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INVESTIGATION OF EXTREME LEADING-EDGE ROUGHNESS ON THICK LOW-DRAG AIRFOILS TO INDICATE THOSE CRITICAL TO SEPARATION

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INVESTIGATION OF EXTREME LEADING-EDGE ROUGHNESS ON THICK LOW-DRAG AIRFOILS TO INDICATE THOSE CRITICAL TO SEPARATION

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SUMMARY

Several airfoils, including a conventional NACA 23021 and some low-drag airfoils for which the thickness had been increased to the point that they were considered doubtfully conservative with respect to separation, were investigated as smooth airfoils and after the application of a standard roughness. The results show some of the airfoils to be critical to separation resulting from such flow disturbances. It is concluded, pending the further investigation of separation difficulties, that airfoil sections falling definitely within the conservative range should be used.

INTRODUCTION

The NACA low-drag airfoils first investigated, the airfoils dealt with in the earlier applications mainly to pursuit airplanes, and most of the airfoils for which data are presented in reference 1 were intended to be of conservative design. No very serious separation difficulties should therefore arise in operation with these airfoils, even though the leading edge becomes very rough. In other words, most of the airfoils were so chosen that the thickness, the camber, and the position of minimum pressure would lead to a conservative pressure recovery over the rearward part of the upper surface. For such airfoils the recovery could be made without marked separation, even in the presence of a boundary layer excessively thickened by premature transition and roughness near the leading edge of the airfoil. Thus, it was expected that the new airfoils would give drag coefficients in the same range as conventional airfoils when both were similarly roughened rather than give excessive drag coefficients associated with turbulent separation.

On some more recent applications to long-range bombers, however, root sections have been increased in thickness to the point that their relation to the conservative range has become, at least, doubtful. The range of conservative airfoil design as contrasted with the critical range as determined by the choice of thickness, camber, and position of minimum pressure is discussed in general terms in reference 1. Results are therein presented on at least one airfoil that was estimated to fall in the doubtful range, or in the range wherein airfoils may be critical to separation resulting from leading-edge roughness.

The present series of tests was undertaken to obtain quantitative data with regard to these limits of conservative airfoil design. The program contemplated an investigation of a series of airfoils estimated to lie close to the doubtful range. It was thus thought that a comparison of the test results for wings with and without a standard roughness applied to the leading edge of each would give quantitative data tending to define the range of conservative design.

CHOICE OF STANDARD ROUGHNESS

It was desired to choose an extreme rough condition as a standard roughness to be applied to the leading edge of the various airfoils and at the same time one that would not alter the contour of the section. The standard roughness might thus simulate an extremely rough condition that might result from mud or rough ice on the leading edge of the airfoil but, of course, could not represent thick ice accumulations of the worst type, which would seriously alter the airfoil contour.

With such considerations in view, a standard roughness consisting of carborundum particles thinly applied over the leading-edge part of the airfoil was adopted. A microscopic examination of the particles used showed them to be shaped like lumps of coal and to have crosswise dimensions near 0.010 inch and seldom greater than 0.015

inch. The particles were applied to one surface of Scotch tape; the tape was, in turn, attached to the leading edge of the airfoil. The use of Scotch tape in applying the roughness permitted its quick removal for the comparative tests of the smooth airfoil. The carborundum particles were retained on the Scotch tape by a thin coat of shellac allowed to become tacky before the application of the particles. The tape and roughness extended around the leading edge of the airfoil section for a total surface length of $3\frac{13}{16}$ inches, equally disposed above and below the leading edge. The carborundum was so thinly spread on this surface that 5 to 10 percent of the area was actually covered by carborundum grains. The airfoil models were of 2-foot chord and 3-foot span; the roughness strip was extended across the entire span from wall to wall in the tunnel.

For the full-scale wing at a Reynolds number corresponding to that of these model tests, the corresponding roughness is geometrically similar to that on the model. The roughness may thus be considered to be something like particles of sand somewhat less than $\frac{1}{16}$ inch across adhering to the leading edge of a wing of 100-inch chord. Such roughness conditions, of course, cannot be considered typical but it was hoped that the comparative results of the same roughness on various wings would be of value as representing a standard roughness condition, extreme, but of a type not markedly altering the original airfoil contour.

TESTS AND RESULTS

The tests of the 2-foot-chord airfoils both with and without roughness were of the routine type, approximately, as described in reference 1. Most of the results were obtained at a Reynolds number of about 10 million. Some results were also included at a Reynolds number of approximately 6 million in order to give some information on scale effects.

The following airfoil sections were investigated smooth and with the standard roughness:

NACA 23021

Boeing 7-series type, 0.20c thickness

NACA 65,2-222 (approx.)

NACA 65,2-422 (approx.)

NACA 65,3-418

The results of the airfoil tests are presented in figures 1 to 5 in standard chart form except that the drag coefficients have been plotted to a smaller scale than that usually employed. The reduced drag scale permits the high drag values associated with separations that occur on some of the rough models to be shown.

