



RESEARCH MEMORANDUM

MEASUREMENT OF THERMAL DISTORTION OF THE SUBMARINE
INTERMEDIATE REACTOR "MARK A" MODERATOR TUBE

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MEASUREMENT OF THERMAL DISTORTION OF THE SUBMARINE

INTERMEDIATE REACTOR "MARK A" MODERATOR TUBE

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SUMMARY

A moderator tube of the Submarine Intermediate Reactor (SIR) ("Mark A") was subjected to temperature gradients considered to be representative of those occurring in the reactor during operation. The distortion of the tube as a result of the imposed temperature gradients was measured under two conditions: (1) with the ends of the tube retained in the same manner as in the reactor; and (2) with the ends of the tube simply supported. Restraining end moments were present in the first case which reduced the maximum distortion by approximately 55 percent of that obtained when the tube was simply supported with end moments known to be zero. When retained in the same manner as in the reactor, the maximum transverse distortion of the moderator tube was 0.060 inch at a point 20 inches from the handle end.

INTRODUCTION

Preliminary theoretical considerations of the design of the SIR "Mark A" reactor have indicated that the moderator tube may be appreciably distorted by temperature gradients which are imposed during full power operation. The distortion of the moderator tube was therefore determined experimentally at the NACA Lewis laboratory under conditions of temperature and temperature gradients specified by the Knolls Atomic Power Laboratory, and considered similar to those that would exist during operation of the reactor.

The moderator tube consists essentially of a 347 stainless steel tube filled with beryllium slugs approximately $1\frac{1}{2}$ inches long, and having a wall thickness of 0.010 inch, a diameter of the order of $1\frac{1}{4}$ inches, and an over-all length of approximately 57 inches.

Distortion measurements were made with the moderator tube held in the same manner as in the reactor and also with the tube simply

supported, with end moments known to be zero. The experimental distortion values were compared with an analytically determined distortion curve.

The moderator tube was furnished by the Knolls Atomic Power Laboratory.

EXPERIMENTAL PROCEDURE AND APPARATUS

The experimental procedure consisted in measuring the distortion of the moderator tube that occurred as a result of the establishment of specified temperature gradients in the tube. Basically, there were three requirements involved in the experimental investigation: (1) That the ends of the moderator tube be held in a manner similar to the retention within the reactor; (2) that the temperature gradients established in the tube should conform closely to values specified by the Knolls Atomic Power Laboratory as representative of conditions to be expected in the reactor; and (3) that any distortion resulting from the established temperature gradients be measured within an accuracy of ± 0.002 inch.

Moderator tube and method of retention in reactor. - The moderator tube is shown in figure 1 with the thermocouples installed. Details of the tube are shown in figure 2 which indicates the method of retention in the reactor. The end of the tube at the left in figure 2 (top, in reactor also called handle end) is supported in the transverse direction by three equally spaced fins, while an axial force applied to the button compresses a spring in the opposite end of the tube $1/2$ inch. The compression load on the tube is approximately 150 pounds. The end at the right in figure 2 has three equally spaced metering struts which are seated in a conical holder. In order to obtain the described end conditions, the moderator tube was mounted horizontally in machined fixtures between two massive concrete blocks as shown in figure 3. An adjustable positioning device was used to locate the handle end of the tube and to provide a means of varying the compression of the spring within the tube.

Between sections 5 and 6 (fig. 2) the tube has a wall thickness of 0.010 inch and is fabricated from 347 stainless steel. The thin walled tube is welded at the ends to solid 347 stainless steel plugs. The plug at the handle end slides into a hole in the solid handle and is pinned with one pin. The plug at the opposite end slides within a thick walled tube which contains the spring. Clearances provide a small amount of play at both pinned joints. The tube contains loose fitting beryllium slugs, approximately $1\frac{1}{2}$ inches long, between sections 5 and 6.

Method of obtaining temperature gradients. - The specified temperature gradients which were to be imposed on the moderator tube are shown in

figure 2. The temperature profile formed by the line ABCD (fig. 2) was to be imposed along an element of the tube parallel to the axis while the profile EFCD was imposed along another element displaced 180° from the first. It was also desired that the temperature gradient across the diameter between the two elements of the tube be linear and, therefore, that the tube temperatures around the circumference vary in a sinusoidal manner.

2652 An approximation to the described set of temperature gradients was obtained through the use of induction heating, localized radiation and convection heating, and localized air cooling. The general arrangement of the heating and cooling equipment is shown in figure 3. The specified axial temperature distribution was obtained by varying the spacing between adjacent turns of the induction heating coil. The diametral or transverse gradients were produced by cooling along one element of the tube with compressed air and adding additional heat to the element displaced 180° from the cooled element by means of steel bars which were in turn heated by the induction coil. Because of the variation in transverse gradient along the length of the tube, a manifold was used in order to permit adjustment of the amounts of cooling air in the various axial sections. Along the element which was to be heated, stainless-steel troughs were supported that contained bars of SAE 1015 steel heated to incandescence by the induction coil. The heat supplied was controlled by the width and the length of the steel bars and by varying the distance between the stainless-steel troughs and the moderator tube. Strips of woven glass sleeving approximately 1/2 inch in diameter were cemented along both sides of the tube to alleviate unfavorable convection.

Temperatures were measured by thermocouples spot welded to the tube at nine stations located along the length of the tube. At each station four thermocouples were located equally spaced around the circumference, with one couple on the cooled element of the tube and one on the heated element of the tube. The thermocouples were fabricated from Brown and Sharpe No. 32 chromel and alumel wires to produce a small junction which could be spot welded to the thin walled tube without injuring the tube. The junctions were not shielded since it was not known at the specific thermocouple locations whether or not the beryllium slugs were in contact with the thin walled tube. The temperature measurements were therefore probably more accurate where the slugs did not touch the tube and less accurate where the slugs did touch the tube at the junction locations. The heating and cooling arrangements were made to obtain heating along the bottom of the tube and cooling along the top of the tube as horizontally oriented in the fixtures between the concrete blocks.

