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RESEARCH MEMORANDUM

RAM-RECOVERY CHARACTERISTICS OF NACA SUBMERGED

INLETS AT HIGH SUBSONIC SPEEDS

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RAM-RECOVERY CHARACTERISTICS OF NACA SUBMERGED

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SUMMARY

Results are presented of an experimental investigation of the
ram-recovery characteristics of NACA submerged inlets on a model of
a fighter airplane at Mach numbers from 0.30 to 0.875. The effects
on the entrance ram-recovery ratio of Mach number, angle of attack,
entrance mass flow, boundary-layer thickness on the fuselage, inlet
location, and boundary-layer deflectors are shown.

The data indicate only a slight decrease in ram-recovery ratio
for the inlets ahead of or just behind the wing leading edge as Mach
number increased, but show large decreases at high Mach numbers for
the inlets aft of the point of maximum thickness of the wing. In
general, the ram-recovery ratio decreased with increasing angle of
attack. The ram-recovery ratio was a maximum at mass-flow ratios
between 0.60 and 0.80. Artificially increasing the boundary-layer
thickness or moving the inlets aft decreased the ram-recovery ratio.
Boundary-layer deflectors increased the maximum ram-recovery ratio
and the mass-flow ratio at which the maximum occurred.

INTRODUCTION

A research program was conducted in the Ames 16-foot high-speed
wind tunnel which, in conjunction with work in an Ames 7- by 10-foot
wind tunnel, continued the investigation of NACA submerged inlets
developed during the tests discussed in references 1 and 2. Attention
was concentrated on the inlet design found to have the most satisfac-
tory pressure-recovery characteristics during the tests of reference 1.
The effects of the following parameters on the pressure recovery at
the inlets were investigated:

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1. Aerodynamic parameters

    (a) Mach number

    (b) Angle of attack

    (c) Mass-flow ratio

    (d) Boundary-layer thickness

2. Model parameters

    (a) Inlet location with respect to wing and fuselage

    (b) Inlet lip angle

    (c) Boundary-layer deflectors

Data obtained during the present investigation of the model without inlets and with inlets 16.7 percent of the root chord ahead of the wing-root leading edge only were presented extensively in reference 3. To expedite the publication of the pressure-recovery characteristics for the inlets in other configurations, the present report was prepared.

SYMBOLS

The symbols used in this report and their definitions are as follows:

d   inlet depth, inches

H   average total pressure, pounds per square foot

$\frac{H_1-p_0}{H_0-p_0}$ ram-recovery ratio

h   the height of an area of unit width in which the complete loss of free-stream ram pressure is equivalent to the integrated loss of the total pressure in unit width of the boundary layer $\left[\int_0^\delta \left(\frac{H_0-H}{H_0-p_0}\right) dy\right]$, inches

M   Mach number

$\dfrac{m_1}{m_0}$ mass-flow ratio (the ratio of the mass flow through the inlet to the mass flow in the free stream through an area equal to the entrance area)

p   static pressure, pounds per square foot

y   increment of boundary-layer thickness, inches

α_u angle of attack uncorrected for tunnel-wall effects (measured relative to the fuselage reference line), degrees

δ boundary-layer thickness, inches

Subscripts

o   free stream

1   duct entrance

APPARATUS

A complete description of the model was given in reference 3. Briefly, the model (shown in figs. 1 and 2) was patterned to represent a typical high-speed fighter airplane. Throughout the tests, a pair of identical inlets was used. They were disposed symmetrically on each side of the fuselage and connected to a common plenum chamber in the aft part of the fuselage. The four longitudinal inlet locations investigated (fig. 2) were at fuselage stations 34.25, 42.50, 50.75, and 59.00 and corresponded, respectively, to 16.7 percent of the root chord ahead of, and 8.3, 33.3, and 58.3 percent of the root chord behind the wing-root leading edge. Dimensions of the ramp, lip, and boundary-layer deflectors are shown in figure 3.

To determine the effect of boundary-layer thickness, the boundary layer along the fuselage surface was artificially increased from the natural thickness to medium and thick by roughening the fuselage 5 inches from the nose by means of small nails projecting from the surface. The boundary-layer thickness was measured with three small rakes, each consisting of 10 total-pressure tubes.

Pressure losses and flow rates at the intake were measured with a rake 2.1 inches behind the lip leading edge. The rake consisted of 30 total-pressure and 30 static-pressure tubes.

10 percent smaller than it would be in free air for the same lift on the wing.

