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by Albert L. Braslow

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SUMMARY

An analysis of fuselage and wing thermocouple data obtained during a flight of the X-15-2 research airplane and of measurements of surface discontinuities and structural roughness made after the flight has provided a strong quantitative indication that premature boundary-layer transition on the airplane was controlled by surface protuberances. Turbulent flow existed on the entire fuselage at all times during the flight as a result of a forward-facing step between the high-speed flow-direction sensor and the fuselage. Premature transition that varied in location during the flight was induced on the wing by a spanwise step caused by a skin joint near the wing leading edge and by leading-edge expansion-joint covers. The movement in the location of transition on the wing was rather conclusively related to changes in roughness Reynolds number during the flight, but the exact transition location is unpredictable for the two-dimensional-type roughness present. No structural roughness of a three-dimensional type of sufficient height to cause premature transition during the temperature-measuring phase of flight was found on the airplane.

INTRODUCTION

The data obtained from the use of thermocouples and temperature-sensitive paints on various surfaces of the X-15 research airplanes have indicated that surface discontinuities or roughness probably had appreciable effects on boundary-layer transition from laminar to turbulent flow. For example, see reference 1. It is also indicated in reference 1 that the location of transition on the wing appeared to vary with changes in flight condition, whereas the flow remained turbulent far forward on the fuselage for all flight conditions.

To provide a more certain indication as to the cause of the varying transition location on the wing and the fixed transition location on the fuselage, a somewhat quantitative analysis was made of the surface protuberances existing on the X-15-2 research airplane during one flight. The results of this analysis are presented herein. An analysis of the thermocouple data in terms of heat-transfer coefficients has been made in reference 2 for the part of the same flight during which turbulent flow existed far forward on the wing as well as on the fuselage.

SYMBOLS

c	local wing chord
k	protuberance height
R_k	roughness Reynolds number based on protuberance height and local flow conditions outside boundary layer, $\frac{u_\delta k}{\nu_\delta}$
u_δ	local velocity outside boundary layer
V	flight velocity
x_t	streamwise transition distance from wing leading edge
α	airplane angle of attack
ν_δ	local coefficient of kinematic viscosity outside boundary layer

RESULTS AND DISCUSSION

After one of the flights of the X-15-2 research airplane, detailed measurements were made of surface protuberances and roughnesses in the forward regions of the fuselage and wings. These measurements were used in combination with the flight velocities and altitudes attained throughout this particular flight to determine values of the roughness Reynolds number. These roughness Reynolds numbers were correlated with the locations of transition as obtained from the surface temperatures. The time history of airplane velocity, altitude, and angle of attack is presented in figure 1.

Fuselage

The skin-temperature measurements on the underside of the fuselage indicated that turbulent flow existed over the entire fuselage length throughout the flight. Evidence of this early transition is presented in figure 11 of reference 1, where skin temperatures

