NATIONAL ADVISORY COMMITTEE
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TECHNICAL MEMORANDUM

No. 1186

COMPARISON OF DROP AND WIND-TUNNEL EXPERIMENTS ON

BOMB DRAG AT HIGH SUBSONIC SPEEDS

By B. Göthert

TRANSLATION

"Vergleich zwischen Abwurf- und Windkanalversuchen hinsichtlich des
Widerstandes von Bomben bei hohen Unterschallgeschwindigkeiten"

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COMPARISON OF DROP AND WIND-TUNNEL EXPERIMENTS ON

BOMB DRAG AT HIGH SUBSONIC SPEEDS[*][1]

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SUMMARY

The drag coefficients of bombs at high velocities (the highest velocity of fall was 97 percent of the speed of sound) are determined by drop tests and compared with measurements taken in the DVL high-speed closed wind tunnel and the open jet at AVA – Göttingen.

I. PURPOSE OF THE DROP EXPERIMENTS

1. Limits of Mensurability in Subsonic Wind Tunnels

The upper limit of the airspeed in subsonic wind tunnels at which it is no longer possible to carry over wind-tunnel measurements to free flight is that velocity at which the supersonic field originating in the flow past the model has spread out to the flow boundary. It is not known how closely this upper limit can be approached, that is, by what amount the airspeed must remain smaller than the limiting velocity. In the closed DVL wind tunnel, the variation of pressure on the wall and the velocity variation along the test length are measured along with all model measurements taken at high airspeeds so that it can be established each time beyond question when the speed of sound, and, therefore, the largest possible

airspeed are attained.   For purposes of evaluation, measurements in
the proximity of the upper velocity limit are discarded from time to
time.   No equivalent sign for the limiting velocity that can be
reached in wind tunnels with open test lengths is known.

Since there is no prospect for acceptable measurement in wind
tunnels in the immediate vicinity of the speed of sound, it is
necessary to extrapolate in this range from measurements made at
lower velocities.   However, this requires high reliability of
measurement, especially in the critical velocity region, that is, in
the vicinity of the limiting airspeed, since, aside from the magni-
tude of the individual measurements, the slope of the experimental
curve is important, too.

2. Correction Factor for the Flow Velocity in Subsonic Tunnels

Wind-tunnel experiments have shown that the air drag of the
models tested rises considerably if the airspeed is increased to
the neighborhood of the speed of sound.   This drag rise of the models,
according to known measurements in wind tunnels, has been larger,
in general, with closed test lengths than in open arrangements.   This
difference is understandable, too, as long as no velocity correction
factors are used as a result of the model obstructing the test length.
As a result of the obstruction of the test length, the air in a closed
tunnel must flow past the model with a higher velocity than in an
empty test length, which produces higher drag and with this, too,
larger drag coefficients are simulated at velocities that are too
low.   Conversely, the air in an open jet can be deflected more easily
than in the unbounded air space so that the effective flow velocity
becomes smaller and the drag and drag coefficients appear too small.

In the operation of the DVL high-speed wind tunnel a correction
factor method was discovered which permits the calculation of the
velocity correction factor for closed wind tunnels at high air speeds,
too, in a simple manner with the help of the dynamic pressure at the
wall measured simultaneously.[2]   Since this semiempirical correction
factor method can not be taken over for an open wind tunnel without
further development and, at present, no other method has been worked
out yet, a velocity correction factor has been omitted, up to now,
for the open arrangement.   This omission of the velocity correction
factor in open jet experiments, for which only a smaller correction
is known to be necessary than for a closed wind tunnel with the same
obstruction of the test length, is justified as long as the dimensions
of the model which must be tested near the speed of sound are chosen
small enough.   However, there is no accurate knowledge of what are to
be considered sufficiently small dimensions of the model.

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[2]Compare B. Göthert: "Windkanalkorrekturen bei hohen Unterschall-
geschwindigkeiten," LGL-Tagungsbericht 127, p. 113.