Measurement of distortion. - The displacement of the moderator tube during the course of the experiment was measured by dial indicators and optical cathetometers (fig. 3). The dial indicators were oriented

to measure deflections in the vertical and horizontal directions. The cathetometers measured vertical and horizontal deflections, also, and were more flexible in operation, permitting measurements at any desired location along the length of the tube. Comparisons made between dial indicator and cathetometer readings at comparable points on the tube showed good agreement. Both cathetometers were mounted on a single pedestal that could be moved on a carriage parallel to the moderator tube. Vertical deflections were measured by direct observation of a longitudinal line scribed on the tube; horizontal deflections were observed in a similar manner through a simple front surface mirror system (fig. 3). All mirror and dial indicator supporting racks were maintained at constant temperature by the circulation of water through the rack bars. Instrument accuracy was ± 0.002 inch.

RESULTS AND DISCUSSION

Distortion with end retention similar to reactor conditions. - The positioning device for the handle end of the moderator tube was set to compress the spring 0.50 inch when the tube was brought up to the desired temperature conditions. Axial expansion of the tube was allowed for in setting the positioning device when the tube was cold. The end retention was therefore the same as that obtained in the reactor with approximately 150 pounds of axial compression loading on the tube.

The measured temperatures along the heated and cooled elements of the tube are shown in figure 4(a) together with the desired temperature profiles. The measured distortion of the tube in the vertical plane as a result of the imposed temperature gradients is also shown in figure 4(a). These results were taken from a series of runs and were chosen because the measured temperatures more nearly conformed to the desired temperature profile curves. The distortion measurements in other runs of the series corroborated those presented. Repeated application of the temperature gradients did not appear to permanently distort the tube.

The maximum measured distortion as seen in figure 4(a) is 0.060 inch, occurring at a distance of 20 inches from the handle end. The theoretical distortion curve accompanying the experimental curve is discussed in the following section.

Theoretical distortion. - The distortion of the moderator tube as a result of the temperature gradients was also determined by a theoretical method which is described in detail in the appendix. In this method the tube was assumed to be simply supported and moments at the ends were assumed to be zero; the temperature distribution around the circumference of the tube was assumed to be sinusoidal. The resulting theoretical distortion curve is shown in the lower portion of figure 4(a) as the

solid line. The maximum distortion is 0.131 inch and occurs at a distance of 24.7 inches from the handle end of the tube. The maximum theoretical distortion is therefore 2.18 times the maximum experimental distortion.

Measured distortion with simply supported ends. - The difference between the previously described experimental and theoretical distortion curves indicated that the end moments were not zero in the method of retention used in the reactor. Another series of distortion measurements were therefore made with the moderator tube supported in a manner in which it was known that the end moments were zero. The handle end of the tube was allowed to rest on the fins, but the metering struts end was supported on a transite V-block and no axial forces were applied to the tube. The specified temperature gradients were established and the measured temperatures and distortion are shown in figure 4(b) together with the same theoretical distortion curve shown in figure 4(a). It is seen that under the conditions of simple support with zero end moments, the experimental distortion curve agrees well with the theoretical curve. The maximum measured distortion was 0.134 inch at a point 25 inches from the handle end.

Deflection with concentrated transverse loading. - In order to substantiate the existence of the end moment effect in reducing the distortion resulting from the imposed temperature gradients, a load-deflection test was employed with the moderator tube supported in two different manners; (1) retention the same as in the reactor, and (2) simply supported in a manner in which the end moments were known to be zero. Weights in 1 pound increments up to 4 pounds were suspended from the tube at a point 24.7 inches from the handle end. The deflections produced were measured in the same manner as the distortions caused by the temperature gradients. The deflection curves for the two methods of support are shown in figure 5. It will be noted that the ratio of the maximum deflections in the two cases is 2.17. The ratio of the maximum experimental distortions in the two cases of support as a result of the imposed temperature gradients was 2.23. Although these two values cannot be strictly compared, they do serve to substantiate the presence of the end moment restraining effect.

It will also be noted by inspection of the shapes of the two deflection curves in figure 5, that the major restraining end moment occurs at the metering struts end. This condition would be expected since the metering struts are forced against the walls of the conical holder with a force of approximately 150 pounds. An appreciable restraining end moment is therefore present, whereas at the opposite end of the tube a smaller end moment is obtained, primarily because of the flexibility in the slim stem connecting the button and the handle.

Significance with respect to reactor operation. - Since the development of excessive temperatures in certain localized regions is largely a result of nonuniform coolant flow, distortion of the moderator tube

within the matrix tube is of particular significance. However, it has been shown in the tests described herein that the distortion of the tube as retained in the reactor and with a specified set of temperature gradients is approximately one-half that for a simply supported tube. The end restraint provided by the metering struts which are forced into the conical holder is therefore of considerable advantage in minimizing nonuniform coolant flow by tending to hold the moderator tube concentric with the matrix tube. It is assumed that, initially, the moderator tube is in axial alinement with the matrix tube. From this standpoint, it would be of further advantage to also incorporate a like end restraint at the handle end. It should be recognized, however, that the machining tolerances involved are somewhat critical since malalignment of the struts bearing against the cone surface can also cause distortion of the moderator tube.