Total pressure and mass flow.— To expedite the publication of this report, the ram-recovery and mass-flow ratios have been computed from the average of the 30 total-pressure and 30 static-pressure readings rather than the more correct but time-consuming method used in reference 3. A comparison of the results from the two methods was made with the data from the inlets at station 34.25 with deflectors on the ramp and the differences are shown in figure 4. To indicate the possibility of adding these differences to correct the data of this report to agree with those which might be computed by the more correct method, calculations were made at random for data from tests of the inlets with deflectors on the ramps at the three other locations. The method using average-pressure values and the curves of figure 4 gave ram-recovery ratios which were in good agreement with the more exact method for mass-flow ratios above approximately 0.60 but which averaged approximately 0.02 lower at low mass-flow ratios.

Ram-Recovery Ratio

The ram-recovery data have been arranged to show first the effects of mass-flow ratio (fig. 5). Figure 6 presents values of the boundary-layer parameter on the fuselage and figures 7 to 9 show the effects of boundary-layer thickness, Mach number, angle of attack, inlet position, and boundary-layer deflectors on the ram-recovery ratio. Last, the original data from which the comparison plots were taken are shown in figures 10 to 18 as supplementary material with no formal discussion.

Effect of lip angle.— It was previously mentioned that the effects of lip angle were investigated during these tests. The data indicate no change in ram-recovery ratio for the range of lip angles tested. This result may be due to the fact that, with the rake at the entrance, it was impossible to obtain mass-flow ratios sufficiently large to exceed the critical Mach number of the inner surface of the lip at angles from –1° to –5°. Conditions under which lip angle might have a large effect on the ram-recovery ratio were not obtained, therefore. Because no effect of lip angle was evident in these tests, data in this report are presented for a lip angle of –3° only.

Effect of mass-flow ratio.— In general, the effect of mass-flow

The effect of boundary–layer thickness on ram–recovery ratio is shown in figure 7 for the inlets at fuselage station 34.25. The effects of boundary–layer thickness remained essentially constant at a given angle of attack and Mach number throughout the range of mass–flow ratios. The data are compared, therefore, at 0.70 mass–flow ratio only.

The data indicate that thickening the boundary layer reduced the ram–recovery ratio throughout the Mach number and angle–of–attack range of the tests. A general statement of the effect of Mach number on the ram–recovery ratio with the medium or thick boundary layers cannot be made because the effect is not consistent throughout the angle–of–attack range. For example, with the thick boundary layer the ram–recovery ratio increased slightly with Mach number for 0° and 2° angle of attack but decreased at -2° and 6° angle of attack. With the natural boundary layer, the ram–recovery ratio in general decreased with Mach number throughout the angle–of–attack range.

Effect of inlet position and Mach number.— The comparison of the ram–recovery ratio for mass–flow ratios of 0.60 and 0.80 for each inlet position (fig. 8) shows that throughout the Mach number and angle–of–attack ranges of the tests the highest ram–recovery ratios were obtained with the inlets in the forward location. This characteristic was expected because of the thinner boundary layer on the fuselage surface at this location. The variation of ram–recovery ratio as Mach number increased was smallest for the inlets in the forward location, being less than 0.02 within the range of data presented.

The ram–recovery ratio for the inlets in the second position (station 42.50) compared satisfactorily with that of the forward location, being within 0.03 at 0.30 Mach number. The decrease in ram–recovery ratio as Mach number increased was slightly greater for the inlets in the second location than in the forward location, resulting in the recovery ratio being as much as 0.05 less for the second location at high Mach numbers. It should be realized, however, that with a fixed engine location the shorter ducting system from the inlets to the compressor face for the second inlet location might result in an increase in the efficiency of the ducting sufficiently large to offset the higher entrance losses.

At 0.30 Mach number, the ram–recovery ratio for the inlets in the two aft locations was within 0.07 of that for the forward location in the angle–of–attack range of -2° to 6°. Except for the inlets at station 50.75 from -2° to 0° angle of attack, however,

the ram-recovery ratio of the inlets in the two aft locations was
poor at high Mach numbers. With the inlets in the aft location,
a ram-recovery ratio of only 0.60 was obtained at a Mach number of
0.80 and 2° angle of attack.