DISCUSSION

Comparison of airfoils.- The NACA 23021 section (fig. 1) is intended to represent a thick conventional airfoil. It is evident that roughness on such a section produces a serious loss in the maximum lift coefficient. The minimum profile-drag coefficient is increased from 0.0068 to nearly 0.0100, indicating the additional drag associated with the premature transition and the roughness. The drag coefficient appears to increase somewhat more rapidly with the lift coefficient than for the smooth airfoil but the variation remains normal, increasing progressively with lift on approaching the reduced maximum lift coefficient of the rough airfoil. Thus, only the usual progressive separation effects are evident as the maximum lift coefficient is approached.

The Boeing 7-series type airfoil in figure 2 is typical of airfoils showing marked separation effects due to roughness. The lift curve begins to show a loss at small positive angles and the upper part of the curve has a reduced slope. The maximum lift coefficient for the rough airfoil is approximately 1.1, a lower value than that of the conventional rough airfoil. The minimum drag coefficient for the rough airfoil is approximately 0.0115, a value only a little more than that of the conventional rough airfoil; but the drag increases sharply above a lift coefficient of 0.5, indicating the onset of marked adverse separation at about the attitude at which the lift-curve slope changes. The drag coefficients are seen to become very high at larger lift coefficients.

A similar, although less drastic, behavior will be observed for the airfoils NACA 65,2-222 (approx.) and NACA 65,2-422 (approx.) in figures 3 and 4. The airfoil with the higher camber appears to be somewhat more unconservative.

The characteristics of a low-drag airfoil of the conservative type, NACA 65,3-418, are shown in figure 5. A reduction in maximum lift to 1.29 is observed to be of the same type as that shown for the conventional airfoil due to roughness. The minimum drag coefficient is increased to approximately the same value as that of the conventional airfoil although the increment due to roughness is, of course, larger on account of the lower initial value for the low-drag airfoil. The drag coefficients show a progressive increase on approaching the maximum lift coefficient, as did the conventional airfoil, thus showing drag coefficients in the same range as those of the rough conventional airfoil for lift coefficients below 1.1. It is therefore concluded that, for a conservative airfoil of the low-drag type, roughness should produce no marked separation effects apart from the effects that normally occur when the maximum-lift attitude is approached.

<u>Significance of wake-survey measurements made in the presence of separation.</u>- In tests made to determine drag by means of wake surveys in the presence of separation, the dead air in the regions of local separation may tend to deviate spanwise in such a way as to pass off at the survey plane, indicating excessive drag, or to deviate outward so as to pass off in some other plane, indicating a deficient drag in the survey plane. For that reason, in most instances where separation was likely to occur spanwise drag surveys were made. Some of the results of such surveys are shown in figures 6 and 7. For the unconservative airfoil (fig. 6), it will be noted that separation does tend to be localized in a region near midspan. It was found that this separation region might tend to shift spanwise; this tendency leads to inconsistent results at the survey plane, such as those shown in figure 2. The results show, therefore, that the separated regions may be local and that the drags measured behind

these regions may be excessive rather than quantitatively correct. It seems clear, nevertheless, that such sections showing even local separation cannot be considered conservative and their use should be avoided.

On the other hand the spanwise surveys shown for a conservative low-drag airfoil in figure 7 indicate a consistent spanwise variation of drag, hence, an airfoil that is not prone to local-flow breakdown. Spanwise surveys are usually made as part of the testing procedure in the NACA two-dimensional tunnel. The results shown in figure 7 for the smooth condition are typical of the results usually obtained when no pronounced separation is present. Spanwise surveys made on large-chord wing sections representing practical construction sometimes show moderately large variations of drag along the span even when the sections are considered to be well within the conservative range. Such variations are attributed to changes in skin friction resulting from local accidentally distributed surface roughness and these variations tend to disappear as the surfaces are improved.

The airfoil boundary layers near the tunnel walls are, of course, affected by the presence of the walls with the possibility of resulting spanwise flows that might affect the resistance to separation of the flows near the center of the airfoil as well as the drag measurements. Tests with different chord-length smooth models of airfoils within the conservative range have failed to show any significant spanwise drag variation or variation of airfoil characteristics with chord that would be expected if such effects were present. It is planned to extend such tests, however, to include rough as well as smooth models of airfoils in or near the critical range because of the possibility that such effects may be present under these conditions.

Application of results.- The present results strongly suggest that the use of airfoils which do not fall within the conservative range should be avoided. Sections of this type that have shown a tendency to break down locally in the presence of a leading-edge disturbance may also break down in the presence of other distrubances, such as those due to fuselage or nacelle interferences, construction irregularities, etc. The precise limits of the conservative range, however, are at present not definitely established. In fact, the only quantitative data tending to define the limits are those herein presented. Fortu-

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nately, the low-drag airfoils, with the exception of a few above 20-percent thickness, in use or under consideration for practical applications may be judged to be conservative by comparison with the NACA 65,3-418 shown to be satisfactory by the present data. Pending further investigations, sections that cannot be judged satisfactory by such comparisons should be specially investigated by tests such as the present ones in the two-dimensional tunnel.

