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NASA MEMO 10-8-58E

NASA MEMORANDUM

NOTE ON A CORRELATION OF BOUNDARY-LAYER TRANSITION RESULTS ON HIGHLY COOLED BLUNT BODIES

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NOTE ON A CORRELATION OF BOUNDARY-LAYER TRANSITION RESULTS ON HIGHLY COOLED BLUNT BODIES*,[1]

By Richard J. Wisniewski

SUMMARY

Boundary-layer transition data on two types of highly cooled blunt bodies are correlated in terms of ratio of wall to total enthalpy, Reynolds number based on displacement thickness, and local Mach number at transition. The proposed correlation indicates that cooling may cause the boundary layer to go from laminar to turbulent flow even if the surface is smooth within practical limits. Furthermore, an effect of roughness on transition on blunt bodies is also noted.

INTRODUCTION

The heat-transfer problem on blunt bodies in hypersonic flow has been of particular concern ever since Allen and Eggers (ref. 1) first proposed high-drag configurations for atmospheric reentry of ballistic missiles. Since the turbulent heating rates on these vehicles are an order of magnitude greater than the laminar rates, optimum design cannot be accomplished without a knowledge of when, where, and whether transition from laminar to turbulent flow will occur.

In recent years, a respectable amount of experimental transition data on such bodies has been obtained; in fact, the Lockheed X-17 reentry test vehicle program was initiated for the specific purpose of obtaining transition data under conditions simulating actual reentry of an intercontinental ballistic missile. The NACA and the Aerophysics Development Corporation in its Hypersonic Test Vehicle (HTV) program also have obtained a substantial amount of transition data on cooled blunt bodies.

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*Title, Unclassified

[1]Supersedes NACA Research Memorandum E57J14, "Preliminary Note on a Correlation of Boundary-Layer Transition Results on Highly Cooled Blunt Bodies," 1958.

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Correlations of these results were attempted by Stewart and Donaldson (ref. 2) and by Tellep and Hoshizaki (ref. 3). The correlation parameters of reference 2 are based on wall- to local-stream-enthalpy ratio, Reynolds number based on momentum thickness, and body position of transition. The correlation of reference 3 relies on ratio of surface roughness to momentum thickness and Reynolds number based on momentum thickness. Neither of these correlations was wholly successful and in many instances both failed completely.

The purpose of this report is to present a new correlation of the aforementioned data. The consequences or implications of this correlation are not as yet understood.

SYMBOLS

The following symbols are used in this report:

A cross-sectional (frontal) area of body, sq ft

C_D body drag coefficient

d body diameter, ft

H form factor, δ^*/θ

H_{tr} low-speed form factor (ref. 4)

h enthalpy

k roughness height, microin.

M Mach number

$Re_{d,1}$ free-stream Reynolds number based on body diameter, $\frac{\rho_1 U_1 d}{\mu_1}$

Re_k roughness Reynolds number, $\frac{U_k k}{\nu_k}$

Re_{δ^*} displacement-thickness Reynolds number, $\frac{\rho_e U_e \delta^*}{\mu_e}$

Re_θ momentum-thickness Reynolds number, $\rho_e U_e \theta/\mu_e$

$\widetilde{Re}$ integrated Reynolds number, $\dfrac{\int_0^s \rho_e \mu_e U_e r_0^2 ds}{\mu_e^2 r_0^2}$

r_n nose radius, in.

r_0 axial radius, ft

s surface distance, ft

T temperature, $^\circ R$

U velocity, ft/sec

W weight, lb

β pressure-gradient parameter

γ_{eff} effective ratio of specific heats (given as γ_e in ref. 3)

δ^* displacement thickness, ft

θ momentum thickness, microin.

θ_c cone half-angle

μ absolute viscosity

ν kinematic viscosity

ρ density

φ_T angle between normal to body surface and free-stream direction

Subscripts:

e local free-stream conditions at edge of boundary layer

k conditions at top of roughness

tr transition conditions

w conditions at wall

0 stagnation conditions behind shock

1 free-stream conditions ahead of shock

REDUCTION OF DATA

Location of Transition

The present report uses data obtained on hemispheres and hemisphere-cones. Table I lists all the data used in this report as well as the various references from which the transition locations were obtained and pertinent comments.

Displacement-Thickness Reynolds Number

In addition to the quantities obtained from the various references listed in table I, the Reynolds number based on displacement thickness is needed. This was obtained from the momentum-thickness Reynolds number as follows:

$$Re_{\delta^*} = HRe_\theta \tag{1}$$

where

$$H = \frac{\delta^*}{\theta} = \frac{T_0}{T_e}(H_{tr} + 1) - 1$$

$$Re_\theta = 0.664(\tilde{Re})^{1/2}$$

The function H_{tr} depends on the pressure-gradient parameter β and the wall- to total-enthalpy ratio h_w/h_0 and is obtained from reference 4. The value of β for the angular position φ_T on a hemisphere or hemisphere segment was approximated by the values listed in the following table:

φ_T, deg	0	20	45	60	90
β	0.50	0.50	0.75	1.03	2.00

Along conical bodies, β equals zero. The temperature ratio T_0/T_e was approximated by

$$\frac{T_0}{T_e} \cong 1 + \frac{\gamma_{eff} - 1}{2} M_e^2 \tag{2}$$

where the effective specific-heat ratio γ_{eff} was taken as 1.40 for $M_1 < 5$ and was varied as suggested in reference 3 for $M_1 > 5$. Local external Mach numbers M_e were found with the aid of modified Newtonian flow theory and perfect gas relations.

RESULTS AND DISCUSSION

Summary of Hemisphere Transition Data

5207 In figure 1 the available transition data for cooled hemispheres from free-flight and wind-tunnel tests are presented in terms of the wall- to local-stream-enthalpy ratio h_w/h_e against the local transition Reynolds number based on momentum thickness $Re_{\theta,tr}$. When these data are analyzed in terms of h_w/h_e and $Re_{\theta,tr}$, no correlation is indicated, and furthermore no apparent effect of cooling is noted.

The cause of transition on cooled hemispheres is not known, and therefore several correlations have been attempted to determine what parameters strongly influence transition on cooled hemispheres. The most widely attempted correlations have relied on roughness as the correlating parameter.

Roughness as a Correlation Parameter

Two of the most logical roughness correlation parameters are presented in figure 2. In figure 2(a) the ratio of roughness height to momentum thickness k/θ obtained from reference 2 is plotted against the transition Reynolds number based on momentum thickness $Re_{\theta,tr}$ for several sets of cooled hemisphere data. Examination of the NACA Langley data (refs. 2, 5, and 6) reveals that the highest values of k/θ yield the smallest values of $Re_{\theta,tr}$, while the smaller values of k/θ yield the largest values of $Re_{\theta,tr}$. However, the Lockheed X-17 data (ref. 2) show no evident trend with the value of k/θ. Therefore, although some type of roughness effect is hinted, it appears that k/θ is an inadequate parameter for correlation.