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SUMMARY OF RESULTS

A specified set of axial and transverse temperature gradients was established in a moderator tube of the Submarine Intermediate Reactor and the distortion of the tube resulting from the temperature gradients was measured with an instrument accuracy of ± 0.002 inch. A theoretical distortion curve was determined on the basis of the same specified temperature gradients with the ends of the moderator tube simply supported. The following results were noted:

1. The maximum measured distortion of the tube with the ends restrained as in the reactor was 0.060 inch at a point 20 inches from the handle end.
2. The maximum measured distortion of the tube with the ends simply supported and the end moments known to be zero was 0.134 inch at a point 25 inches from the handle end.
3. The theoretical distortion curve with the ends assumed to be simply supported and with zero end moments indicated a maximum distortion of 0.131 inch at a point 24.7 inches from the handle end, agreeing well with the experimentally measured results.
4. The end restraining moment caused by the method of retention in the reactor is therefore appreciable and results in a 55 percent reduction in the maximum distortion. Initial axial alinement of the moderator tube with the matrix tube is assumed.

APPENDIX - DETERMINATION OF THEORETICAL DEFORMATION CURVE

The deformation curve of the moderator tube as produced by the temperature pattern shown in figures 2 and 6 was theoretically determined for the end conditions of zero restraining moments. The temperatures along one element of the tube are described by the line ABCD in figure 6 and the temperatures along another element of the tube displaced 180° from the first are described by the line EFCD. The temperature gradient across the diameter is assumed to be linear or, in other words, to vary sinusoidally around the circumference; the tube is therefore assumed to be stress free.

Between sections 4 and 3 in figure 6, the temperature gradient across the tube diameter is zero and the tube in this region does not deform. In relation to the coordinate system shown in figure 7, the axis of the tube is described by $y = 0$ from $x = 0$ to $x = -13.55$.

Between sections 3 and 2 the temperature gradient across the diameter of the tube varies linearly with length (from $x = 0$ to $x = 27.25$). Figure 7 shows a small element of the tube in this region having the original conditions of length equal to ΔS , diameter of d , and uniform temperature T_0 . The tube is then considered to be subjected to a linear diametral gradient with the temperature along the top element of the tube equal to T_T and with the temperature along the bottom element of the tube equal to T_B . Deformation of the element occurs in the form of an arc with a radius of curvature R as shown with an included angle of $\Delta\theta$. The new diameter of the tube becomes

$d \left[1 + \alpha \left(\frac{T_T + T_B}{2} - T_0 \right) \right]$, the new length of the tube element along the bottom is $\Delta S \left[1 + \alpha (T_B - T_0) \right]$, and the new length along the top is $\Delta S \left[1 + \alpha (T_T - T_0) \right]$. The following equations can then be written:

$$\Delta S \left[1 + \alpha (T_B - T_0) \right] = R \Delta\theta \quad (1)$$

$$\Delta S \left[1 + \alpha (T_T - T_0) \right] = \left\{ R + d \left[1 + \alpha \left(\frac{T_T + T_B}{2} - T_0 \right) \right] \right\} \Delta\theta \quad (2)$$

where α is the coefficient of expansion and taken to be 10×10^{-6} °F for 347 stainless steel in the temperature range considered.

From equations (1) and (2), the radius of curvature of the bottom of the tube can then be written:

$$R = \frac{d \left[1 + \alpha \left(\frac{T_T + T_B}{2} - T_0 \right) \right] \left[1 + \alpha (T_B - T_0) \right]}{\alpha (T_T - T_B)} \quad (3)$$

The radius of curvature R' of the axis of the tube, which by good approximation is equal to the reciprocal of the second derivative of the deformation of the tube axis, is expressed as follows:

$$R' = R + \frac{d}{2} \left[1 + \alpha \left(\frac{T_T + T_B}{2} - T_0 \right) \right] = \frac{1}{y''} \quad (4)$$

T_T and T_B are now expressed as functions of the length of the tube x which leads to the following equation:

$$y'' = \frac{x}{Ax^2 + Bx + C} \quad (5)$$

where A , B , and C are constants and found equal to

$$A = 0.00034894$$

$$B = 7.0138$$

$$C = 35,244$$

The term Ax^2 is assumed to be insignificant and the resulting equation is integrated twice to obtain the deformation curve between sections 3 and 2:

$$y' = \frac{x}{B} - \frac{C}{B^2} \log \left(\frac{Bx+C}{C} \right) \quad (6)$$

$$y = \frac{x^2}{2B} - \frac{C^2}{B^3} \left[\frac{Bx+C}{C} \right] \left[\log \left(\frac{Bx+C}{C} \right) - 1 \right] - \frac{C^2}{B^3} \quad (7)$$

Between sections 2 and 1 the diametral temperature gradient is constant; the deformation curve of the axis of the tube takes the form of a circle with a radius as obtained from equation (4) equal to

$$R' = \frac{Fd}{2} \frac{E+D}{E-D} \quad (8)$$

where

$$D = 1 + \alpha (T_B - T_0)$$

$$E = 1 + \alpha (T_T - T_0)$$

$$F = 1 + \alpha \left(\frac{T_T + T_B}{2} - T_0 \right)$$

From equations (6) and (7), the slope and the deformation of the tube can be obtained at section 2. Having given then, the radius (equation (8)), a point through which the circle must pass, and the slope of the circle at that point, the equation of the correct circle can be determined. The complete deformation curve of the tube axis shown in figure 6 is now described by a straight line (from $x = -13.55$ to $x = 0$) joined to a section of equation (7) (from $x = 0$ to $x = +27.25$) which is in turn joined to a section of a circle (from $x = +27.25$ to $x = 38.50$).