Difficulties have usually arisen through the use of excessively thick sections. A suitable remedy is obvious: While keeping the same spar depth, the wing chord may be increased to reduce the thickness ratio until the section falls within the conservative range. During the tests of a bomber model in the 8-foot high-speed tunnel a leading-edge glove was used to reduce the section thickness ratio. A better plan would have been to increase the chord of the entire section in order to obtain the same reduction in thickness ratio.

Finally, two other possible methods that may eventually lead to obviation of the difficulties herein considered may be mentioned. With relatively large nose-opening air intakes it appears to be possible to employ thick sections without excessively low minimum pressures and the attendant unconservative pressure recoveries. The use of suitable lift-control flaps with slots or other forms of boundary-layer control should be advantageous in obviating the separation difficulties.

CONCLUSIONS

Pending the further investigation of separation difficulties, airfoil sections falling definitely within the conservative range should be used.

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REFERENCES

1. Jacobs, Eastman N., Abbott, Ira H., and Davidson, Milton: Preliminary Low-Drag-Airfoil and Flap Data from Tests at Large Reynolds Numbers and Low Turbulence. NACA A.C.R., March 1942.

ERRATA ON FIGURES

The values of section lift coefficient (figs. 1 to 5) should be corrected by the following equation

$$c_{l_{(corrected)}} = 0.965c_l + 0.015$$

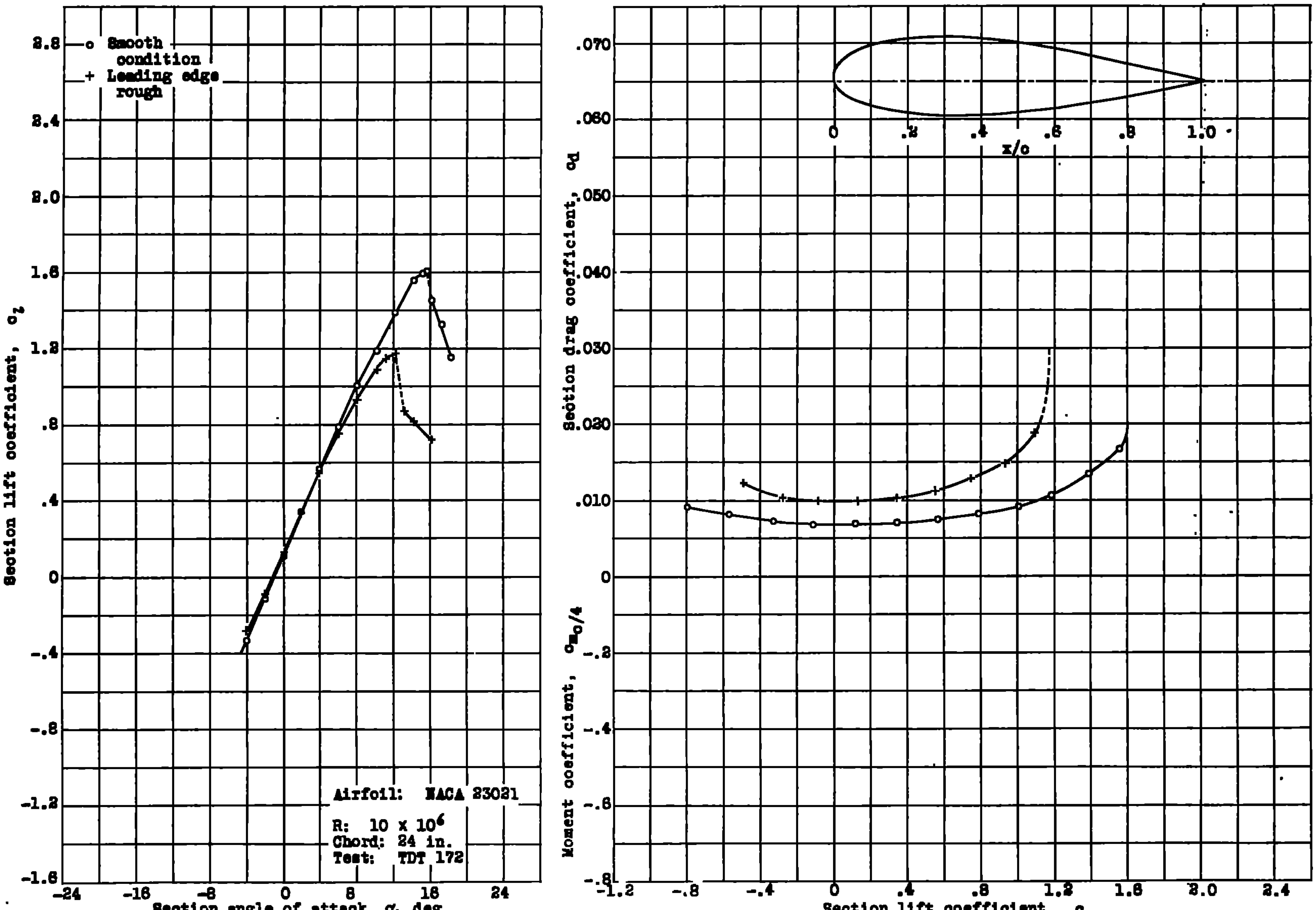

Figure 1.- NACA 23021 airfoil.