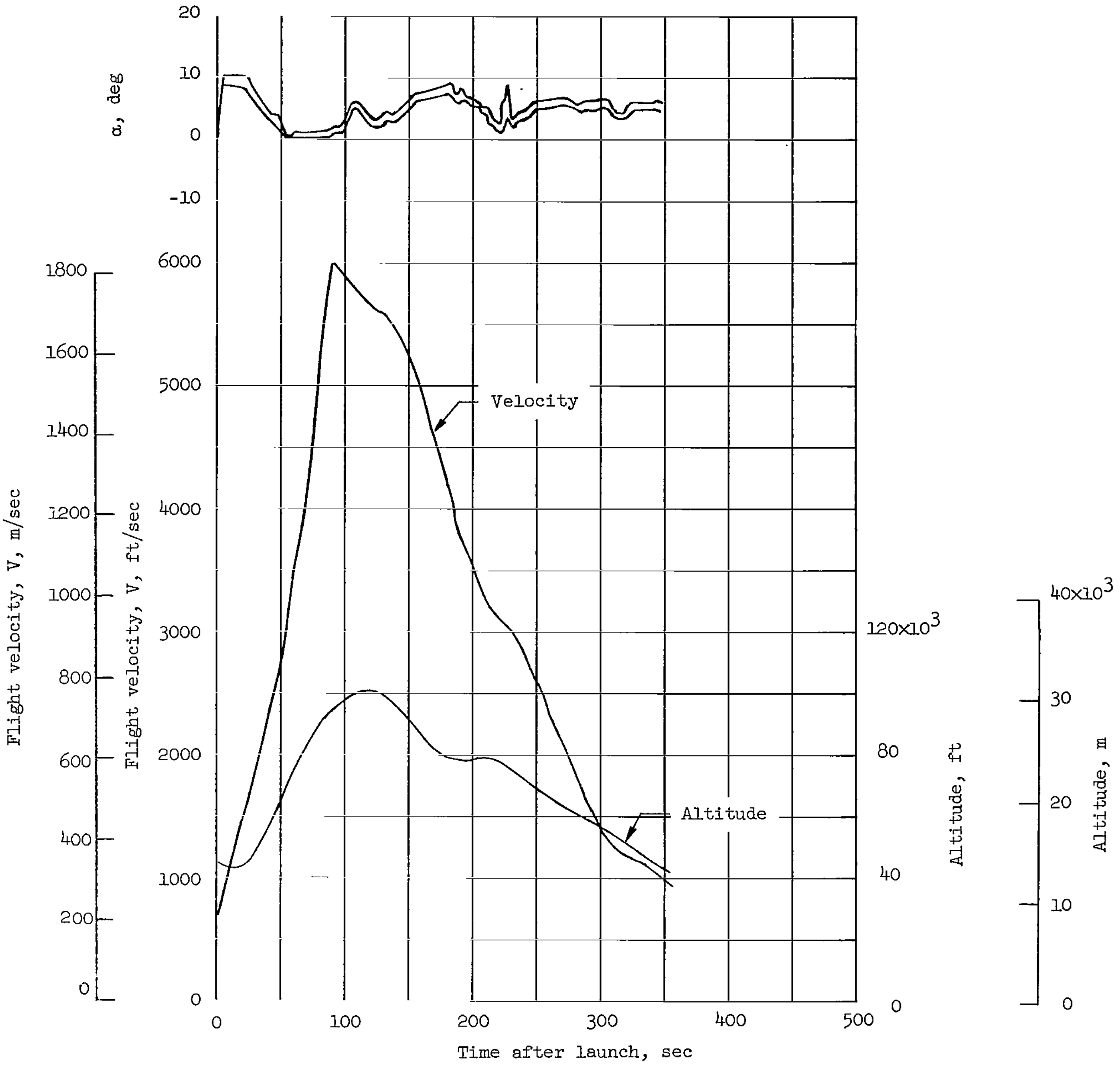

Figure 1.- Time history of velocity, altitude, and angle of attack for particular flight used in the analysis.

measured 11 feet (3.353 m) behind the fuselage nose on the lower center line are compared with values calculated for turbulent flow. The high-speed flow-direction sensor located in the fuselage nose produced a forward-facing step around the fuselage perimeter 0.172 inch (0.437 cm) high. The maximum thickness of the boundary layer at the location of this step was calculated to be 0.017 inch (0.043 cm). It is apparent, therefore, that this two-dimensional step at the ball-nose—fuselage juncture was more than sufficient to fix transition near the step. (See ref. 3, for example.)

Wing

The chordwise position of transition on the lower wing surface throughout the flight was obtained by calculating the magnitude of the heat-transfer coefficients from the measured skin temperatures. Plotted against flight time from launch in the lower part of figure 2 is the location of transition in terms of x_t/c, where x_t is the transition distance from the wing leading edge and c is the chord length of the spanwise station at which the measurements were made (c = 88.35 inches or 224.41 cm). Consistent results were obtained during the flight from 0 to 115 seconds and after 240 seconds (indicated by the solid portions of the curve). From 115 seconds to 240 seconds, however, considerable scatter in the calculated heat-transfer coefficients prevented accurate determination of the transition location (indicated by the dashed portion of the curve). This scatter is largely due to the inaccuracy in determining the rate of change of surface temperature with time during this phase of flight when the temperature change was rather small after the peak Mach number had been reached. In addition, variations in the spanwise intersection of the fuselage bow shock with the wing surface, resulting from large transients in angle of attack and Mach number, occurred during this time period. Study of the skin-temperature data, Mach numbers, and Reynolds numbers at these times, however, indicated that transition probably occurs near the locations shown.