In figure 2(b) the mean value of the critical roughness Reynolds number for the NACA Langley and the Lockheed X-17 hemisphere flights and various three-dimensional distributed roughness tests is presented. The data on the hemispheres were obtained under conditions of extreme cooling. The three-dimensional distributed roughness tests presented in an unpublished NACA work were on bodies with little or no cooling. The roughness Reynolds number is defined in terms of the roughness height and local conditions evaluated at the roughness height. The critical roughness Reynolds number is that value of the roughness Reynolds number for which transition first moves from its natural position. In figure 2(b) the critical roughness Reynolds number for a subsonic wing, a subsonic hemisphere, and a supersonic cone is approximately 600. The roughness Reynolds number of the uncooled hemisphere flights, evaluated by using the roughness height measured before flight, yields values between 0.05 and 20. Therefore, assuming no large order change in the measured roughness during flight, it must be concluded that the roughness is not large enough to affect transition in the same manner as that found for the three-dimensional distributed roughness tests.

Correlation of Hemisphere Data

The fact that no distinct roughness effect is shown in figures 2(a) and (b) does not mean that roughness is not affecting transition. It is quite possible that there are other parameters in the problem which mask the roughness effect. Therefore, it is reasonable to examine correlation parameters that are independent of roughness. An empirical correlation parameter of this type is presented in figure 3. In figure 3(a), data from smooth hemispheres (1/2 to 6 microin.) are presented on a log-log scale in terms of the ratio of wall to total enthalpy h_w/h_0 and the ratio of the local displacement thickness Reynolds number to the local Mach number Re_{δ^*}/M_e. Examination of figure 3(a) shows that the transition data are well correlated and that the region between laminar and turbulent flow is well defined. It is also interesting to note in figure 3(a) that at a constant value of the correlation parameter cooling will cause the boundary layer to go from laminar to turbulent flow.

Presented in figure 3(b) are all of the data[2] of figure 1 classified in terms of surface roughness and plotted in terms of h_w/h_0 and Re_{δ^*}/M_e. Again, three regions are clearly defined, laminar, transitional, and turbulent. Now, however, the transition region is influenced by the amount of roughness present on the hemisphere. Nevertheless, the data appear to be well correlated.

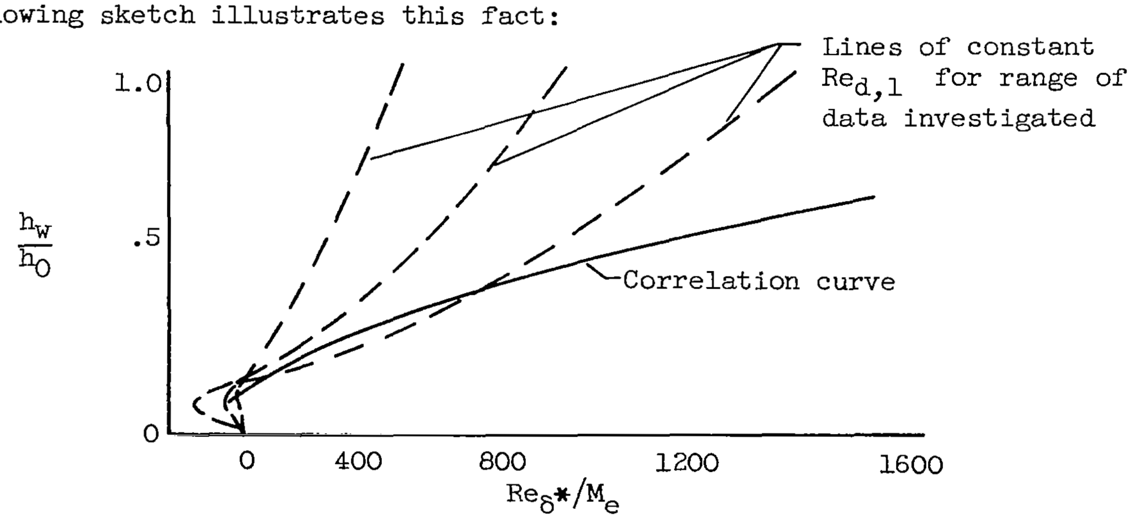
The method of applying the suggested correlation is presented in figure 4. Besides the various correlation curves for the various degrees of surface roughness, the variation of the correlation parameter between an angular position of 20° and 80° is also included under three different

[2]The log-log scale restricts the inclusion of additional points that fall on the correlation curve but have negative values of the correlation parameter.

conditions in a constant wall- to total-enthalpy ratio trajectory. The correlation indicates that, at a given enthalpy ratio, three regions can be distinguished. When the variation of the correlation parameter along the body is such that it falls in region 1, the flow on a body will be laminar even if the surface is quite rough. A second region exists when the flow is transitional; in this region the transition position depends largely on the roughness. That is, for a rough body transition will occur far forward, while for a smooth body transition will occur well back on a body. In a third region, the flow will be turbulent over most of the
5207 body, even if the body is smooth within practical limits.

This correlation does not represent an answer to the entire problem of transition on cooled blunt bodies. The correlation parameter is of an empirical nature, and no physical model exists to base it on.

The question naturally arises as to whether these results do indeed represent a correlation, or whether the correlating parameters are such that all points on a body will fall along the predicted curve. Although it is difficult to establish an exact relation between Re_{δ^*}/M_e and h_w/h_0 for laminar flow, an approximate functional relation can be written for the forward stations on a hemisphere (0° to 15°). The results of this theoretical prediction of Re_{δ^*}/M_e and h_w/h_0 show that the correlation is not coincidental, but represents a true correlation. The following sketch illustrates this fact:



However, the calculations do demonstrate a rather discouraging fact concerning the usefulness of the correlation at the very low wall- to total-enthalpy ratios. At ratios of less than 0.15 the nature of the correlation parameter is such that all data points would tend to merge regardless of angular position. Moreover, large changes in the free-stream Reynolds number are required to change the values of Re_{δ^*}/M_e appreciably.

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Correlation as Applied to Typical Reentry Conditions

In figure 5 the smooth hemisphere correlation curve is plotted on a regular scale, and the variation of the correlation parameter between angular positions of 20° and 80° is included for a hemispherical intercontinental ballistic missile. The trajectory is for a 6-foot-diameter hemisphere having a W/C_DA of 130 pounds per square foot and a wall temperature of 1000° R. The low-temperature portion of the trajectory corresponds to the high-altitude portion of flight. Extrapolating the correlation to the lower enthalpy levels and applying the correlation to include large-diameter bodies, as in figure 5, show that transition will occur on or near the 20° position during the entire time of reentry. The results presented in this figure indicate a serious question as to the possibility of obtaining extensive laminar flow on a hemisphere under full-scale reentry conditions.

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In accepting the previous conclusion one must consider the fact that the most important part of the reentry flight (maximum heating) occurs at wall- to total-enthalpy ratios below any of the experimental data presented here. Therefore, a prediction of extensive turbulent flow must be based on an extrapolation of transition data, which can be very unreliable.