The decrease in ram-recovery ratio as Mach number increased
could be due to an increase in the boundary-layer thickness; separa-
tion; or to shock waves along the fuselage, in the wing-fuselage
juncture, or on the ramps. In reference 3 it was indicated that sep-
aration occurred at approximately fuselage station 50 at 0.30 Mach
number and 12.5° angle of attack and moved aft to fuselage station
60 at 1° angle of attack as Mach number increased to 0.875. At low
Mach numbers, the separation was caused by poor flow in the wing-
fuselage juncture at high angles of attack. At high Mach numbers
the separation was due to the large increase in the boundary-layer
thickness caused by the shock wave at the wing-fuselage juncture.
With the inlets in the two forward locations, the decrease in ram-
recovery ratio as Mach number increased is believed to be due
primarily to the thickening boundary layer caused by a forward
movement of the transition point with increasing Reynolds number.
This effect was indicated in the section discussing the effects of
boundary-layer thickness and also by the fact that the decrease of
ram-recovery ratio as Mach number increased was fairly steady
throughout the Mach number range. Reference 3 showed that critical
speeds along the ramp were barely exceeded at 0.875 Mach number with
the inlets in the forward location, thus indicating that shock waves
on the fuselage or the ramp were not the cause of the decrease of
ram-recovery ratio. Reference 3 also indicated that it was unlikely
that critical speeds would be reached on the ramps of the inlets at
station 42.50 because the speeds in that region without inlets were
below those in the region of station 34.25.

With the inlets in the two aft locations, much of the pressure
loss can be attributed to the influence of the boundary layer. For
example, when the boundary layer became thick and separated from
the surface, pressure losses greater than free-stream ram pressure
were obtained at subcritical speeds with the inlets in the aft loca-
tion. (See fig. 18 for results at 12° angle of attack and a Mach
number of 0.60 for which conditions reference 3 indicated sub-
critical speeds and a thick, possibly separated, boundary layer on
the fuselage surface without inlets.) For conditions having a
similar boundary-layer growth at supercritical speeds, it is
believed that large losses also would be caused primarily by the
thick boundary layer. (See figs. 6 and 8 for results at the highest
angles of attack at Mach numbers of 0.70 and 0.80.) When the

boundary layer on the fuselage did not thicken, as indicated by the
boundary-layer data obtained without inlets (fig. 6), some of the
losses might be attributed to boundary-layer and shock-wave inter-
action on the ramp. For example, in figure 8 the results snow that
the increase in losses with angle of attack at high Mach numbers was
larger at 0.60 than 0.80 mass-flow ratio. This characteristic was
probably due to the interaction of the shock wave and the thicker
boundary layer on the ramp caused by the more adverse pressure gra-
dient at 0.60 mass-flow ratio because the shock waves on the ramp
were probably weaker at 0.60 mass-flow ratio. Reference 3 showed
that along the ramps of the inlets in the forward location the
increase in static pressure from the point of minimum pressure to
the inlets was larger and the maximum airspeeds were lower at 0.60
than 0.80 mass-flow ratio. The effect of the boundary layer in the
presence of shock waves would be less severe with a thinner boundary
layer at the beginning of the ramp. This effect, together with the
fact that for some conditions the losses are caused primarily by the
extremely thick boundary layer, suggests that the characteristics of
submerged inlets in regions of airspeeds as high as those obtained in
the aft location would be much better in the absence of the thick
boundary layer.

Effect of angle of attack.- The effect of angle of attack on
the ram-recovery ratio also is shown in figure 8 for the four inlet
locations. The data indicate that throughout the Mach number range
at both 0.60 and 0.80 mass-flow ratio, the ram-recovery ratio
decreased with increasing angle of attack. This decrease was prob-
ably caused by the increase in the boundary-layer parameter with
angle of attack, as generally indicated in figure 6. Also for inlets
in the two aft locations, this effect would be combined with that of
the greater shock-wave intensity caused by the increase in airspeed
along the fuselage induced by the wing at high Mach numbers.

Effect of deflectors.- The effect of deflectors on the ram-
recovery ratio was essentially constant throughout the Mach number
range. A comparison of the data obtained with and without deflectors
at each of the four locations is shown, therefore, only for 0.70 Mach
number in figure 9. The apparent extrapolation of some of the data
for the inlets with deflectors at low mass-flow ratios is due to the
fact that some of the end points for such data were beyond the limits
of the plots of figure 9. Such curves were traced from the more
complete curves of figures 15 to 18.

The data of figure 9 show that the effect of the deflectors was
to increase the maximum ram-recovery ratio for all inlet locations.

inlets in the forward location.