In order to obtain deformation values comparable to the measured quantities, a straight line (HK) is drawn, passing through the ends of the deformation curve which represent the supporting points of the tube. The distance between the straight line and the deformation curve is then comparable with the measured quantities.

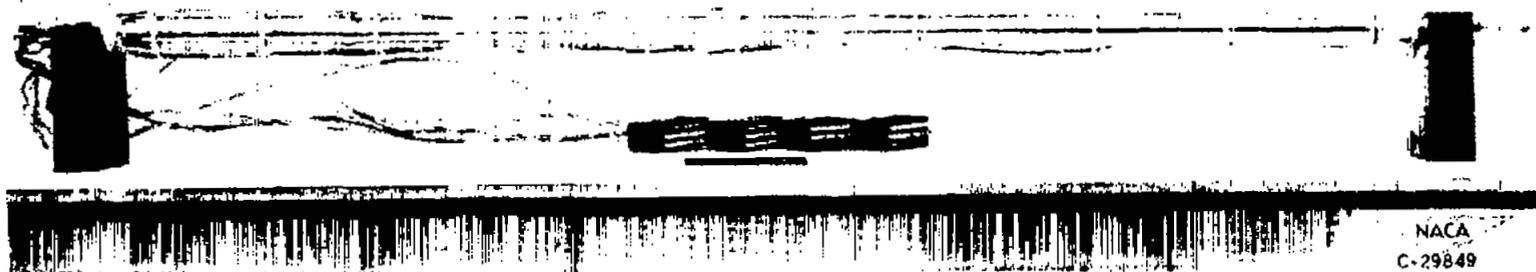


Figure 1. - Moderator tube with thermocouples installed.

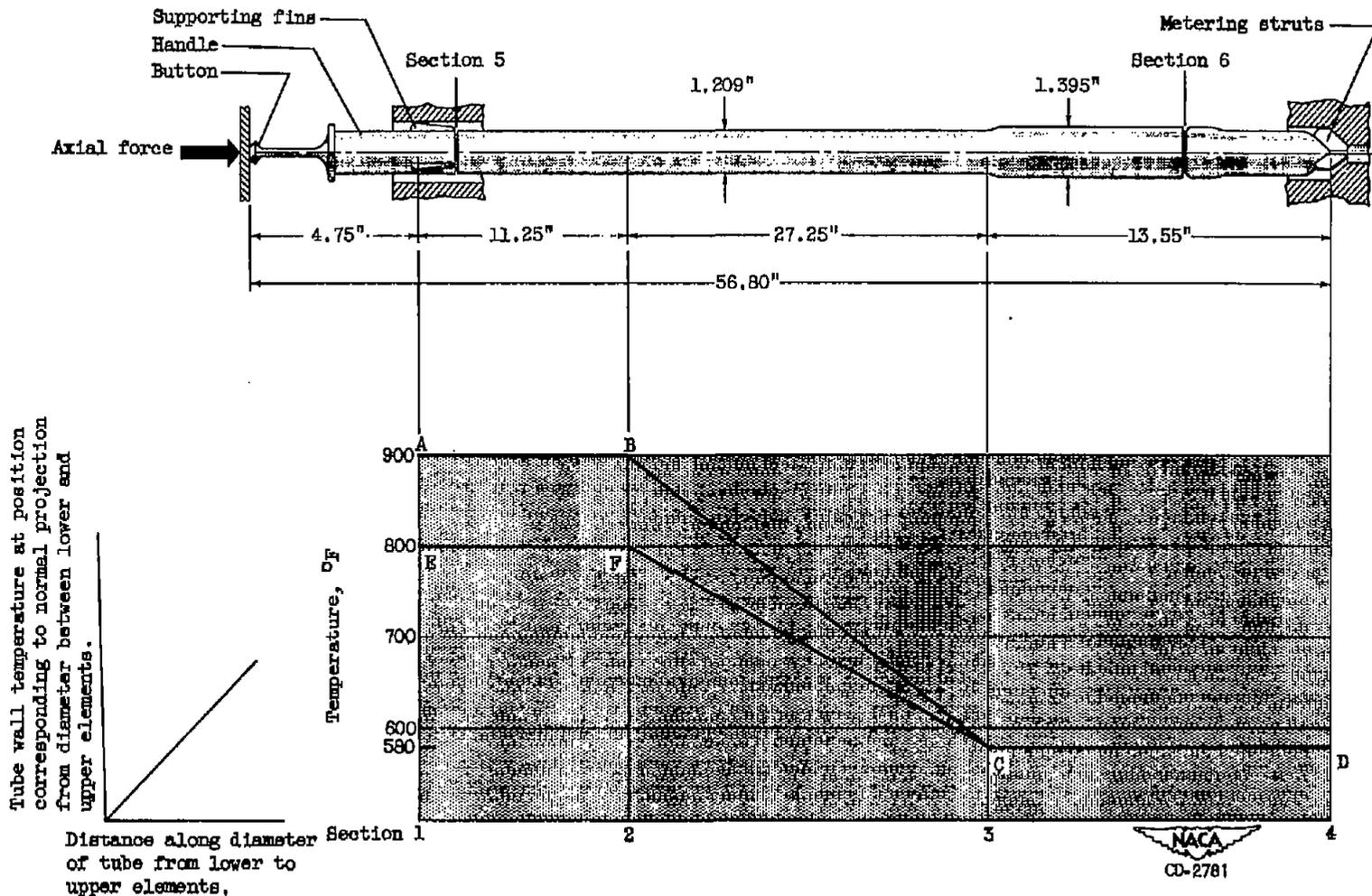


Figure 2. - Method of retention of moderator tube in reactor and specified temperature.