An estimated location of natural transition throughout the flight is also presented in the lower plot of figure 2. This estimate was based on a combination of the results of references 4 and 5 for the same wing sweep and leading-edge bluntness as the X-15-2 airplane and for assumed adiabatic-wall temperatures. However, because temperatures during flight are generally cooler than adiabatic-wall temperatures and also because adverse effects of wind-tunnel turbulence in the data used are unaccounted for, the estimated locations of natural transition should be more forward than would actually be the case for the flight conditions. The results of figure 2 clearly indicate, therefore, that the actual transition location is forward of the natural transition location at all flight times.

To determine whether three-dimensional-type surface roughness contributed to this forward location of boundary-layer transition, figure 3 was prepared. The figure presents, as a function of flight time, the height of three-dimensional roughness (located near the wing leading edge) that is necessary to move transition forward of the natural transition point. The calculations were made in accordance with the procedure and charts of reference 6. The largest structural three-dimensional roughness measured near the wing leading edge consisted of rivets 0.002 to 0.004 inch (0.005 cm to 0.010 cm) high. These heights are smaller than those presented in figure 3 as necessary to affect transition.

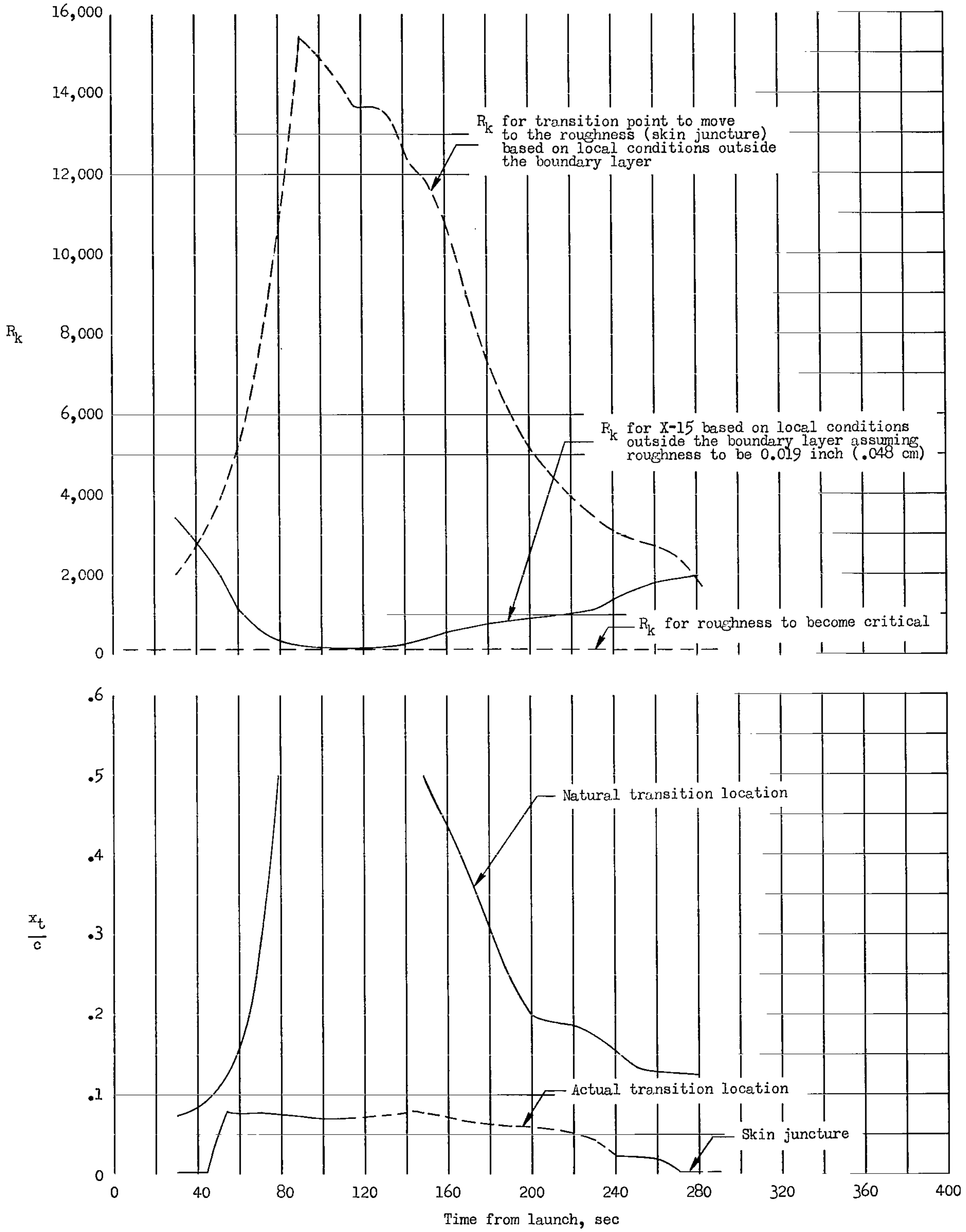

Figure 2.- Two-dimensional roughness effects on transition on wing of X-15-2 airplane during flight.