3. Increasing the boundary-layer thickness decreased the ram-recovery ratio.

4. In general, the ram-recovery ratio decreased with increasing angle of attack.

5. With no deflectors on the ramp the ram-recovery ratio increased greatly as mass-flow ratio increased to approximately 0.60, reached a maximum between 0.60 and 0.80 mass-flow ratio, and slowly decreased for greater flow rates.

6. The boundary-layer deflectors increased the maximum ram-recovery ratio and the mass-flow ratio at which it occurred. They reduced the ram-recovery ratio between approximately 0.40 and 0.70 mass-flow ratio and also reduced the change in ram-recovery ratio with angle of attack for inlets in the two forward locations.

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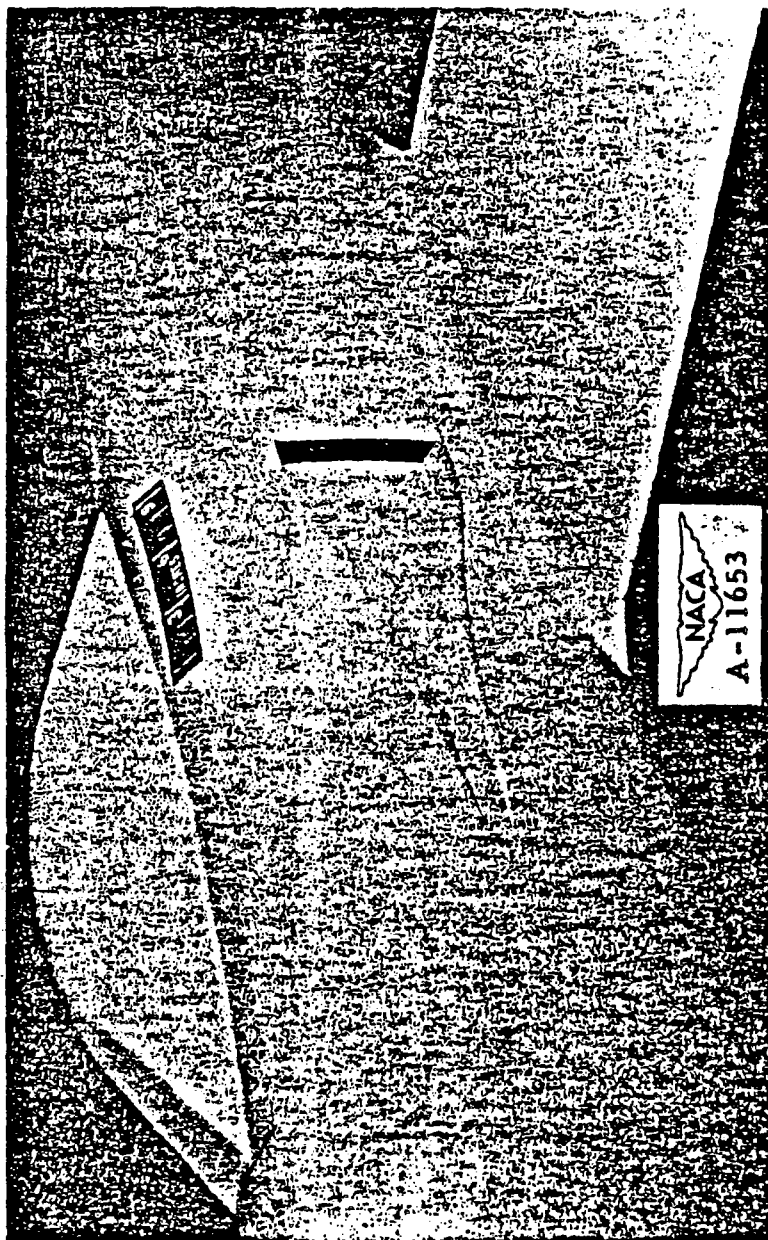   NACA RM No. A8A20, 1948.
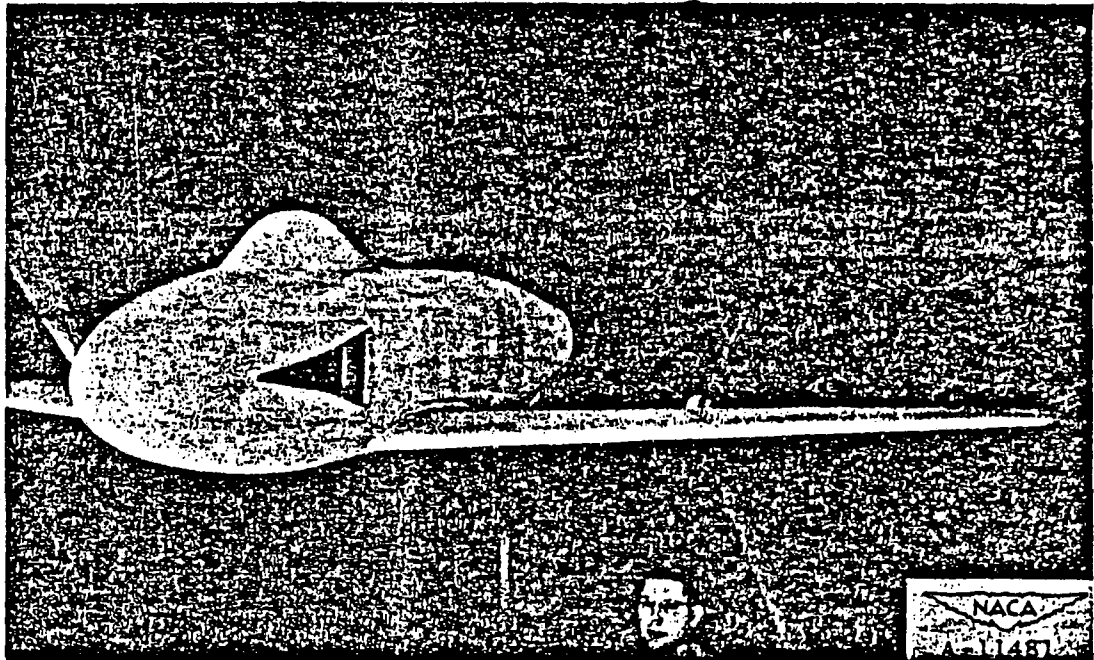
(a) Inlet with deflectors at fuselage station 34.25.
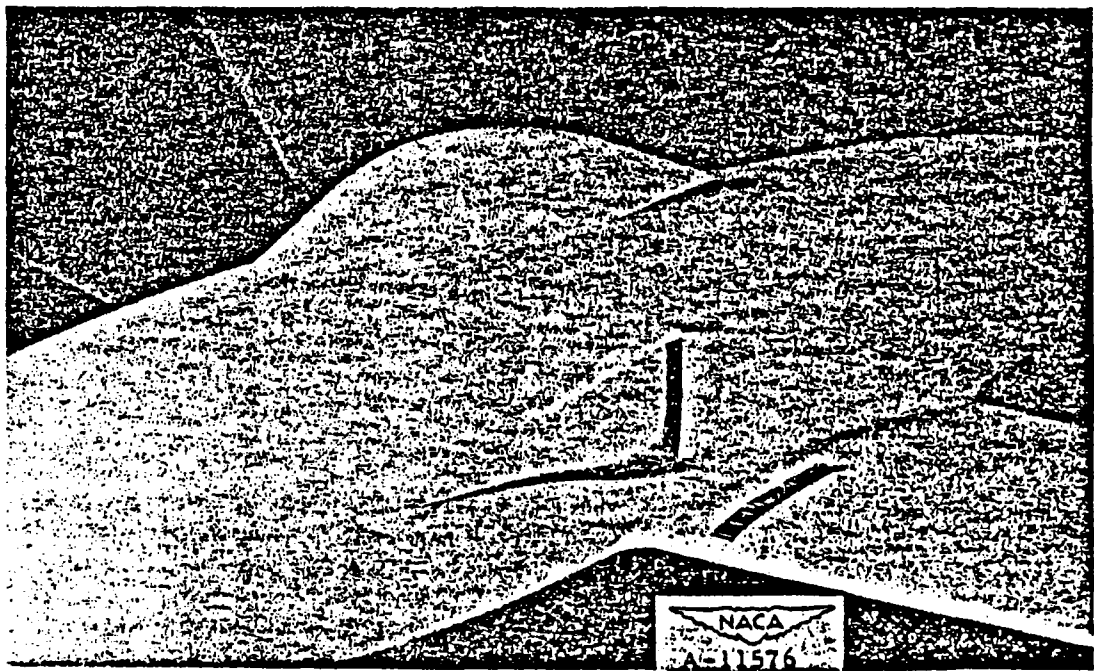
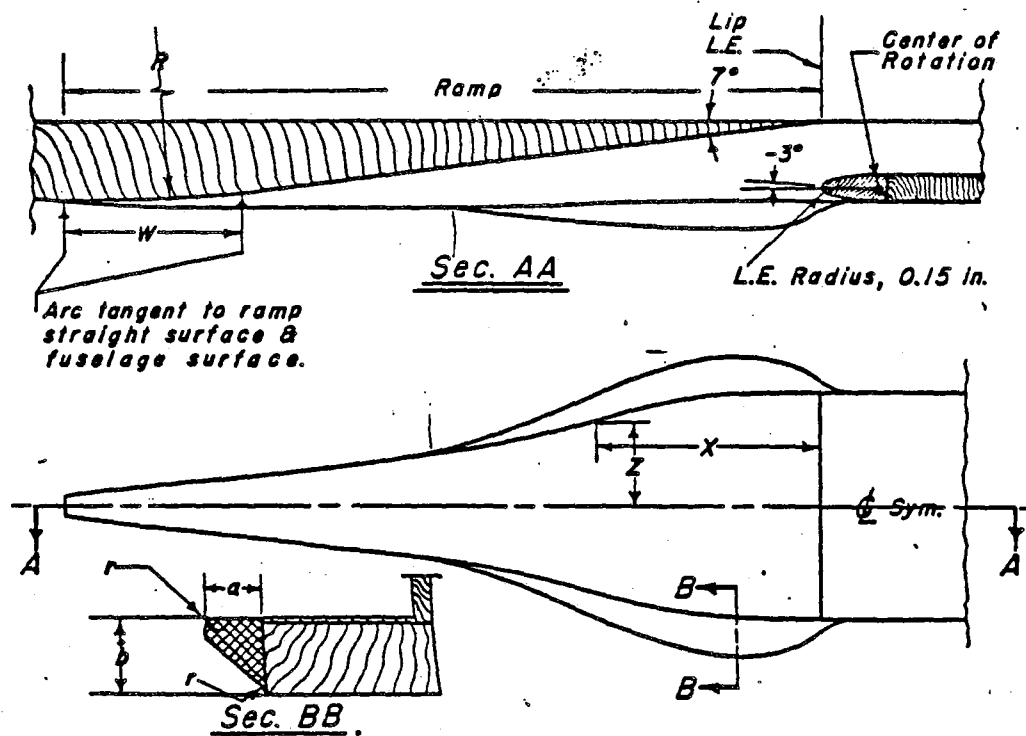(b) Inlet with deflectors at fuselage station 42.50.