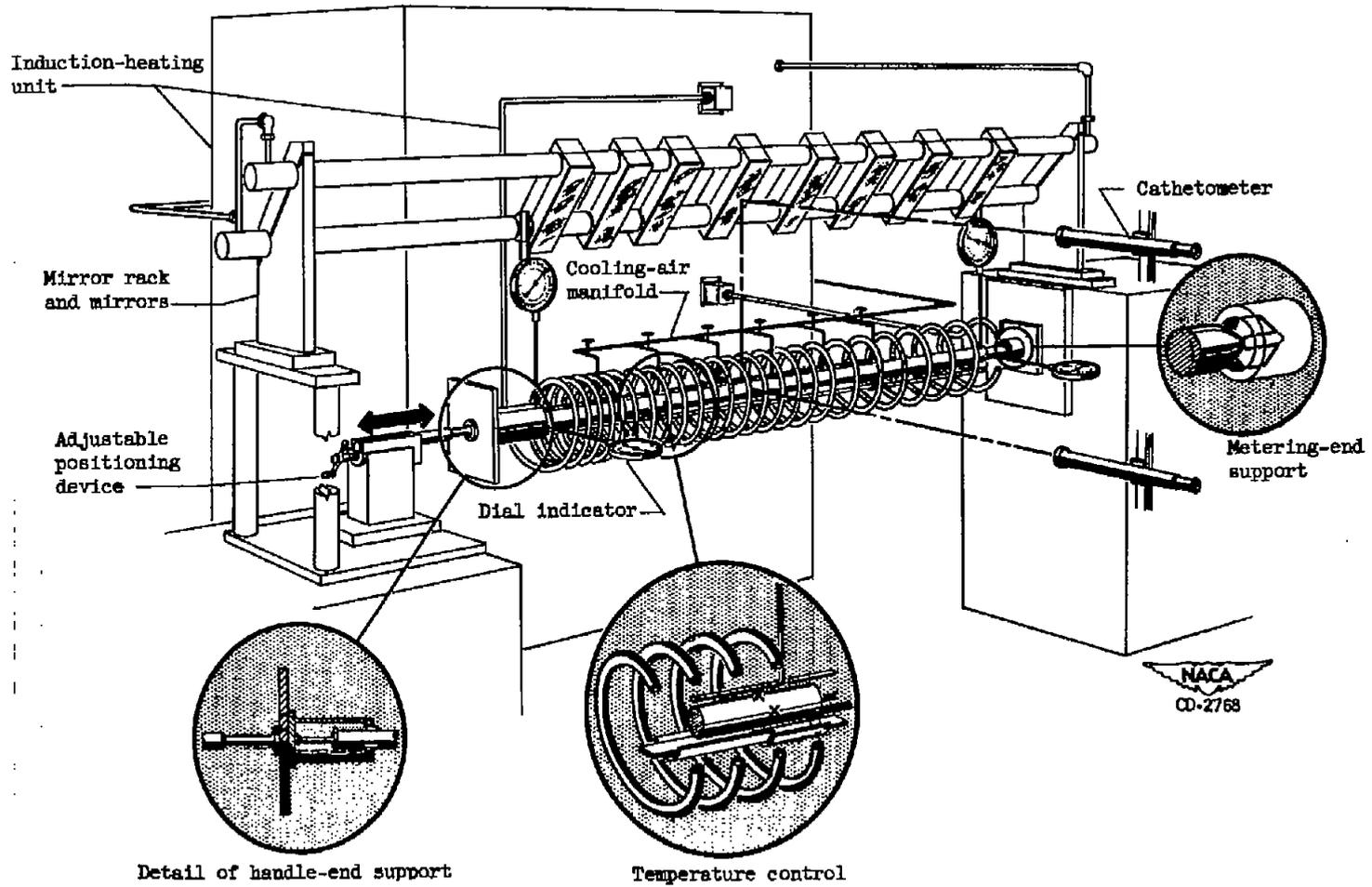
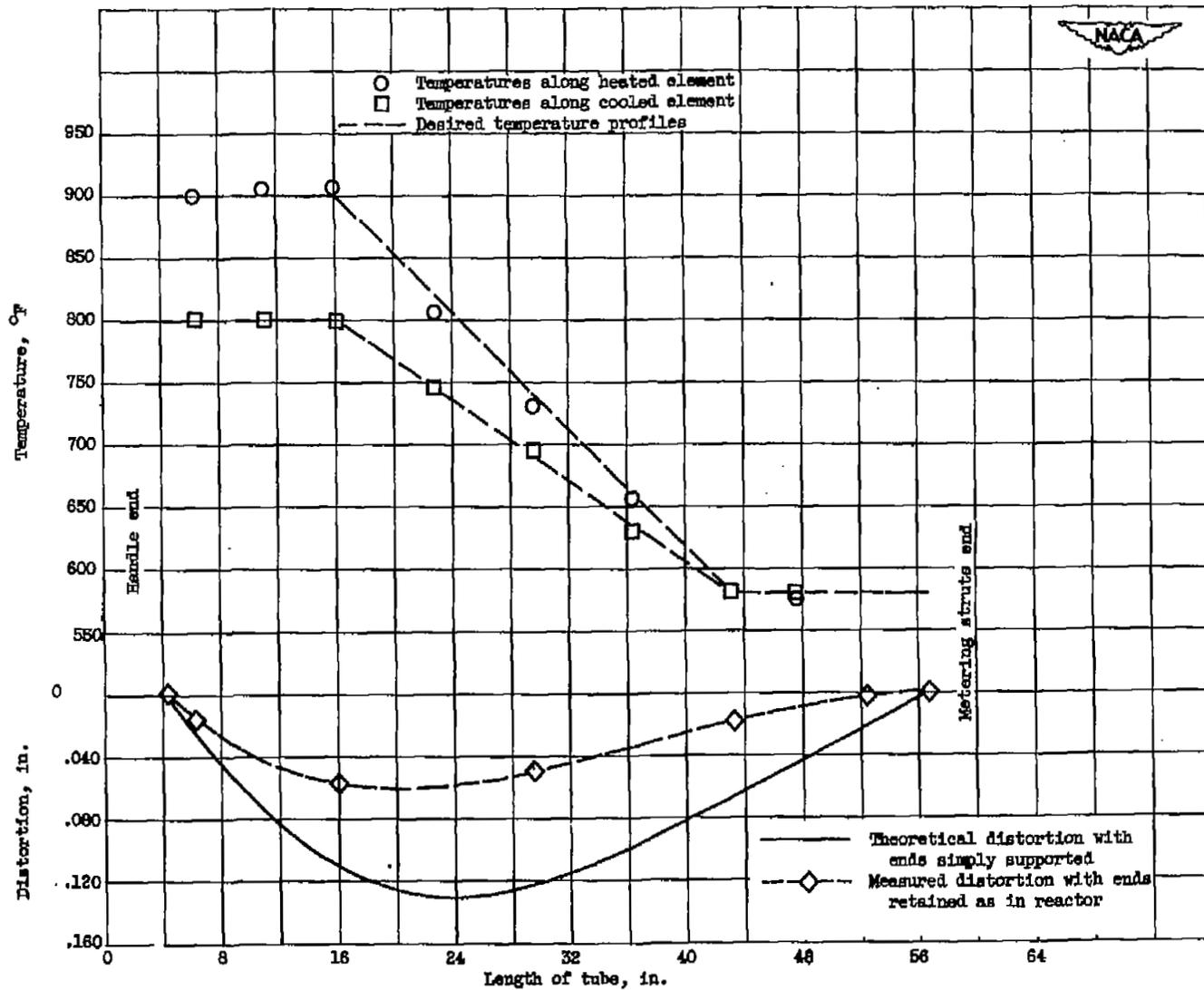