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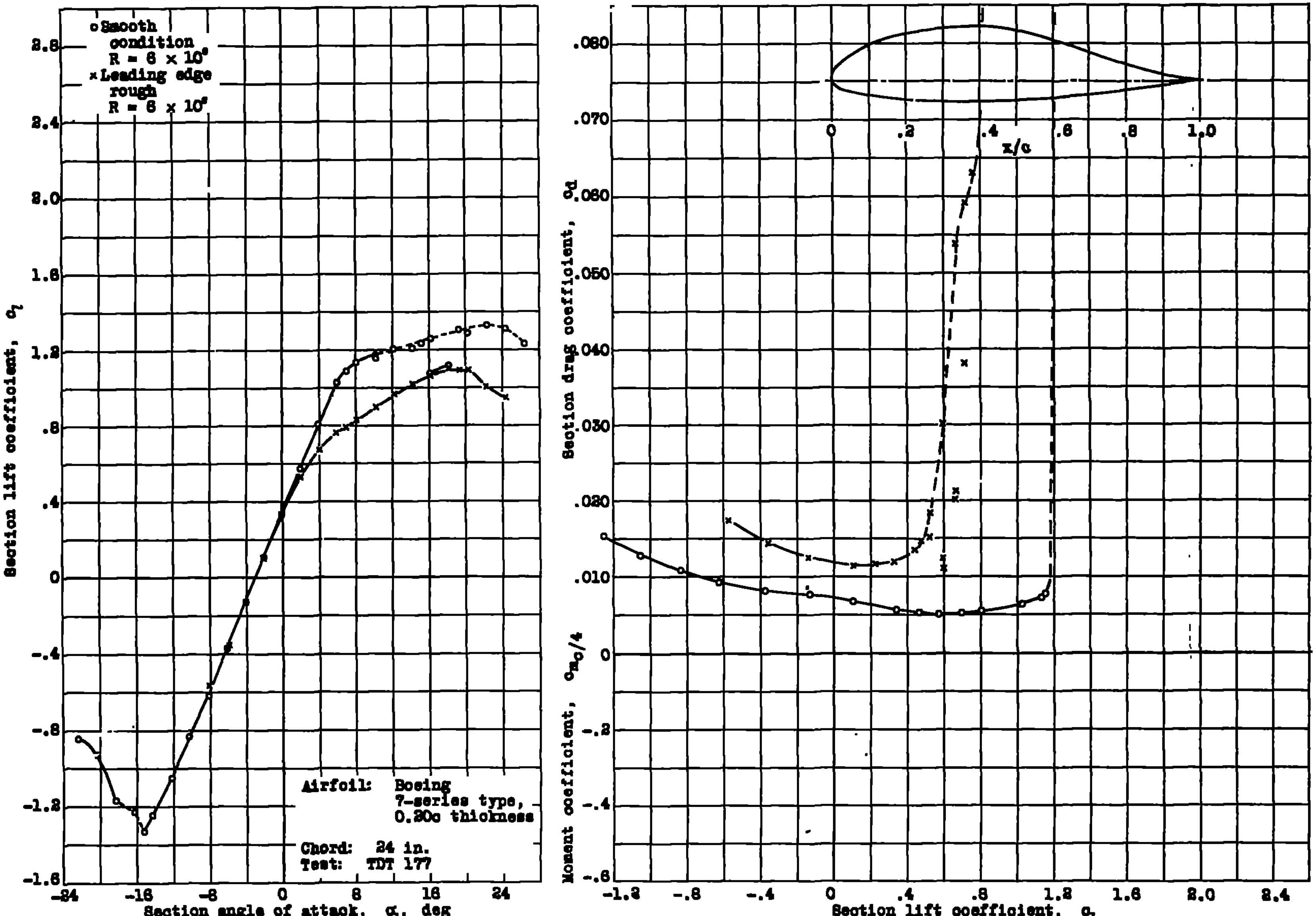

Figure 2.- Boeing 7-series type, 0.20c thickness, airfoil.