Figure 1.- Submerged inlet model in 16-foot wind tunnel.

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(c) Inlet without deflectors at fuselage station 50.75.

Figure 1.— Concluded.

Sec. AA

Sec. BB

Deflector Coordinates

X-(in.)	a-(in.)	b-(in.)	r-(in.)
-0.63	0	0	0
-.32	.069	.099	.014
0	.224	.323	.047
.63	.446	.642	.094
1.27	.630	.907	.132
1.90	.721	1.038	.151
2.53	.745	1.073	.156
3.17	.741	1.067	.156
3.80	.723	1.041	.152
4.43	.694	.999	.146
5.06	.648	.933	.136
5.70	.588	.847	.123
6.33	.522	.752	.110
6.96	.452	.651	.095
7.60	.370	.533	.078
8.23	.284	.409	.060
8.86	.200	.288	.042
9.50	.122	.176	.026
10.13	.058	.084	.012
10.76	0	0	0

Lip Coordinates at -3° Lip Angle

Station	Outer Surface	Inner Surface
Inches From Nose	Inches From Fuselage Surface	Inches From Fuselage Surface
0	0.372	0.372
.2	.193	.568
.4	.131	.638
.6	.085	.691
.8	.055	.725
1.0	.032	.747
1.2	.015	.759
1.4	.004	.761
1.6	0	.762
1.8	0	.762

Ramp Wall Coordinates

X-(in.)	Z-(in.)
0	3.20
2.11	3.18
4.22	2.93
6.33	2.45
8.44	1.94
10.55	1.55
12.66	1.25
14.77	.99
16.88	.75
18.99	.51
21.10	.27

Ramp Coordinates

No.	Inlet Location	W-(in.)	R-(in.)
1	34.25	8.60	32.40
2	42.50	5.02	29.70
3	50.75	-3.75	28.85
4	59.00	3.75	30.70

Figure 3.— Dimensional data for inlets.