3. Checking the Wind-Tunnel Results By Drop Tests

Although valuable evidence concerning the magnitude of the influence of the stream boundary and the limiting airspeed is acquired by systematic wind-tunnel experiments[3], for example with large and with very small models of the same form in the same tunnel, there exists the pressing necessity of at least knowing the variation of the aerodynamic forces for several bodies in unlimited air space and thereby possessing a means of examining the reliability of the wind-tunnel method of measurement.

In the present report we will deal with an attempt to determine the drag variation of bombs at high subsonic speeds by drop tests of original bombs from an airplane. Bombs were selected as test bodies because there were sufficient numbers of them and the supports and release installations were available in quantity, also. According to how favorably these first tests run off, these tests will be extended to other bodies such as rectangular wings, sweptback wings, and so forth. Among other things, several falling bodies are to be selected with the correct weight and dropped from the right altitude to exceed the speed of sound in order to obtain evidence in the same range covered in wind-tunnel experiments.

II. PERFORMANCE OF THE DROP EXPERIMENTS

The drop tests were carried out by DVL with the support of the Rheinmetall-Borseg firm. The measurement of the trajectory was made by the measuring squad of the Luftwaffe research establishment at Peenemünde.

Several original bombs SC-50 and SC-250 with and without tail fin struts (fig. 1) were released and observed. The bombs were equipped with flares (flare dimensions 190 × 60 millimeters diameter) which were installed on the bomb axis behind the corresponding cut out of the bomb tail in the SC-50 bombs, somewhat off center in the angle between two fins in the SC-250 bombs.

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[3]B. Göthert: "Hochgeschwindigkeits-Untersuchungen an symmetrischen Profilen mit verschiedenen Dickenverhältnissen im DVL-Hochgeschwind-igkeits-Windkanal (2.7 m ∅) und Vergleich mit Messungen in Anderen Windkanälen," Forschungsbericht Nr. 1506, p. 17.
G. Richter: "Einfluss der Modellgrösse in Hochgeschwindigkeitskanälen (Messungen an vier verschieden grossen Flügeln von gleichem Profil im DVL-Hochgeschwindigkeits-Windkanal)," LGL-Tagungsbericht 127, p. 121.

The bombs were dropped from a height of approximately
11 kilometers and their trajectories recorded with two phototheodolites set up on the ground. From time to time after drops a
balloon rising from the ground was observed to determine wind
intensity and direction. With these measurements the true velocity
relative to the air was determined. To continue, during the ascent
and descent of the airplane from which the bombs were dropped, the
air temperature was measured at various heights with an electric
thermometer calibrated prior to the experiment to determine the air
density and the speed of sound. A median curve was drawn through the
experimental temperature points; the experimental points are scattered
within $2°$ or $3°$ C of the curve. The uncertainty, due to this, in
the determination of speed of sound, therefore, is in the order
of 1/2 percent.

The choice of the altitude of release of 11 kilometers is
based on arguments which are explained in detail in the following
section III.

III. INTERPRETATION OF EXPERIMENTAL RESULTS

The evaluation of the phototheodolite measurements gives, as
raw data, the position of the bomb at intervals of 1/4 or 1/2 second.
At every instant, the path which the bomb covered in 1/2 second was
calculated by means of the determination of position previously made.
This path for each 1/2 second shows the bomb velocity (measured in
meters per 1/2 sec) which was plotted against the time elapsed and
averaged by a suitable curve. The experimental values for acceptable
measurements of the velocity lie within 2 or 3 meters per 1/2 second of
the average curve.