Fig. 2

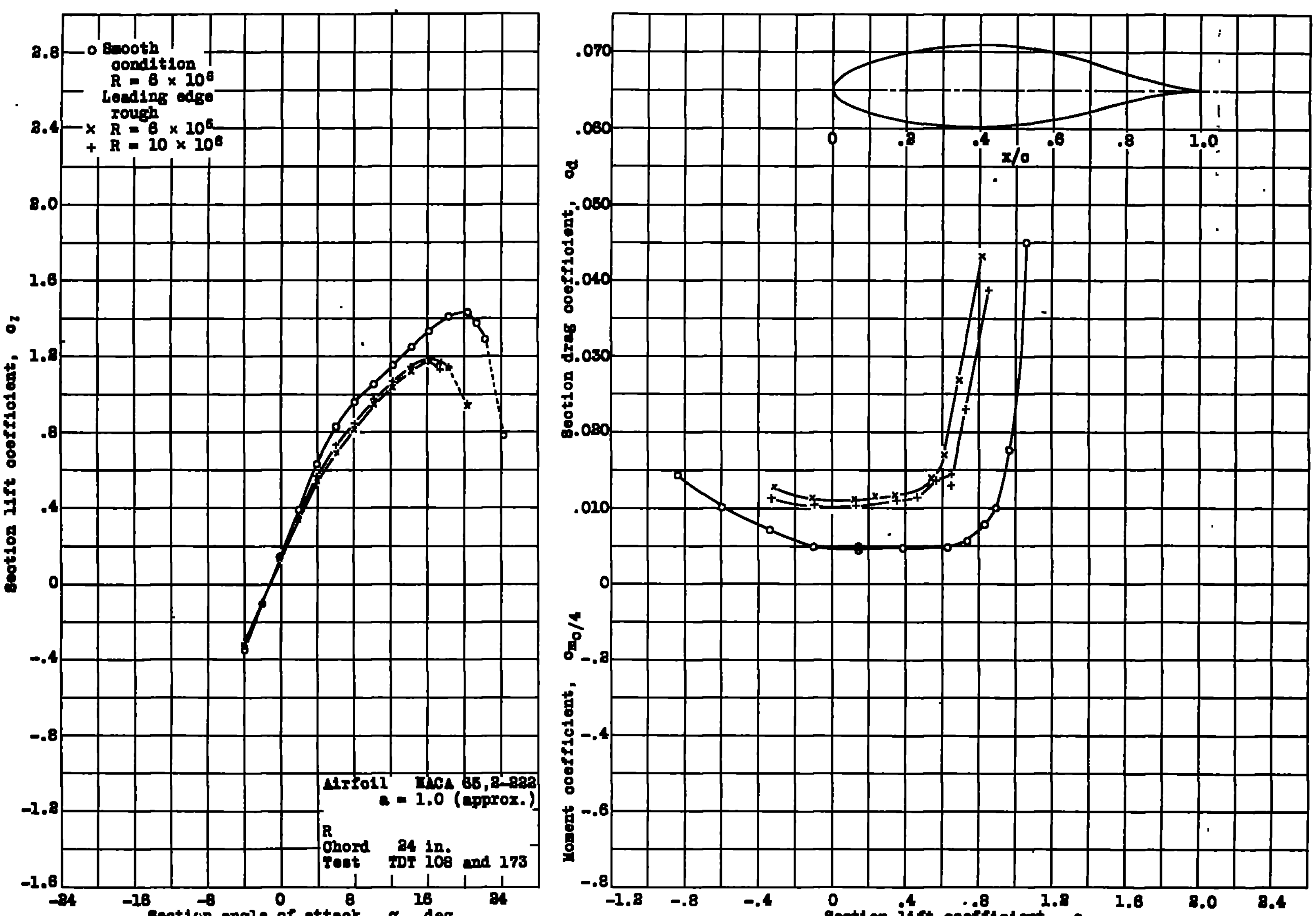

Figure 3.- NACA 65,2-222 (approx.) airfoil.