Extension of Correlation Parameter to Other Shapes

Since the actual reentry noses may not be hemispherical, it is desirable to show that the correlation of transition data from other shapes can be attained with the parameter $Re_\delta*/M_e$. A plot of the correlation parameter for both the hemisphere and a large blunt cone is shown in figure 6. This figure shows that the correlation works equally well for the large blunt cone and that two distinct correlation curves are obtained. In fact, at a given enthalpy ratio, the blunt cone shape yields a larger value of $Re_\delta*/M_e$ than the hemisphere. This fact should not be interpreted to mean that, insofar as transition is concerned, one shape is superior to the other. Such a conclusion could be made only after studying both configurations under identical trajectories.

The use of transition data on hemispheres in this report should not be taken as an indication that the hemisphere is the most suitable high-drag body for laminar flow. For example, under the same free-stream conditions, the flat-face body (ref. 11) has demonstrated both lower heating rates and more extensive laminar flow than the hemisphere.

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CONCLUDING REMARKS

A reasonable correlation of transition results on a hemisphere and a large blunt cone have been attained. Whether the correlation parameter will be useful for other high-drag shapes remains to be seen.

The proposed correlation indicates that cooling may cause the boundary layer to go from laminar to turbulent flow even if the surface is smooth within practical limits. Furthermore, an effect of roughness on transition is also noted on blunt bodies.

Applying the correlation to larger diameter bodies and extrapolating to lower wall- to total-enthalpy ratios indicate extensive turbulent flow over a full-scale hemispherical reentry body. However, such an extrapolation must be viewed with caution.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 25, 1958.

REFERENCES

1. Allen, H. Julian, and Eggers, A. J., Jr.: A Study of the Motion and Aerodynamic Heating of Missiles Entering the Earth's Atmosphere at High Supersonic Speeds. NACA TN 4047, 1957. (Supersedes NACA RM A53D28.)

2. Stewart, J. D., and Donaldson, C. du P.: An Analysis of Experimental Data on Transition for Blunt Bodies. Thermodynamics Tech. Memo. No. 73, General Electric Co., June 24, 1957.

3. Tellep, D. M., and Hoshizaki, H.: X-17 R-9 Preliminary Flight Report - Analysis of Transition and Aerodynamic Heating. MSD 2016, Missile Systems Div., Lockheed Aircraft Corp., Oct. 26, 1956.

4. Cohen, Clarence B., and Reshotko, Eli: The Compressible Laminar Boundary Layer with Heat Transfer and Arbitrary Pressure Gradient. NACA Rep. 1294, 1956. (Supersedes NACA TN 3326.)

5. Hall, James R., Speegle, Katherine C., and Piland, Robert O.: Preliminary Results from a Free-Flight Investigation of Boundary-Layer Transition and Heat Transfer on a Highly Polished 8-Inch-Diameter Hemisphere-Cylinder at Mach Numbers up to 3 and Reynolds Numbers Based on a Length of 1 foot up to 17.7×10^6. NACA RM L57D18c, 1957.

6. Chauvin, Leo T., and Speegle, Katherine C.: Boundary-Layer-Transition and Heat-Transfer Measurements from Flight Tests of Blunt and Sharp 50° Cones at Mach Numbers from 1.7 to 4.7. NACA RM L57D04, 1957.

7. Beckwith, Ivan E., and Gallagher, James J.: Heat Transfer and Recovery Temperatures on a Sphere with Laminar, Transitional, and Turbulent Boundary Layers at Mach Numbers of 2.00 and 4.15. NACA TN 4125, 1957.

8. Krasnican, M. J., and Wisniewski, R. J.: Free-Flight Determination of Boundary-Layer Transition and Heat Transfer for a Hemisphere-Cylinder at Mach Numbers to 5.6. NACA RM E57F10, 1957. 5207

9. Diaconis, N. S., Wisniewski, Richard J., and Jack, John R.: Heat Transfer and Boundary-Layer Transition on Two Blunt Bodies at Mach Number 3.12. NACA TN 4099, 1957.

10. Seiff, Alvin, Sommer, Simon C., and Canning, Thomas N.: Some Experiments at High Supersonic Speeds on the Aerodynamic and Boundary-Layer Transition Characteristics of High-Drag Bodies of Revolution. NACA RM A56I05, 1957.

11. Canning, Thomas N., and Sommer, Simon C.: Investigation of Boundary-Layer Transition on Flat-Faced Bodies of Revolution at High Supersonic Speeds. NACA RM A57C25, 1957.

[redacted]