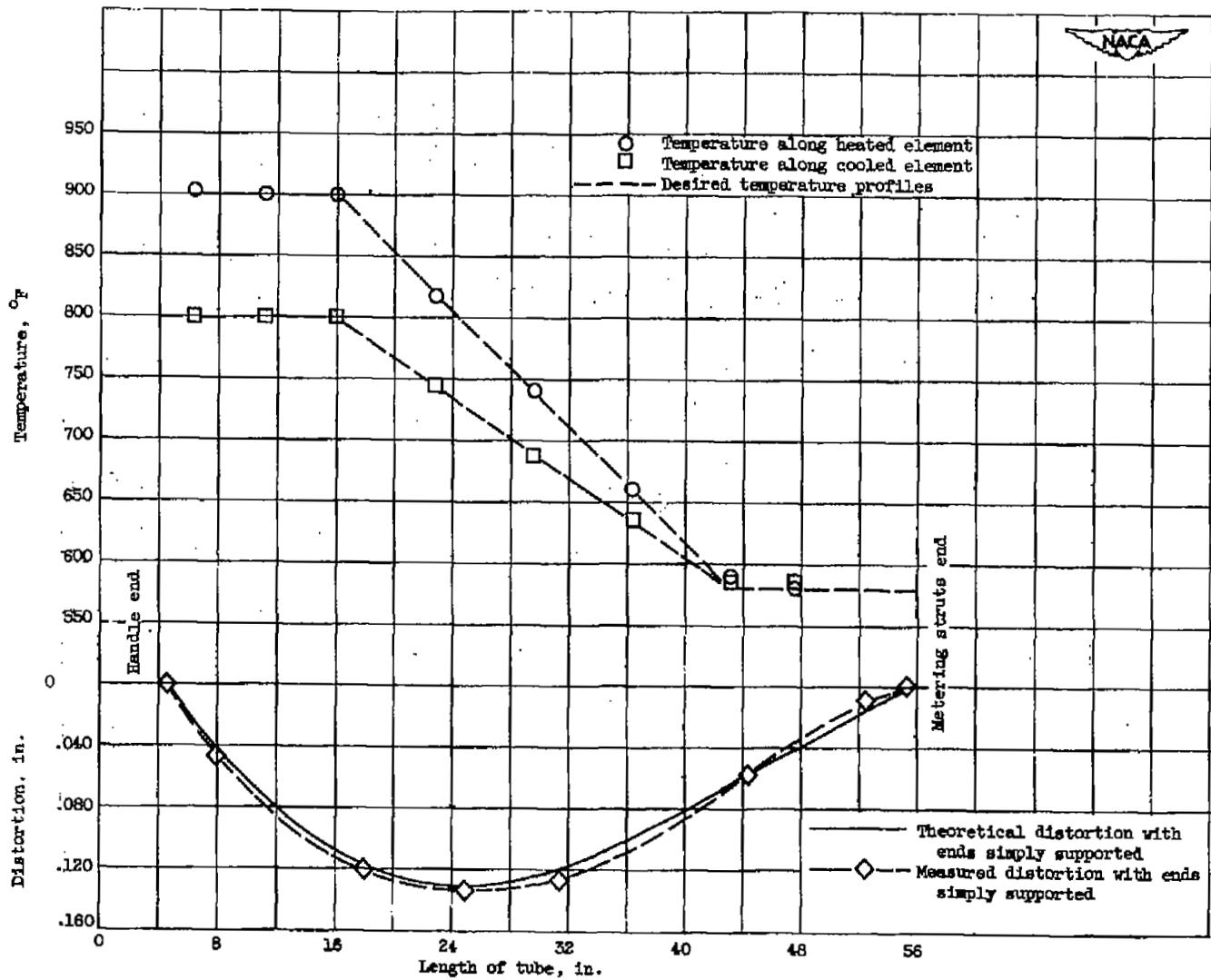


