
75.
14.04226092
26.82442477
77.5

```

MICROBALLOON SHELL
WITH INNER COATING

Required Input

Register

```

K2 = θ entrance angle
K3 =
K4 = n' index of refraction of shell
K5 = n'' index of refraction of inner
coating

```

$K6 = r_1$ outside radius of shell
 $K7 = r_2$ inside radius of shell
 $K8 = r_0$ inside radius of inner coating
 $K9 = a$ wall thickness of shell
 $K1 = a'$ thickness of inner coating

Storage

Register

$R01 = \theta_1$
 $R02 = \delta$
 $R03 = \theta_2$
 $R04 = \phi_1$
 $R05 = \sigma$
 $R06 = \phi_2$
 $R07 = \theta_3$
 $R08 = \phi_3$
 $R09 = \sigma'$
 $R10 = \phi_4$
 $R11 = \theta_4$
 $R12 = \delta'$
 $R13 = \theta_5$
 $R14 = \theta_6$
 $R15 = \beta$
 $R16 = \gamma$
 $R17 = \epsilon$
 $R18 = k$
 $R19 = f$

Program Steps

0000 R
 0001 3
 0002
 0003 F
 0004 O
 0005 R
 0006
 0007 R
 0008 A
 0009 Y
 0010
 0011 4
 0012 +
 0013 3
 0014 N
 0015 P
 0016 E
 0017 N

0018 T
 0019 E
 0020 R
 0021
 0022 D
 0023 A
 0024 T
 0025 A
 0026 STOP
 0027 K-
 0028 2
 0029 PRNT
 0030 K-
 0031 4
 0032 PRNT
 0033 K-
 0034 5
 0035 PRNT
 0036 K-
 0037 6
 0038 PRNT
 0039 K-
 0040 7
 0041 PRNT
 0042 K-
 0043 8
 0044 PRNT
 0045 K-
 0046 9
 0047 PRNT
 0048 K-
 0049 1
 0050 PRNT
 0051 K-
 0052 2
 0053 SIN
 0054 /
 0055 K-
 0056 4
 0057 =
 0058 ARC
 0059 SIN
 0060 =
 0061 R--
 0062 0
 0063 1
 0064 TAN
 0065 *
 0066 K-
 0067 9
 0068 =
 0069 /
 0070 K-
 0071 7
 0072 =
 0073 ARC
 0074 TAN
 0075 =
 0076 R--
 0077 0
 0078 2
 0079 +
 0080 R--

0081 0
 0082 1
 0083 =
 0084 R--
 0085 0
 0086 3
 0087 SIN
 0088 *
 0089 K-
 0090 4
 0091 =
 0092 /
 0093 K-
 0094 5
 0095 =
 0096 ARC
 0097 SIN
 0098 =
 0099 R--
 0100 0
 0101 4
 0102 TAN
 0103 *
 0104 K-
 0105 1
 0106 =
 0107 /
 0108 K-
 0109 8
 0110 =
 0111 ARC
 0112 TAN
 0113 =
 0114 R--
 0115 0
 0116 5
 0117 +
 0118 R--
 0119 0
 0120 4
 0121 =
 0122 R--
 0123 0
 0124 6
 0125 SIN
 0126 *
 0127 K-
 0128 5
 0129 =
 0130 ARC
 0131 SIN
 0132 =
 0133 R--
 0134 0
 0135 7
 0136 SIN
 0137 /
 0138 K-
 0139 5
 0140 =
 0141 ARC
 0142 SIN

0143 =
 0144 R--
 0145 0
 0146 8
 0147 TAN
 0148 *
 0149 K-
 0150 1
 0151 =
 0152 /
 0153 K-
 0154 8
 0155 =
 0156 ARC
 0157 TAN
 0158 =
 0159 R--
 0160 0
 0161 9
 0162 =
 0163 R--
 0164 0
 0165 8
 0166 =
 0167 +/-
 0168 R--
 0169 1
 0170 0
 0171 SIN
 0172 *
 0173 K-
 0174 5
 0175 =
 0176 /
 0177 K-
 0178 4
 0179 =
 0180 ARC
 0181 SIN
 0182 =
 0183 R--
 0184 1
 0185 1
 0186 TAN
 0187 *
 0188 K-
 0189 9
 0190 =
 0191 /
 0192 K-
 0193 6
 0194 =
 0195 ARC
 0196 TAN
 0197 =
 0198 R--
 0199 1
 0200 2
 0201 =
 0202 R--
 0203 1
 0204 1

0205 =
 0206 +/-
 0207 R--
 0208 1
 0209 3
 0210 SIN
 0211 ^
 0212 K-
 0213 4
 0214 *
 0215 ARC
 0216 SIN
 0217 =
 0218 R--
 0219 1
 0220 4
 0221 CLDP
 0222 R--
 0223 0
 0224 7
 0225 +
 0226 2
 0227 =
 0228 ^
 0229 1
 0230 8
 0231 0
 0232 =
 0233 +/-
 0234 =
 0235 R--
 0236 1
 0237 5
 0238 +
 0239 R--
 0240 1
 0241 4
 0242 =
 0243 +
 0244 R--
 0245 0
 0246 9
 0247 =
 0248 +
 0249 R--
 0250 0
 0251 5
 0252 =
 0253 +
 0254 R--
 0255 1
 0256 2
 0257 =
 0258 +
 0259 R--
 0260 0
 0261 2
 0262 =
 0263 +
 0264 K-
 0265 2
 0266 =

0267 -
 0268 1
 0269 8
 0270 0
 0271 *
 0272 +/-
 0273 IF<0
 0274 STOP
 0275 CONT
 0276 PRNT
 0277 *
 0278 R--
 0279 1
 0280 6
 0281 +
 0282 R--
 0283 1
 0284 4
 0285 *
 0286 R--
 0287 1
 0288 7
 0289 SIN
 0290 ^
 0291 K-
 0292 6
 0293 =
 0294 R--
 0295 1
 0296 8
 0297 CLDP
 0298 K-
 0299 6
 0300 X12
 0301 -
 0302 R--
 0303 1
 0304 8
 0305 X12
 0306 =
 0307 SQRT
 0308 -
 0309 K-
 0310 6
 0311 =
 0312 +/-
 0313 =
 0314 R--
 0315 1
 0316 9
 0317 CLDP
 0318 K-
 0319 6
 0320 -
 0321 R--
 0322 1
 0323 9
 0324 =
 0325 +
 0326 K-
 0327 6
 0328 =

0329 R--
 0330 2
 0331 0
 0332 CLDP
 0333 R--
 0334 1
 0335 6
 0336 TAN
 0337
 0338 R--
 0339 2
 0340 0
 0341 =
 0342 -
 0343 R--
 0344 1
 0345 H
 0346 =
 0347 +/-
 0348 PRNT
 0349 CLDP
 0350 3SM2
 0351 K-
 0352 2
 0353 PRNT
 0354 CLDP
 0355 GOTO
 0356 0
 0357 0
 0358 5
 0359 1

Printout

R3 FOR RAY 4+3N
 ENTER DATA

50. 0
 1.51 n'
 1.2 n''
 36. r1
 35. r2
 33. r0
 1. a
 2. a1
 5.283603136 7
 24.17007493 r3
 52.5 new 0
 6.253616147
 24.37091226
 55.
 7.486744208
 24.77115436
 57.5
 9.10109444
 24.71768245
 60.
 11.30788224
 24.30193896
 62.5
 14.55338525
 23.31770288
 65.
 20.17504564
 21.16160275
 67.5

largest r3