TABLE I. - SUMMARY OF DATA

Reference	φ_T, deg	M_1	$Re_{d,1}\times10^{-6}$	h_w/h_0	h_w/h_e	Re_θ	Re_{δ^*}	Re_{δ^*}/M_e	$k\times10^6$	r_n, in.	Source	Shape
2	20	11.5	20.2	0.159	0.161	206	32.3	76.2	2	4.5	X-17 R-2	Hemisphere
	30	12.0	19.6	.147	.152	420	33.4	51.2	2	4.5	X-17 R-2	Hemisphere
	20	10.9	12.7	0.136	0.138	240	15.0	35.4	2	4.5	X-17 R-8	Hemisphere
	30	10.3	10.6	.123	.128	325	11.8	18.1	↓	↓	↓	↓
	40	9.9	9.4	.115	.124	397	11.1	12.3	↓	↓	↓	↓
	20	12.0	6.3	0.103	0.104	163	-2.4	-5.7	30	4.5	X-17 R-9	Hemisphere
	30	13.5	13.9	.114	.118	311	4.0	6.1	1	↓	↓	↓
	40	13.7	12.0	.091	.097	384	-12.6	-13.9	1	↓	↓	↓
	50	12.4	23.6	0.110	0.124	684	4.3	3.6	1/2	4.5	X-17 R-11	Hemisphere
	50	11.8	13.0	.090	.101	566	-21.9	-18.3	6	↓	↓	↓
	60	12.4	21.9	.101	.122	714	-3.0	-1.9	1/2	↓	↓	↓
	22.5	11.1	15.4	0.179	0.183	285	46.8	97.6	20	4.5	X-17 R-22	Hemisphere
	30.0	10.9	14.4	.176	.183	360	59.2	90.8	20	↓	↓	↓
	37.5	9.4	9.3	.195	.209	370	83.6	100.0	20	↓	↓	↓
	52.5	9.5	7.2	.165	.192	445	80.2	63.1	20	↓	↓	↓
	52.5	10.7	13.6	.152	.175	580	73.3	57.6	6	↓	↓	↓
	52.5	10.7	13.6	.152	.175	580	73.3	57.6	1/2	↓	↓	↓
3	40	4.30	7.75	0.365	0.423	451	325	367	30	4.5	X-17 R-9	Hemisphere
		5.35	2.75	.305	.353	235	143	261	30	4.5	Lewis	Hemisphere
2	30	4.36	9.8	0.297	0.321	387	195	305	2	3.0	HTV RD1	Hemisphere
	45	3.98	9.8	.342	.411	553	411	409	2	3.0	HTV RD1	Hemisphere
	52.5	3.94	12.0	0.407	0.528	754	773	634	2	3.0	HTV RD3	Hemisphere
	60	3.97	12.4	.383	.530	875	880	636	2	3.0	HTV RD3	Hemisphere
	45	2.58	7.8	0.490	0.580	596	674	704	2	3.0	HTV RD8	Hemisphere
	30	2.58	7.8	.515	.553	398	431	707	11	3.0	HTV RD8	Hemisphere
	38	2.80	24.1	0.575	0.661	794	1077	1246	5	6.50	Langley	Hemisphere-cone, θ_c = 14.5°
		2.97	23.2	.544	.625	798	1019	1178	↓	↓	↓	↓
		3.14	22.2	.517	.594	804	962	1113	↓	↓	↓	↓
5	60	2.96		0.469	0.700	940	1361	906	5	4.00	Langley	Hemisphere
	75	2.14		.528	.860	1110	1981	1075	↓	↓	↓	↓
	75	2.73		.415	.676	1200	1615	760	↓	↓	↓	↓
6	22	4.70	16.1	0.476	0.499	390	370	789	25	4.44	Langley	Hemisphere-cone, θ_c = 25°
		2.50	9.8	.673	.701	350	513	1127	25	4.44	Langley	Hemisphere-cone, θ_c = 25°
2	14	2.00	9.0	0.680	0.69	260	395	1439	25	4.00	Langley	Hemisphere-cone, θ_c = 25°
	15.8	2.50	11.1	.582	.58	292	336	1039	↓	↓	↓	Hemisphere
	15.2	2.80	11.9	.535	.55	294	320	1017	↓	↓	↓	↓
	9.6	3.05	12.6	.533	.54	159	168	846	↓	↓	↓	↓
	30.3	2.80	11.3	.886	.95	574	1244	1923	↓	↓	↓	↓
7	25	2.00	2.74	0.49	0.52	204	206	414	>140	1.75	Langley	Hemisphere
	10	↓	3.43	.58	.59	93	106	544	↓	↓	↓	↓
	15	↓	3.45	.58	.59	136	160	543	↓	↓	↓	↓
	30	↓	3.50	.77	.83	275	508	842	↓	↓	↓	↓
	20	↓	4.38	.79	.82	206	368	932	↓	↓	↓	↓
	5	↓	4.45	.69	.69	59	85	876	↓	↓	↓	↓
8	≈5	2.34	7.66	0.515	0.516	≈80	≈77	≈749	5	4.50	Lewis	Hemisphere
	45	3.03	9.84	.396	.475	642	575	575	5	4.50	Lewis	Hemisphere
9	67	3.12	1.34	0.486	0.978	506	1031	462	145	0.70	Lewis	Hemisphere-cone, θ_c = 4.75°
	72	3.12	1.80	.571	.450	506	960	522	145	.70	Lewis	Hemisphere-cone, θ_c = 4.75°
Unpublished data	63	3.12	2.16	0.441	0.646	425	552	329	145	0.70	Lewis	Hemisphere-cone, θ_c = 4.25°
				.615	.900	↓	826	492	↓	↓	↓	↓
				.769	1.127	↓	1094	652	↓	↓	↓	↓
10	40	4.00	3.80	0.241		325	137	155	5	1.65	Ames	Hemisphere
2		7.9	20.6	0.237	0.260	484	207	243	1/2		X-17 R-17	Blunt cone
		8.3	21.0	.245	.268	548	248	291	↓		↓	↓
		8.7	21.5	.177	.193	608	153	179	↓		↓	↓
		10.7	15.8	.121	.130	500	35.S	41.6	↓		↓	↓
2		11.4	23.0	0.124	.133	450	30.6	35.9	1/2		X-17 R-18	Blunt cone
		11.5	20.9	.114	.123	535	36.4	42.7	↓		↓	↓
		10.0	12.4	.112	.120	460	35.4	41.5	↓		↓	↓
		10.0	12.4	.111	.119	500	37.5	44.0	↓		↓	↓
		14.0	9.0	0.088	0.094	270	7.3	8.6	30		X-17 R-21	Blunt cone
		13.0	7.0	.085	.091	240	3.4	4.0	1/2		↓	↓
		13.3	7.5	.084	.090	280	4.2	4.9	30		↓	↓
		13.0	7.0	.082	.088	300	-4.6	-5.4	30		↓	↓
		12.0	5.8	.077	.082	285	-4.8	-5.6	1/2		↓	↓
		10.9	15.4	0.115	0.124	394	27.6	32.4	5		X-17 R-23	Blunt cone
		10.6	14.0	.118	.126	375	26.6	31.2	15		↓	↓
		10.2	12.0	.112	.120	386	28.6	33.5	5		↓	↓
		10.6	14.0	.108	.116	415	29.5	34.6	15		↓	↓
		10.2	12.0	.109	.117	430	31.8	37.3	5		↓	↓
		10.6	14.0	0.116	0.124	467	33.2	38.9	15		X-17 R-23	Blunt cone
		9.8	10.2	.116	.125	438	33.7	39.5	5		↓	↓
		9.6	9.7	.116	.125	420	35.2	38.9	15		↓	↓
		9.8	10.2	.121	.130	460	35.4	41.5	5		↓	↓
		9.5	9.2	.115	.124	438	35.0	41.0	15		↓	↓