Figure 3. - Experimental apparatus.



(a) Ends supported as in reactor.

Figure 4. - Temperature profiles and distortion of moderator tube.



(b) Ends simply supported.

Figure 4. - Concluded. Temperature profiles and distortion of moderator tube.

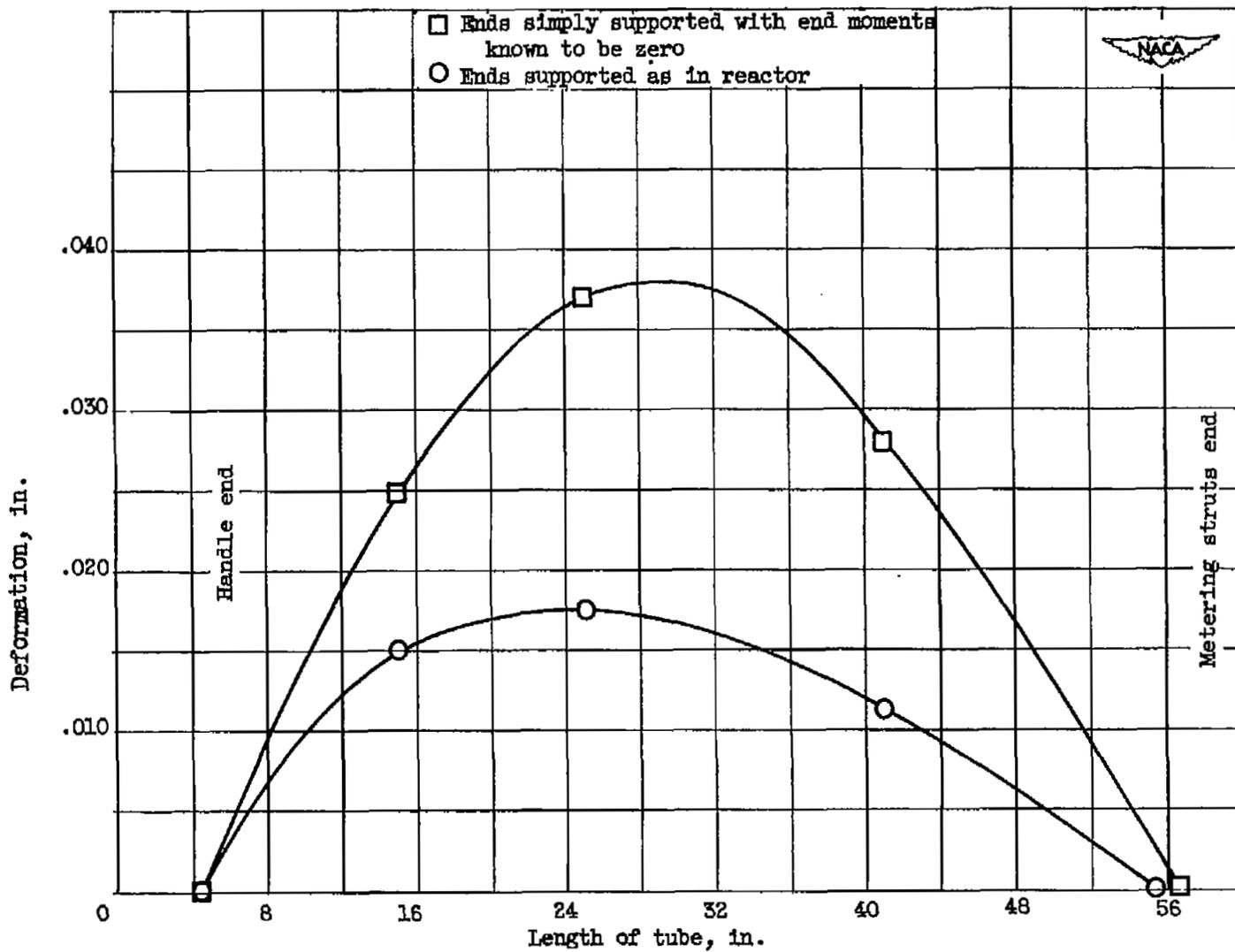


Figure 5. - Deformation of moderator tube with concentrated transverse load of 4 pounds acting at point 24.7 inches from the handle end.