By graphical differentiation of the velocity-time curve, the
acceleration $\partial V_B / \partial t$ acting on the bomb and from that the air drag
was ascertained from the following equation.

$$W = c_W \frac{\rho_L}{2} V_B^2 F = \frac{G}{g} \left(\frac{V_S}{V_B} g - \frac{\partial V_B}{\partial t} \right)$$

where

V_B path velocity of the bomb

V_S velocity component in the direction of gravity

g   gravity

G   bomb weight

F   bomb cross-sectional area $\left(\frac{\pi}{4} D^2\right)$

ρ_L air density

It is seen from this equation, that the determination of drag is more inaccurate, the larger the acceleration of the bomb $\partial V_B/\partial t$ relative to gravity. For example, if $\frac{\partial V_B}{\partial t} = 9.0$ meters per second^2 and $(V_S/V_B)g = 9.5$ meters per seconds^2, then the value governing the drag is the difference $9.5 - 9.0 = 0.5$ meters per second^2. Small errors in the determination of the acceleration $\partial V_B/\partial t$ appear many times larger in the determination of drag in this case. The range of high accuracy of measurement possibly, therefore, depends on the velocities which equal the terminal velocity of the bomb or fall free of acceleration. To extend this favorable range over the largest possible portion of the drop curve, the bombs were released at the altitude of 11 kilometers previously mentioned, so that the bombs reached their highest velocity at an altitude of 4 or 5 kilometers and then were decelerated, instead of accelerated, on falling through the lower altitudes as a result of the increasing air density.

Corresponding to the different orders of accuracy of measurement, the following three ranges of measurement are differentiated in the description of the results and are made recognizable on the graphs by individual point designations:

1. Range of small accuracy of measurement.— The acceleration of the bomb is even larger than the arbitrarily fixed limiting value of 5.0 meters per second^2, that it is at the highest elevation of the drop. Not more than a few points were evaluated from time to time in this range, when a good straight variation of the measurements permitted this.

2. Range of increasing Mach number[4].— The bomb acceleration here is already smaller than 5.0 meters per second^2 and falls off to $\frac{\partial V_B}{\partial t} = 0$, possibly. This range terminates where the bomb attains its closest approach to the speed of sound in the vicinity of the limiting velocity.

3. Range of decreasing Mach number.— In this range the bomb acceleration is almost always negative, that is, the bombs are retarded

[4]M = The ratio of path velocity/velocity of sound

as a result of the drag so that the highest accuracy of measurement
is obtained in this range. This range ends on impact with the ground.

Good control of the results is obtained, therefore, due to the
fact that each drop is made from a high enough altitude so that the
range of high Mach numbers is traversed first with increasing and
then with decreasing Mach number. Thereby, two different, mutually
independent parts of a curve are obtained which must fit together.

In the manner described, for each drop only that portion of the
drag curve is obtained which is well placed, that is, located in
the vicinity of the limiting Mach number. If the drag curve for a
larger Mach number range should be determined, the limiting Mach
number would have to be shifted accordingly. This could be accom-
plished by dropping more models of different weights but the same
external form. Corresponding experiments on bombs, which are partly
unloaded, partly more or less heavily loaded with weighty materials
are in preparation.

The accuracy of evaluation can be increased further, if, instead
of the graphical method employed here, that is graphic differen-
tiation of the average curve drawn through the experimental values,
an average is determined by mathematical averaging calculations and
then differentiated. However, it is not to be expected that a
considerable improvement will be obtained in the range of high Mach
numbers. The advantage of these refined methods of evaluation is
seen principally in the range which is termed "The range of small
accuracy of measurement" in the foregoing.

IV. RESULT OF DROP TESTS AND COMPARISON WITH WIND-

TUNNEL MEASUREMENTS

The drag coefficients c_w obtained by the drop tests are
shown as functions of the Mach number in figures 2 and 3. The drop
tests made are shown as follows:

2 SC–50 bombs. . . . . In figure 2

1 SC–250 bomb without tail fin struts
    for comparison . . . . .In figures 2 and 3

1 SC–250 bomb with tail fin struts . . . . In figure 3

The SC–50 bomb used in carrying out the experiment has no tail
fin struts. The original SC–250 bomb had tail fin struts as

standard equipment in order to stiffen the tail surfaces. The tail
fin struts have a diameter of 16 millimeters for a bomb diameter of
368 millimeters.