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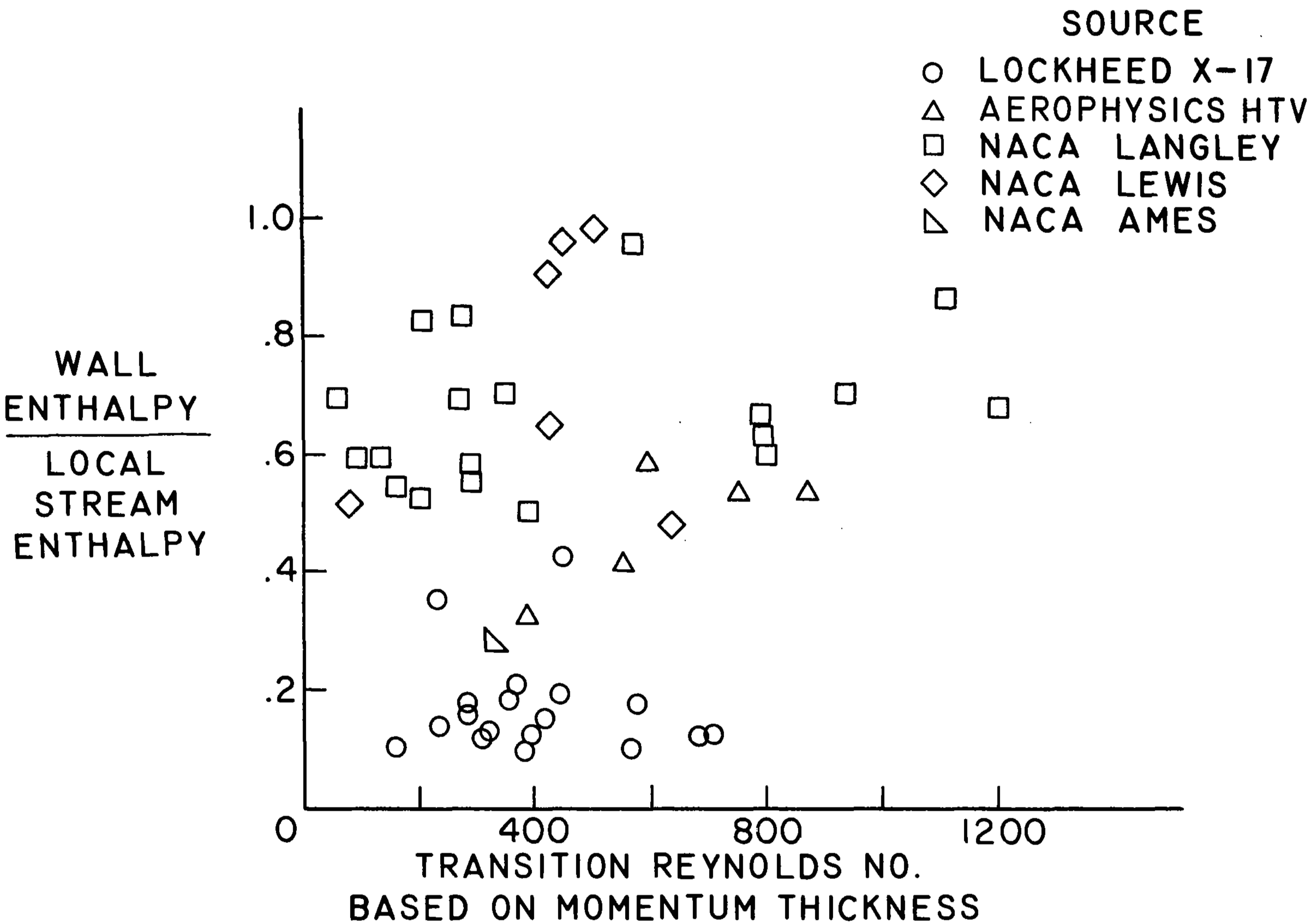
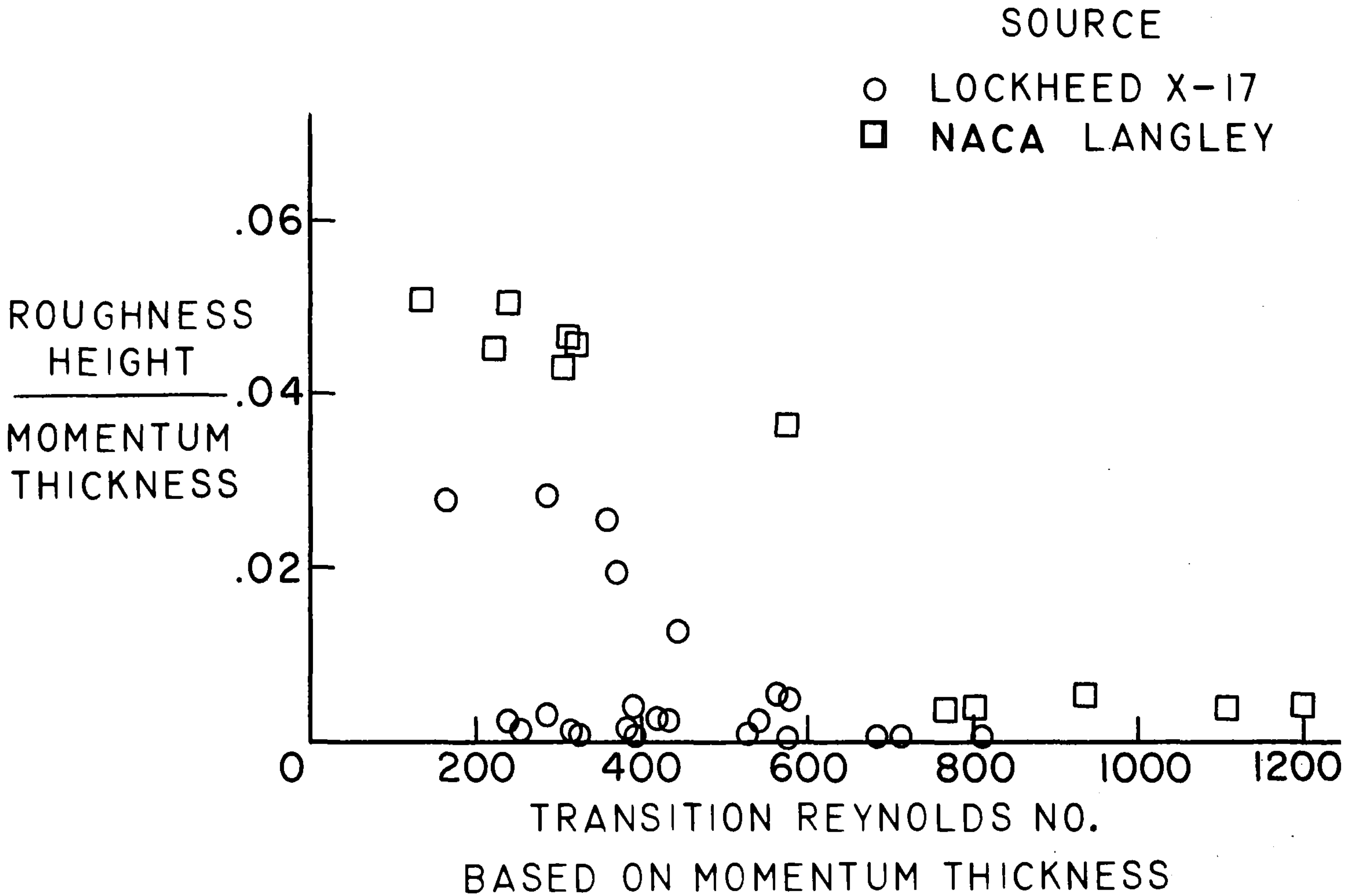
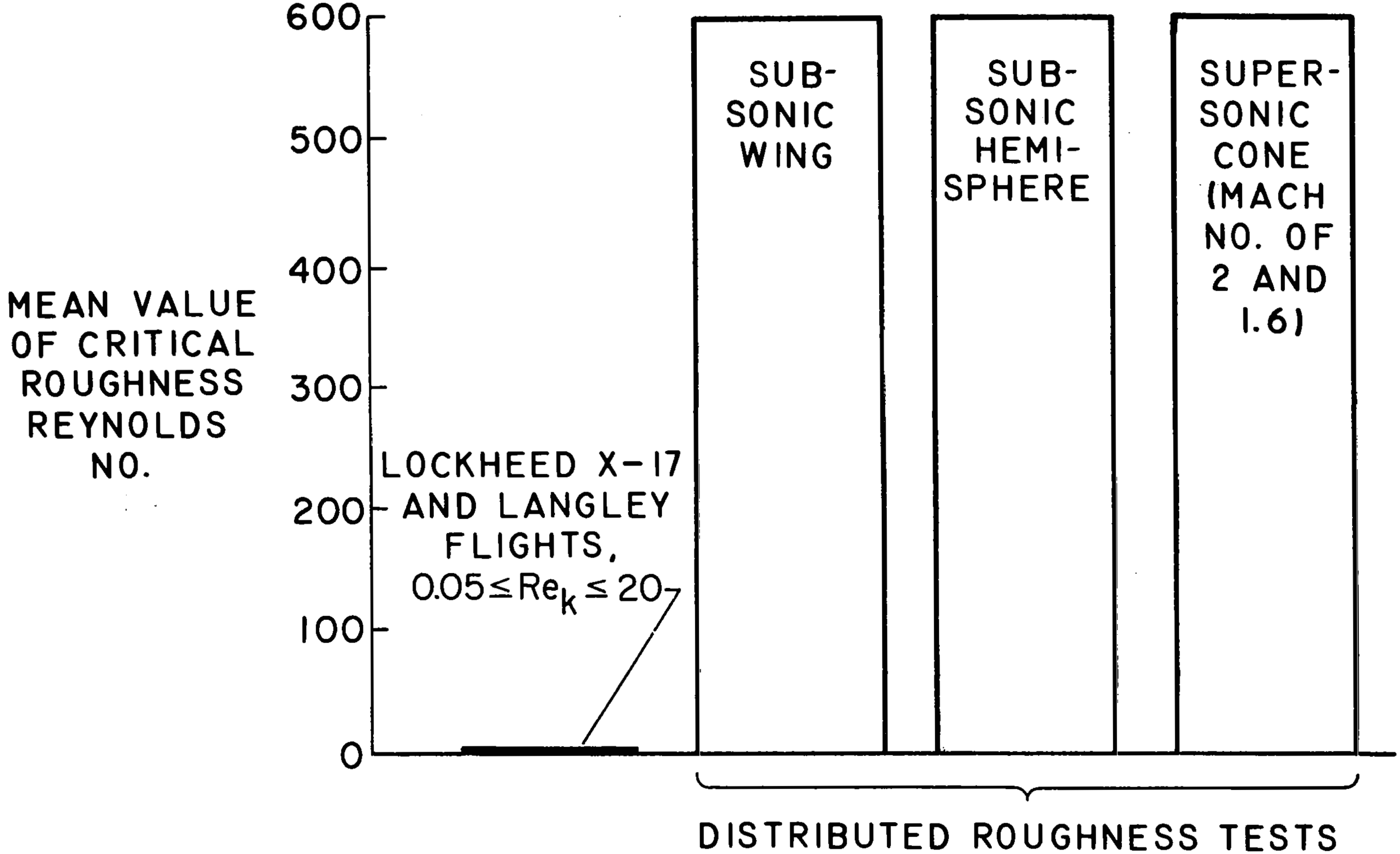