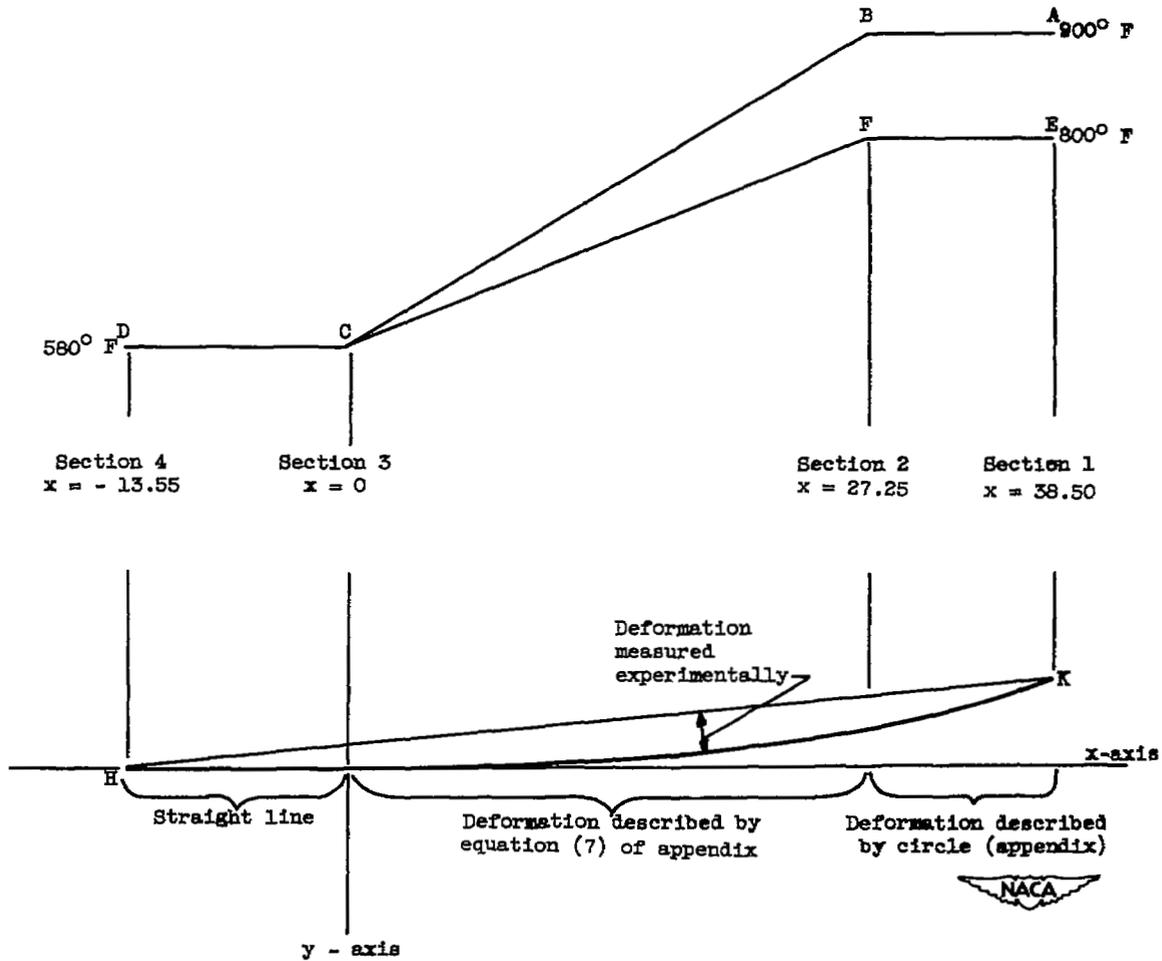


Figure 6. - Temperature pattern and deformation curve illustrating theoretical method of determining deformation.

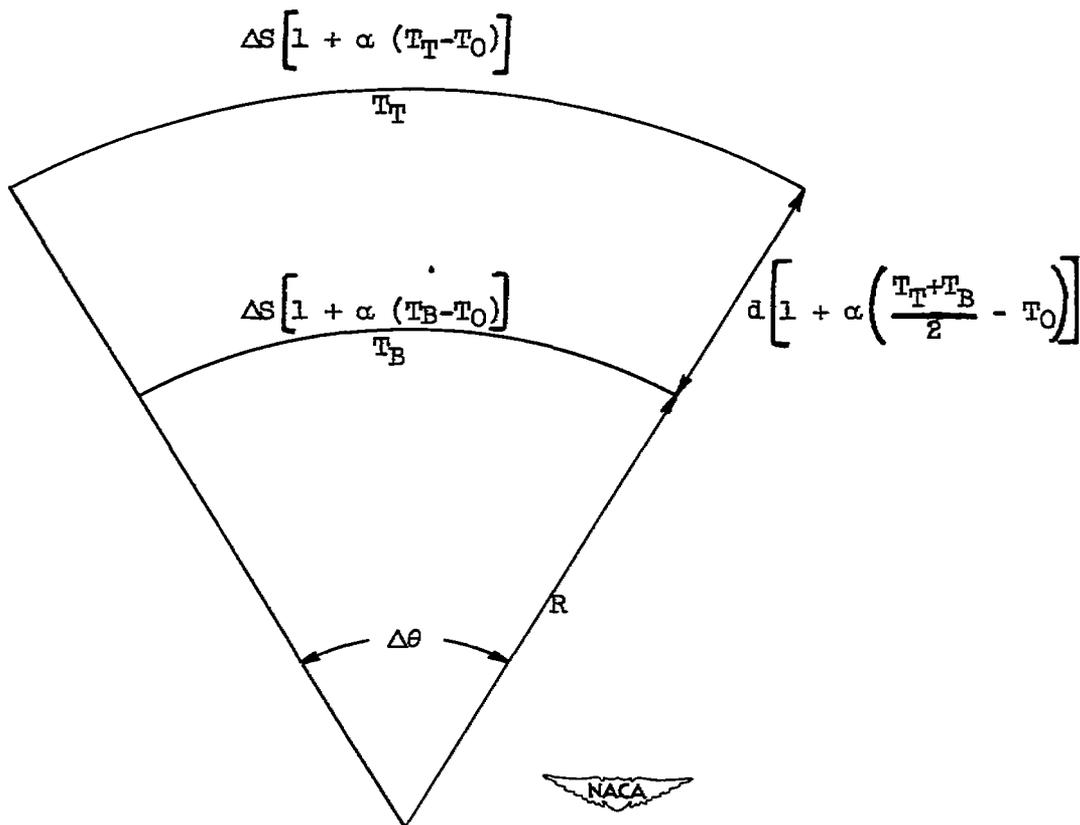


Figure 7. - Element of tube subjected to diametral temperature gradient.

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