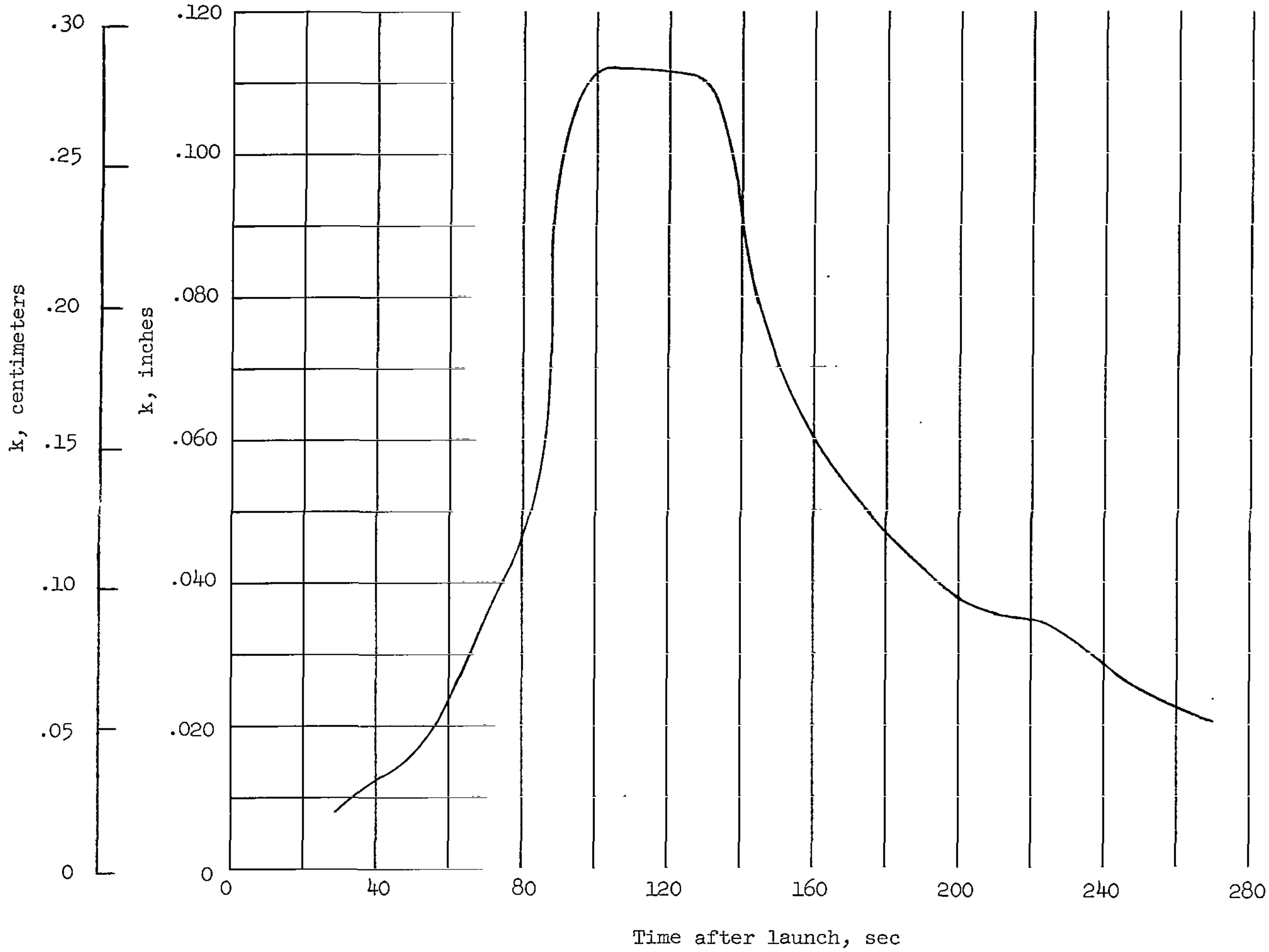

Figure 3.- Three-dimensional roughness height necessary to cause premature transition on wing of X-15-2 airplane during flight. (Roughness located 3.55 inches (9.02 cm) from leading edge.)