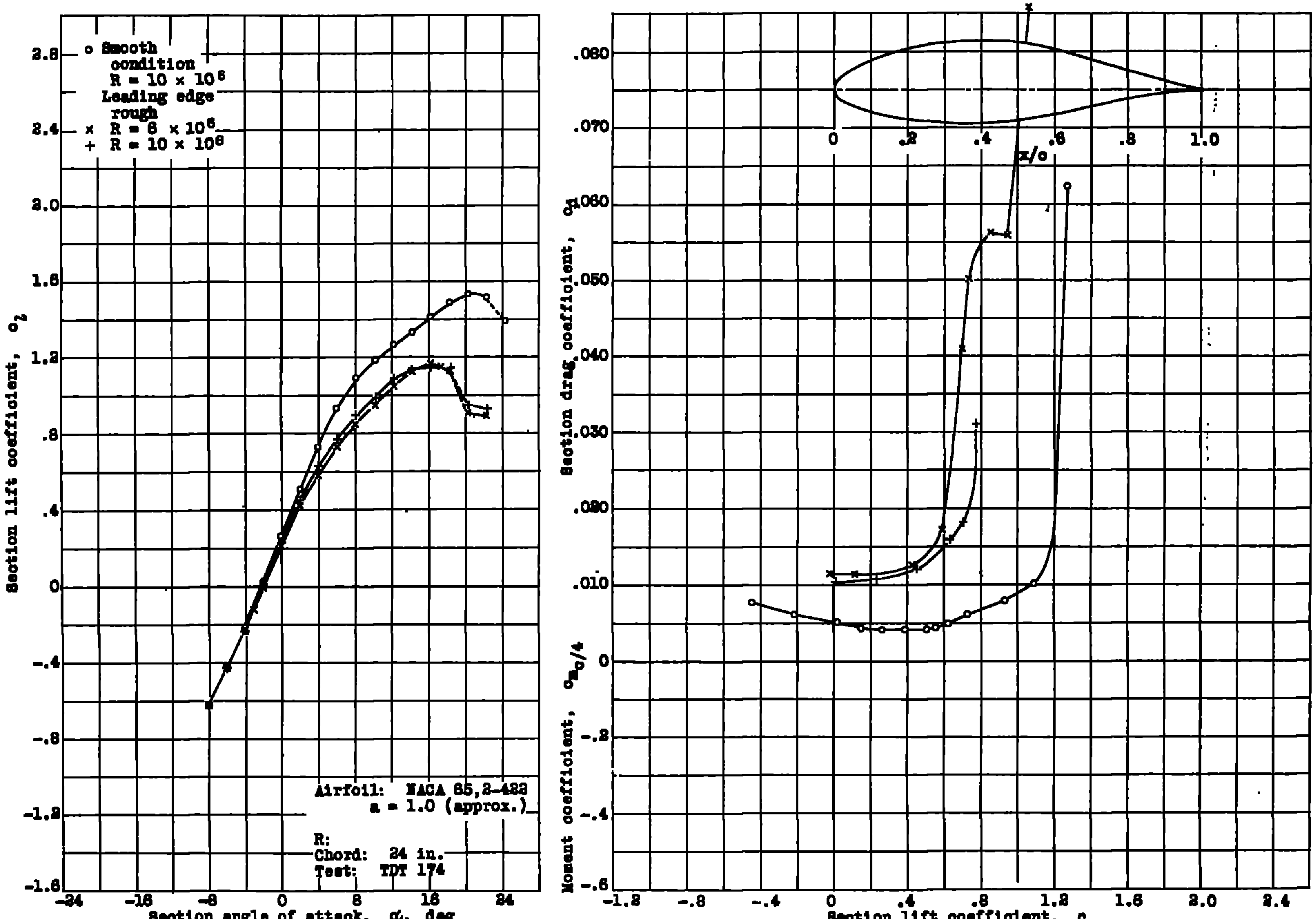

Figure 4.- NACA 65,2-422 (approx.) airfoil.