Figure 1. - Transition on cooled hemispheres.



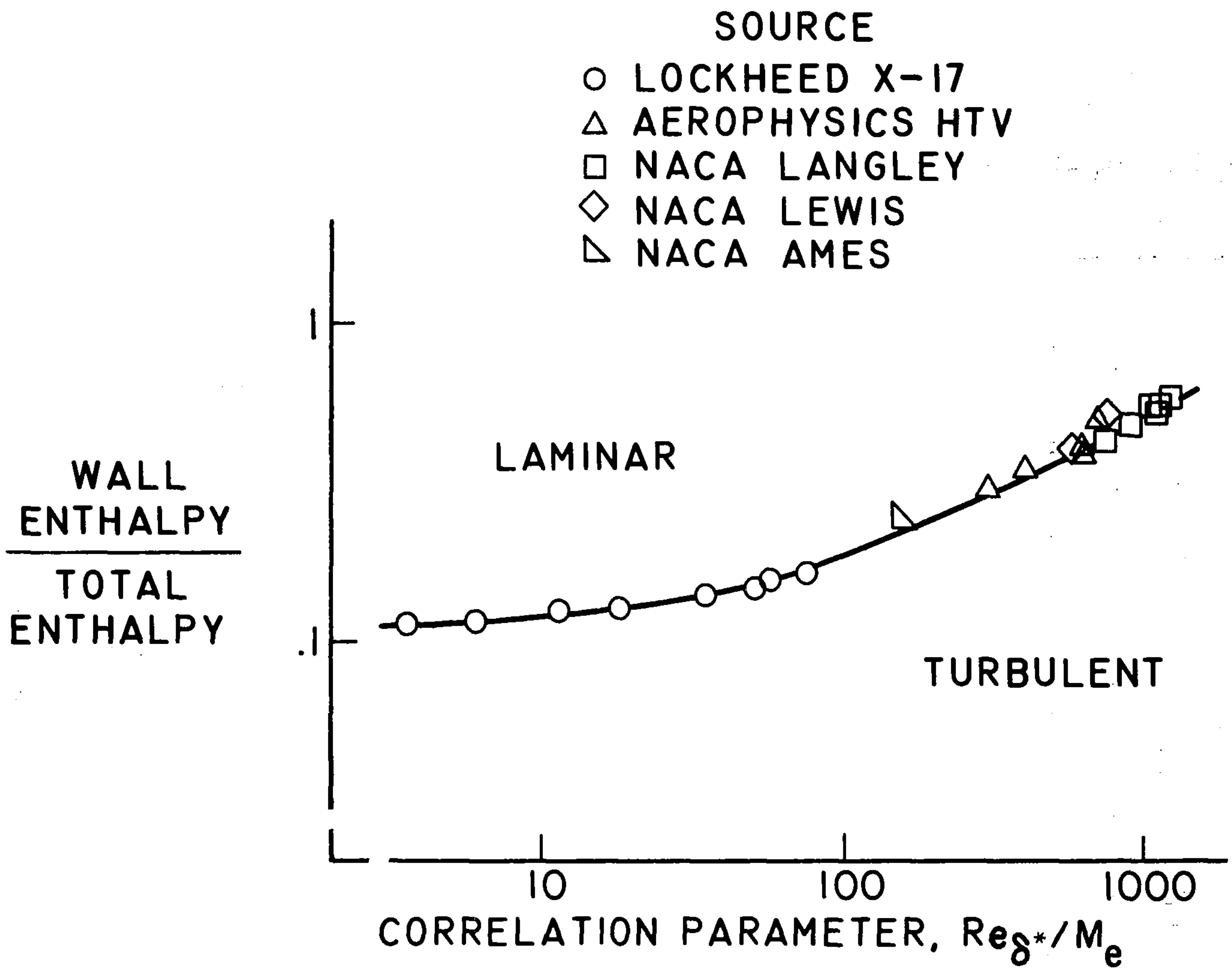
(a) Ratio of roughness height to momentum thickness.

Figure 2. - Roughness as a correlation parameter.



(b) Critical roughness Reynolds number. $Re_k = \frac{U_k k}{\nu_k}$.