The closest approach to the velocity of sound was made by the
SC-250 bomb without tail fin struts with a velocity 97 percent of the
speed of sound. All of the drag curves obtained from the drop tests
show a very steep increase of drag on approaching the speed of
sound. This agrees very well with the experimental curves from the
closed DVL high-speed wind tunnel which are drawn in for comparison.
Admittedly, the wind-tunnel and drop-test curves are displaced by a
definite amount of drag from one another; however, the increase of
drag on approaching the speed of sound shows very good agreement;
the increase of drag, incidentally, was observed especially clearly
in this experiment.

The measurements from the DVL high-speed wind tunnel, cited
for comparison, have been carried out for a model of the SC-250 bomb
which had a diameter of 123 millimeters. Two fuse openings and a
suspension lug for horizontal mounting of the bomb were added to the
model. The variation of drag for the SC-50 bomb has not been measured
in the wind tunnel as yet. The measurements are now being prepared
for.[5] However, as a result of the great similarity between the SC-50
and SC-250 bombs (compare fig. 1), it is to be expected that the drag
curves for the two bombs would differ from one another by only a small
amount.

In figure 4 the variation of drag of the bombs investigated in
the closed DVL high-speed wind tunnel has been compared with that of
the open jet, AVA — Göttingen.[6] The experimental curves have been
extrapolated somewhat beyond the measured range to larger Mach
numbers in conformity with the slope at the end of the curve. The
experimental curves for the same bombs could not always be used for
purposes of comparison of bomb drag in these illustrations. However,
since the bomb shapes are extraordinarily alike (compare fig. 1), for
example, the SC-250 and SC-500 bombs without tail fin struts have

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[5]The report on the wind-tunnel measurements for all bombs will be
published as soon as the measurements on the model of the SC-50 bomb
have been completed.

[6]A. Roth: "Untersuchungen von Bomben im kompressiblen
Unterschallgebiet", AVA-Bericht 41/8/8, September 1941.

On the basis of more recent calibrations of the wind tunnel at
Göttingen, the experimental results presented in the AVA report had
been corrected before they were cited for the comparison in figure 4.
This conversion is in the direction to reduce the differences between
the DVL and the AVA measurements.

practically the same shape. The curves, therefore, can be compared
with one another and be used satisfactorily for the comparison in
mind.

The reproduction of the experimental curves obtained in the
drop tests has not been made in figure 4 because the drop-test
measurements agree well with the measurements of the closed DVL high-
speed wind tunnel. (Compare figs. 2 and 3.)

The comparison of the curves shows that the measurements in the
open jet do not exhibit the sharp drag increase like those of the
closed DVL wind tunnel and, therefore, are also unlike the drop
tests. The cause of the deviation may be looked for in the fact that
no velocity correction factors were applied in the open-jet measure-
ments to take care of the effects of the obstruction of the test
length by the model, or that the Reynolds number in the open-jet
measurements were extraordinarily low as a result of the limited wind-
tunnel dimensions (the bomb model diameter was 25 millimeters in the
AVA measurements).

V. SUMMARY

1. Drop tests were made by dropping original bombs from a high
altitude and by taking measurements along the drop curve. The largest
velocity of fall in these experiments amounted to 97 percent of the
speed of sound.

2. The variation of the drag coefficients for bombs obtained
from the drop tests agreed closely with the measurements in the
closed high-speed wind tunnel of DVL. In particular, according to
drop and wind-tunnel measurements there is an extraordinarily
steep drag increase when the velocity of fall approaches the velocity
of sound.

3. A comparison of drop measurements with drag measurements
of the same bombs in the open jet of AVA - Göttingen shows that the
increase of drag is undervalued on approaching the speed of sound
in the open-jet measurements.