The conditions existing with respect to two-dimensional protuberances, however, are quite different. At a distance of 0.75 inch (1.905 cm) from the wing leading edge, a skin joint formed a spanwise step varying in height from 0.015 inch (0.038 cm) to 0.027 inch (0.069 cm). Covers over leading-edge expansion joints formed two-dimensional steps up to 0.033 inch (0.084 cm) high. Also, during the flight, the wing leading edge buckled at the expansion joints as shown in figures 15 and 16 of reference 7. This buckling caused protuberance heights that were larger than the 0.033-inch-high (0.084-cm) expansion-joint covers.

To provide a quantitative indication of the effects of these two-dimensional protuberances on the boundary-layer transition, the upper plot of figure 2 was prepared. Values of two-dimensional roughness Reynolds number R_k based on the protuberance height and local flow conditions outside the boundary layer at the protuberance $\left(\frac{u_\delta k}{\nu_\delta}\right)$ are plotted against flight time for various conditions. The dashed straight line represents the approximate value of R_k (refs. 3 and 6, for example) required for two-dimensional roughness to begin a forward movement in transition from its natural location (critical value). The upper dashed curve presents at any flight time the value of R_k required to move transition completely forward to the step (ref. 3). The solid curve represents the actual values of R_k obtained with a step height assumed equal to the mean height of 0.019 inch (0.048 cm). If the value of R_k is smaller than the critical value, the roughness will have no effect on transition. If R_k is equal to or larger than the value indicated by the upper dashed curve, transition will occur very near the two-dimensional step. If R_k is larger than critical but smaller than the value of the upper dashed curve, transition will occur someplace between the natural location and the step but its exact location is unpredictable. The forward location of transition in the vicinity of the skin juncture measured at flight times up to 45 seconds and after 270 seconds (lower curve of fig. 2) is seen from the upper part of figure 2 to be almost certainly caused by the skin juncture. At flight times between these values, the actual transition moved rearward (lower curve of fig. 2) but was still forward of the natural location as would be predicted from the upper curves of figure 2, except for flight times near 110 seconds.

The discrepancy near 110 seconds and the considerable forward shift in transition at other flight times between about 60 seconds and 240 seconds most likely result from the following factors. First, a mean step height of 0.019 inch (0.048 cm) was used in the calculation of the step R_k, but heights as large as 0.027 inch (0.069 cm) were actually measured, as stated previously. Also, under aerodynamic load during flight, the step height was probably even larger. Second, during this intermediate time period, a turbulent wedge originating at the leading-edge expansion-joint cover (measured step height of 0.033 inch (0.084 cm)) inboard of the measurement station crossed the row of thermocouples closer to the wing leading edge. (Turbulent wedges can be seen in fig. 13 of ref. 7.) Third, at some unknown time during the flight, the skin at the wing leading edge buckled at the expansion joints and thus caused much larger roughness heights than the height considered. Variable conditions of this kind make it impossible to correlate rigorously the transition location with surface condition. The results, however, provide a strong quantitative indication that movements in transition location on the wing of the X-15-2 airplane measured during the flight were controlled by the two-dimensional-type roughness formed by the skin joint near the wing leading edge and the cover plates over the leading-edge expansion joints.

CONCLUDING REMARKS

Analysis of the fuselage data indicated that turbulent flow existed on the entire fuselage at all times during the flight of the X-15-2 research airplane and that the early transition was caused by a 0.172-inch-high (0.437-cm) forward-facing step between the high-speed flow-direction sensor and the fuselage. Analysis of the wing data indicated that boundary-layer transition occurred forward of the natural transition location throughout the complete flight. The forward movement of transition on the wing was caused by the two-dimensional-type roughness present - either the spanwise step caused by the skin joint near the wing leading edge or the leading-edge expansion-joint covers. Variations in the location of the premature transition on the wing during changes in flight trajectory were indicated to be caused by changes in roughness Reynolds number, but the exact location of transition behind the two-dimensional-type roughness present cannot be predicted. No structural roughness of a three-dimensional type of sufficient height to cause premature transition during the temperature-measuring phase of flight was found on the airplane.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 11, 1966.

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