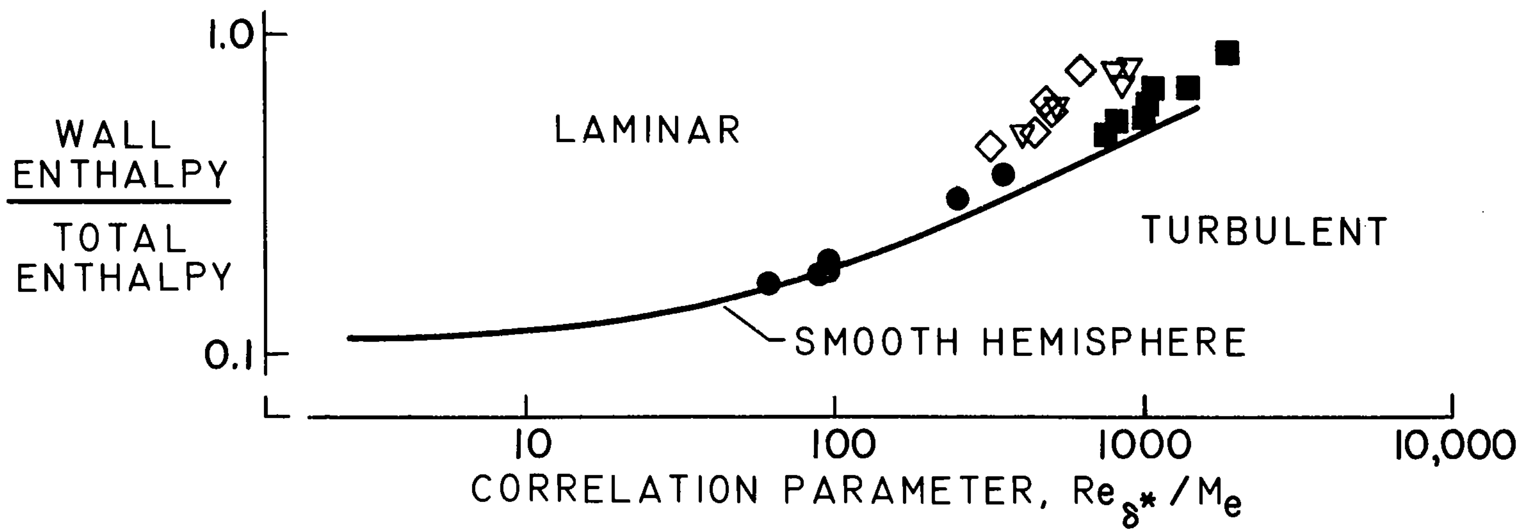
Figure 2. - Concluded. Roughness as a correlation parameter.



(a) Surfaces 1/2 to 6 microinches.

Figure 3. - Correlation of hemisphere data.

	SOURCE	ROOT MEAN SQUARE SURFACE ROUGHNESS, MICROIN.
●	LOCKHEED X-17	20-30
■	NACA LANGLEY	25
◇	NACA LEWIS	145
▽	NACA LANGLEY	>140



(b) Roughened surfaces.

Figure 3. - Concluded. Correlation of hemisphere data.

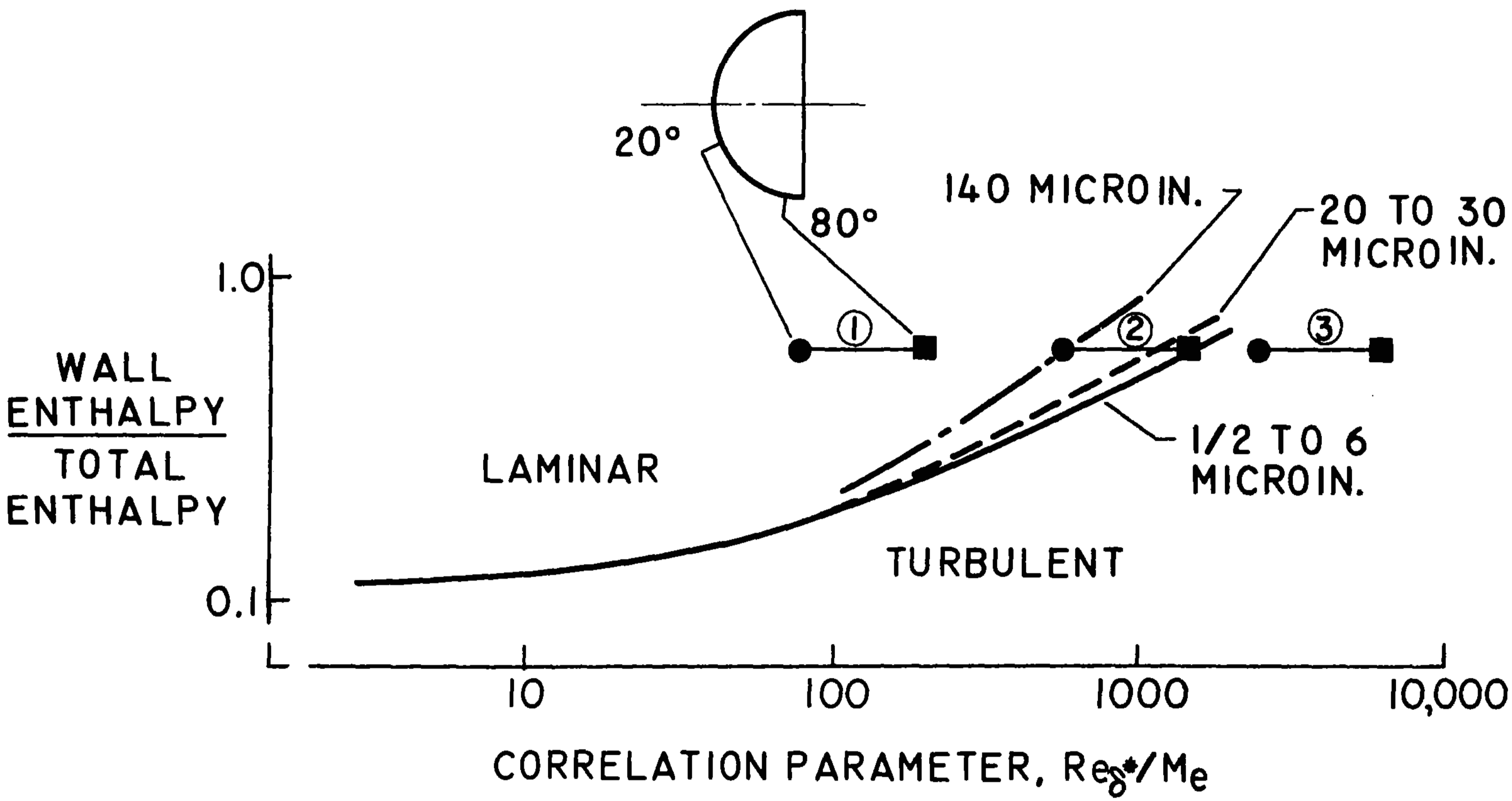


Figure 4. - Method of application.