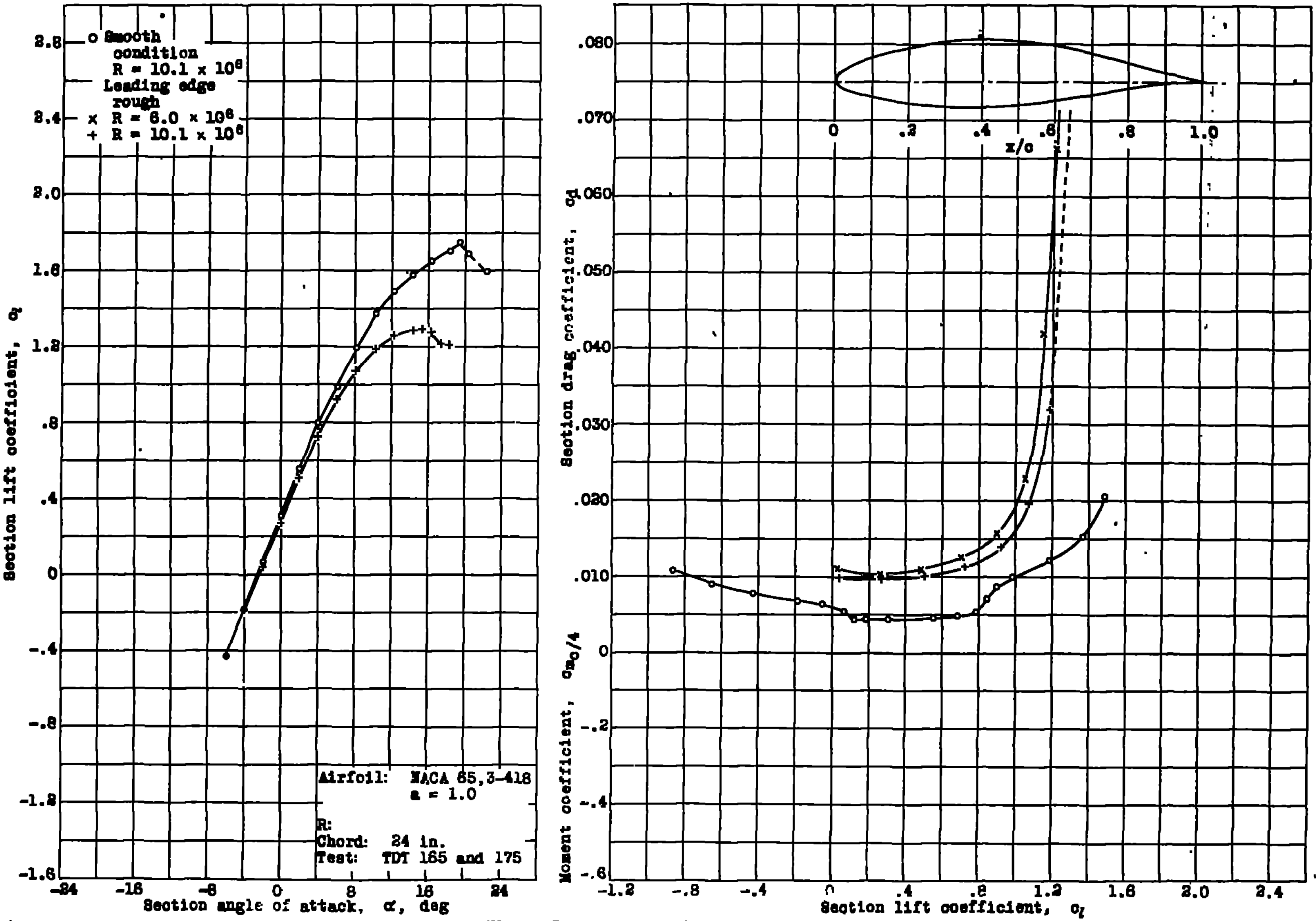

Figure 5.- NACA 65,3-418 airfoil.