Translated by Dave Feingold
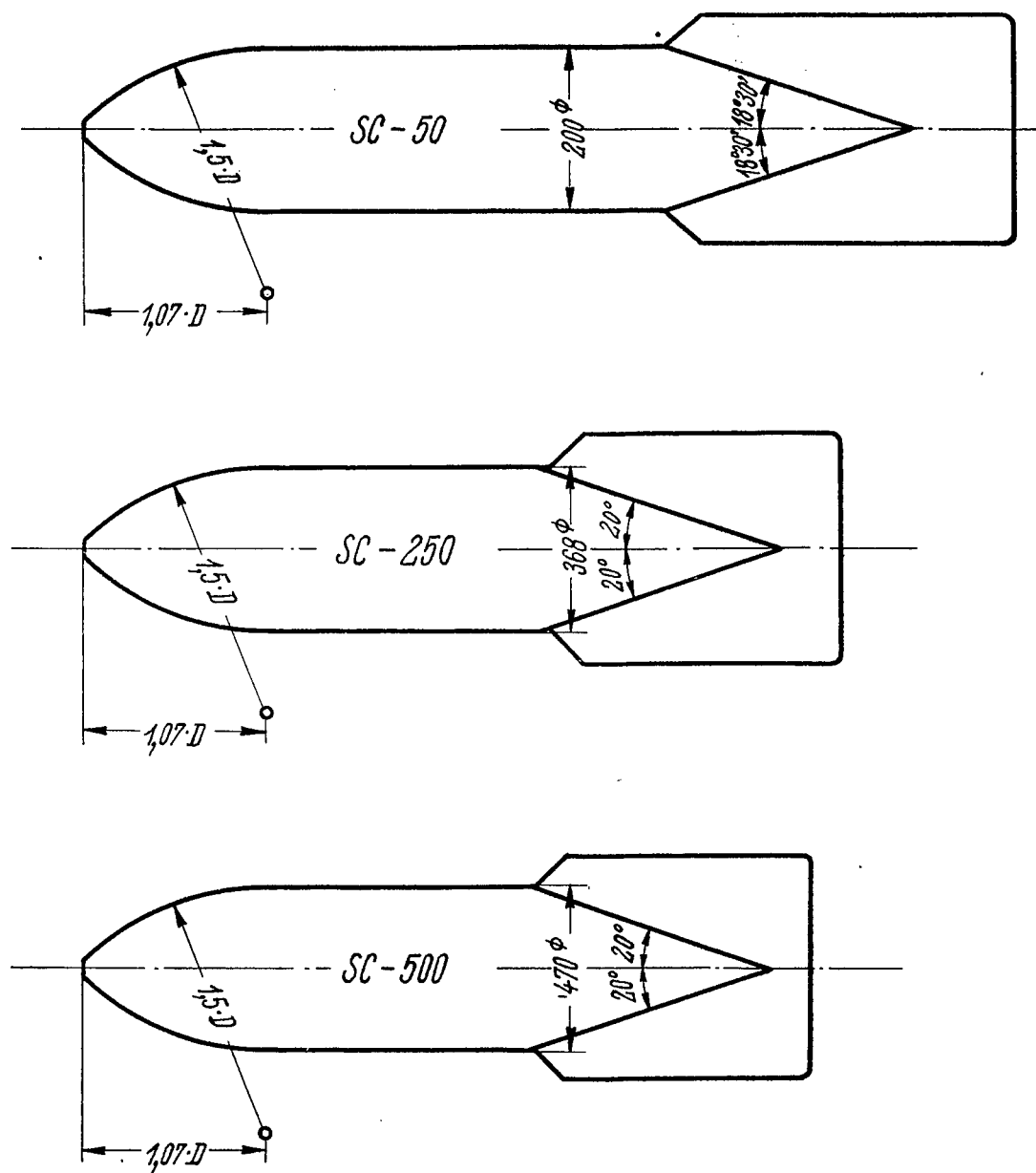National Advisory Committee
for Aeronautics