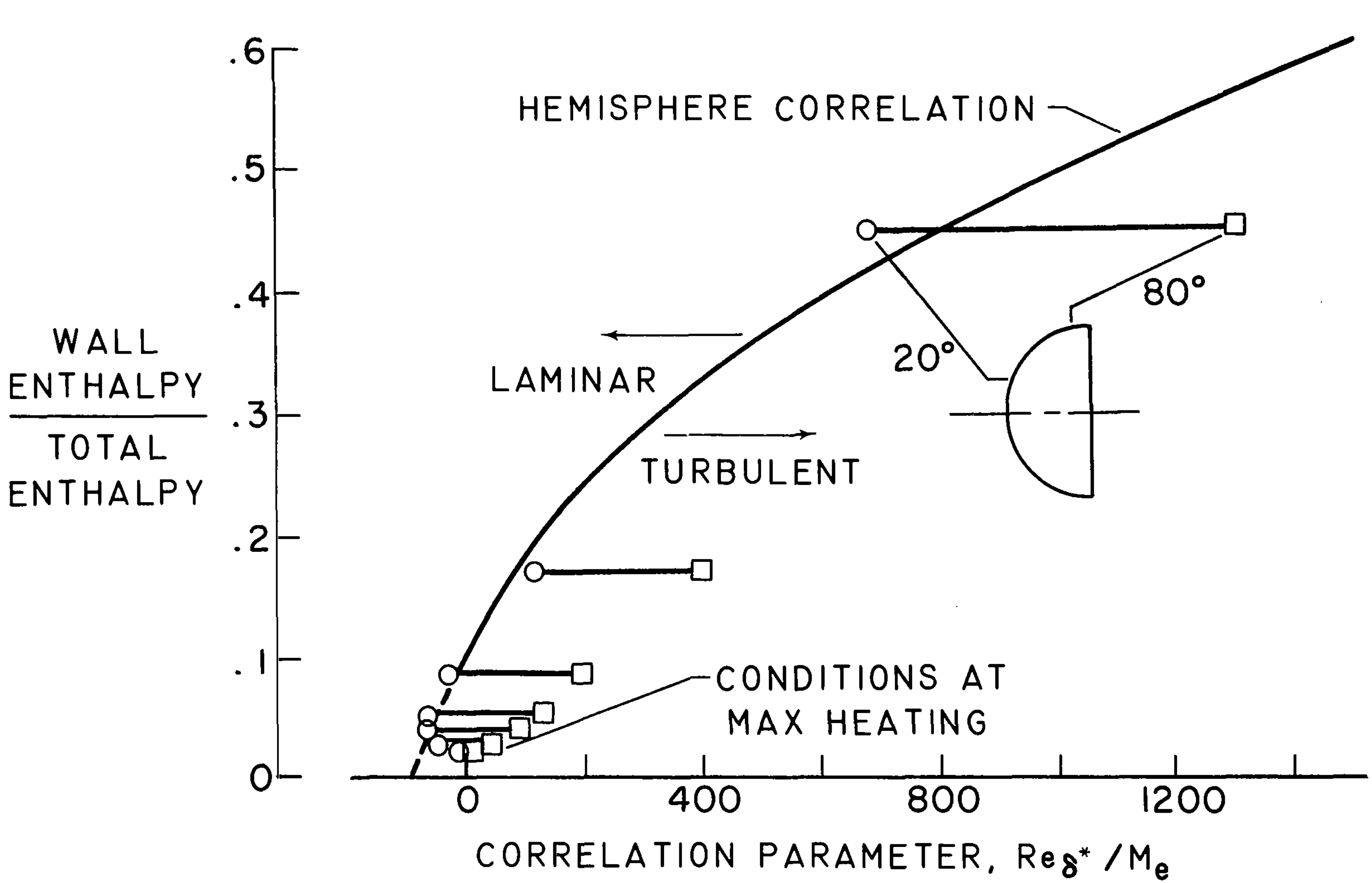


Figure 5. - Correlation parameters for hemispherical ICBM reentry body. Diameter, 6 feet; wall temperature, 1000° R; W/C_DA, 130 pounds per square foot.

NASA - Langley Field, Va.

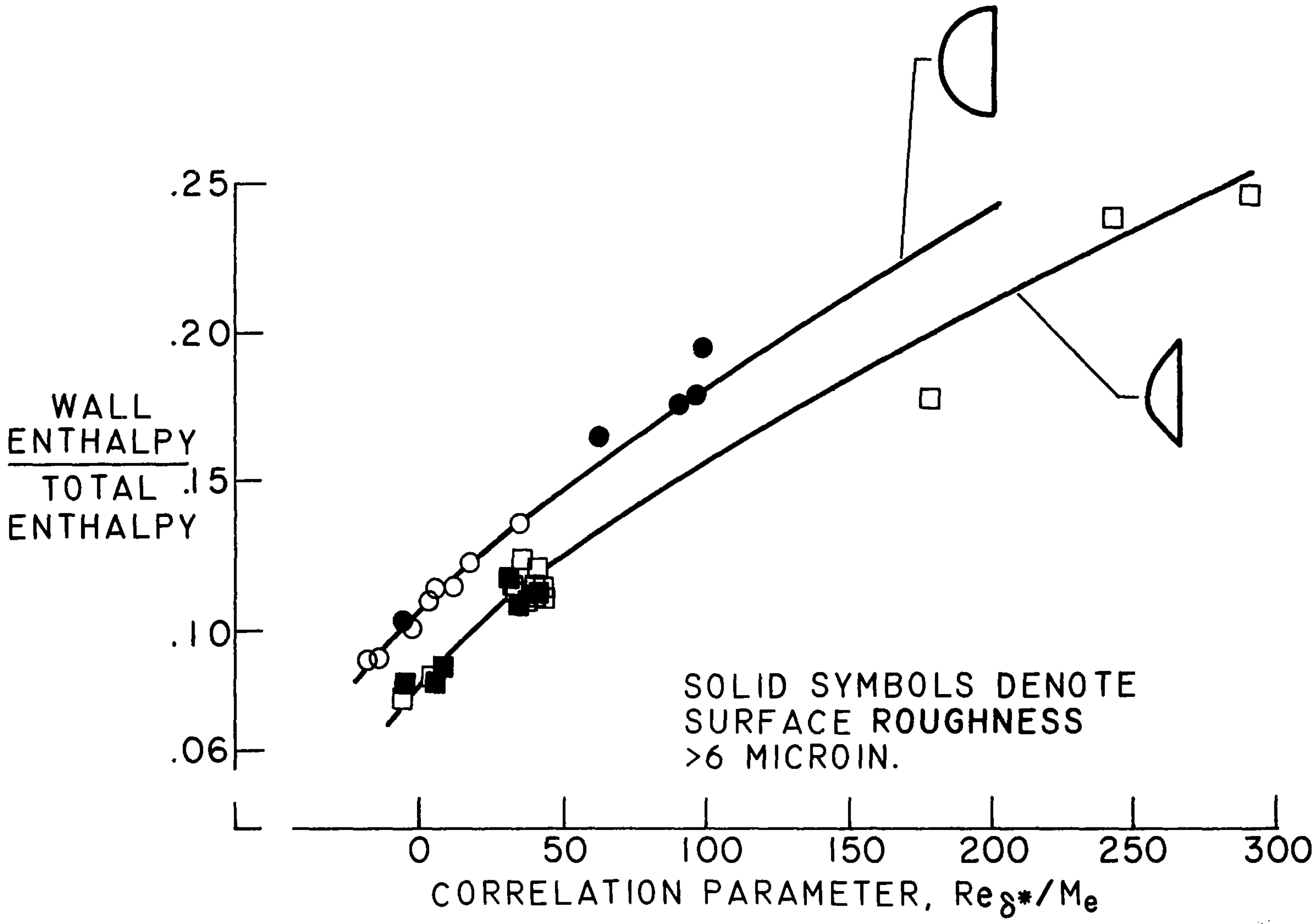


Figure 6. - Variation of correlation with body shape.