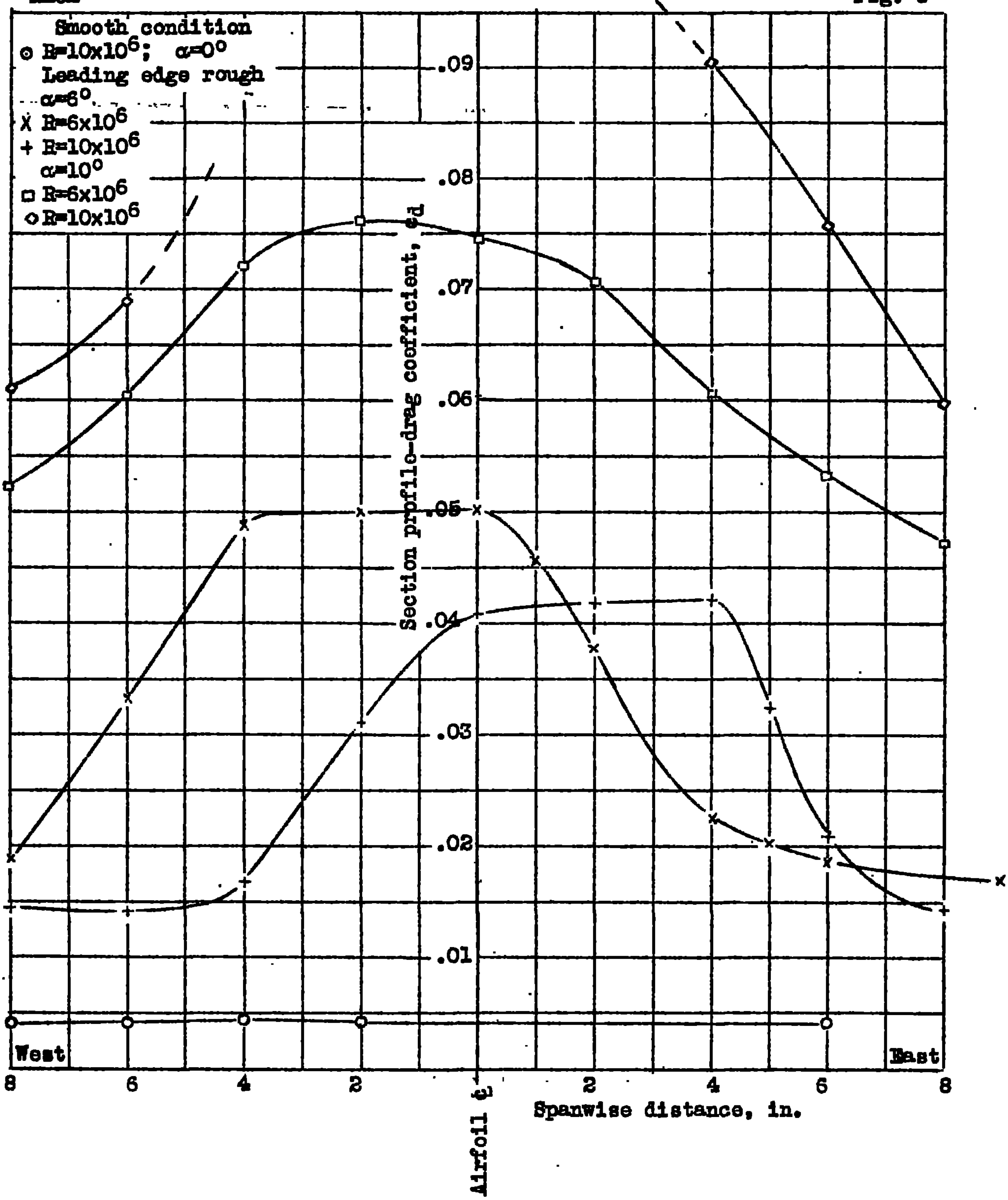

Figure 6.- Spanwise drag survey for the NACA 65,2-422, a=1.0(approx.) airfoil.

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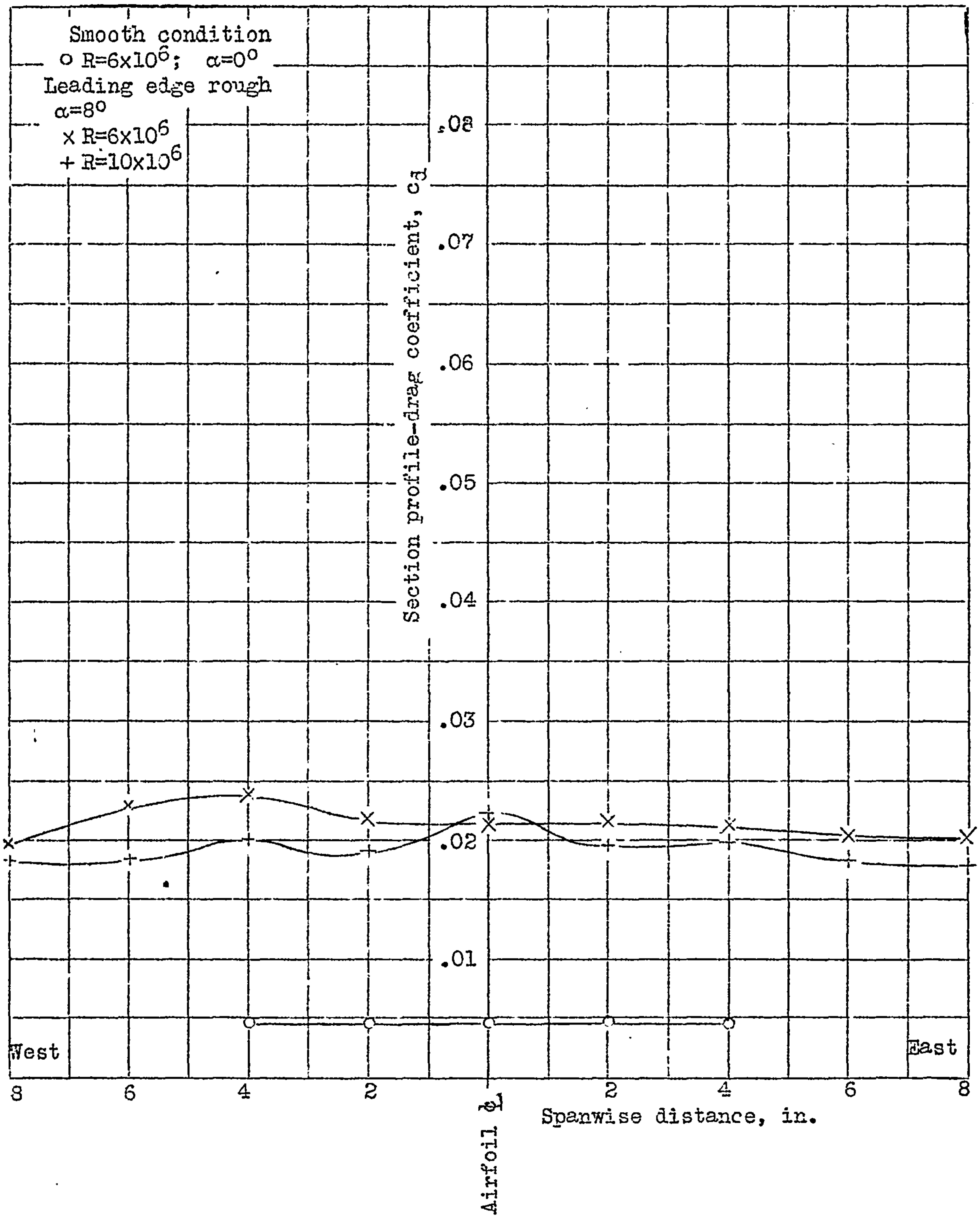

Figure 7.- Spanwise drag survey for the NACA 65,3-418, a=1.0, airfoil.