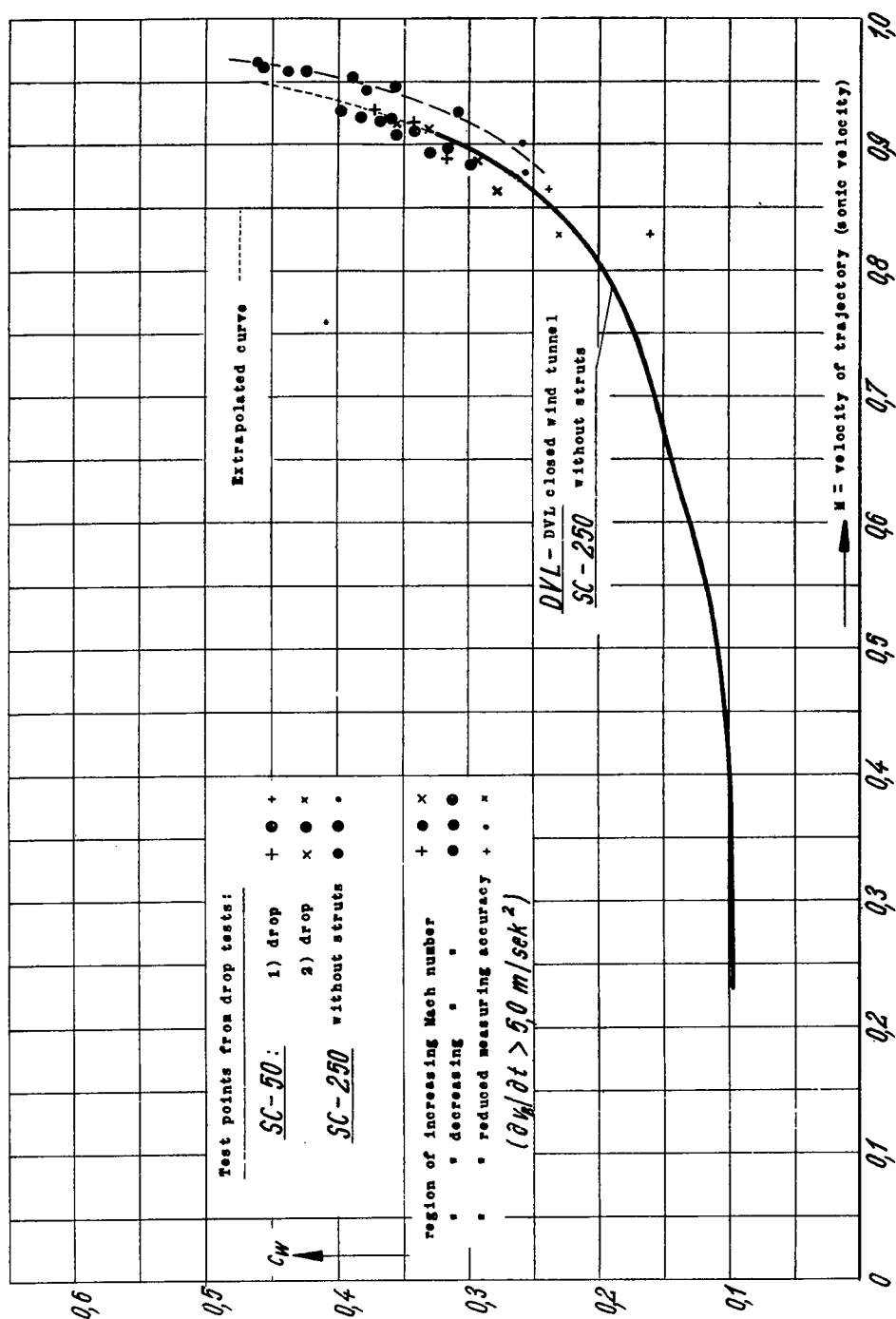Figure 1.- Comparison of the shapes of bombs SC-50, SC-250 and SC-500.

Figure 2.- Comparison of the drag coefficients obtained from wind tunnel and release experiments for SC-bombs without tail fin struts for various Mach numbers.

Drag coefficient $c_W = \dfrac{W}{\rho/2\, V^2 F}$

Bomb frontal area $F = \dfrac{\pi}{4} D^2$

Mach number $M = \dfrac{\text{Trajectory speed}}{\text{Sonic speed}}$
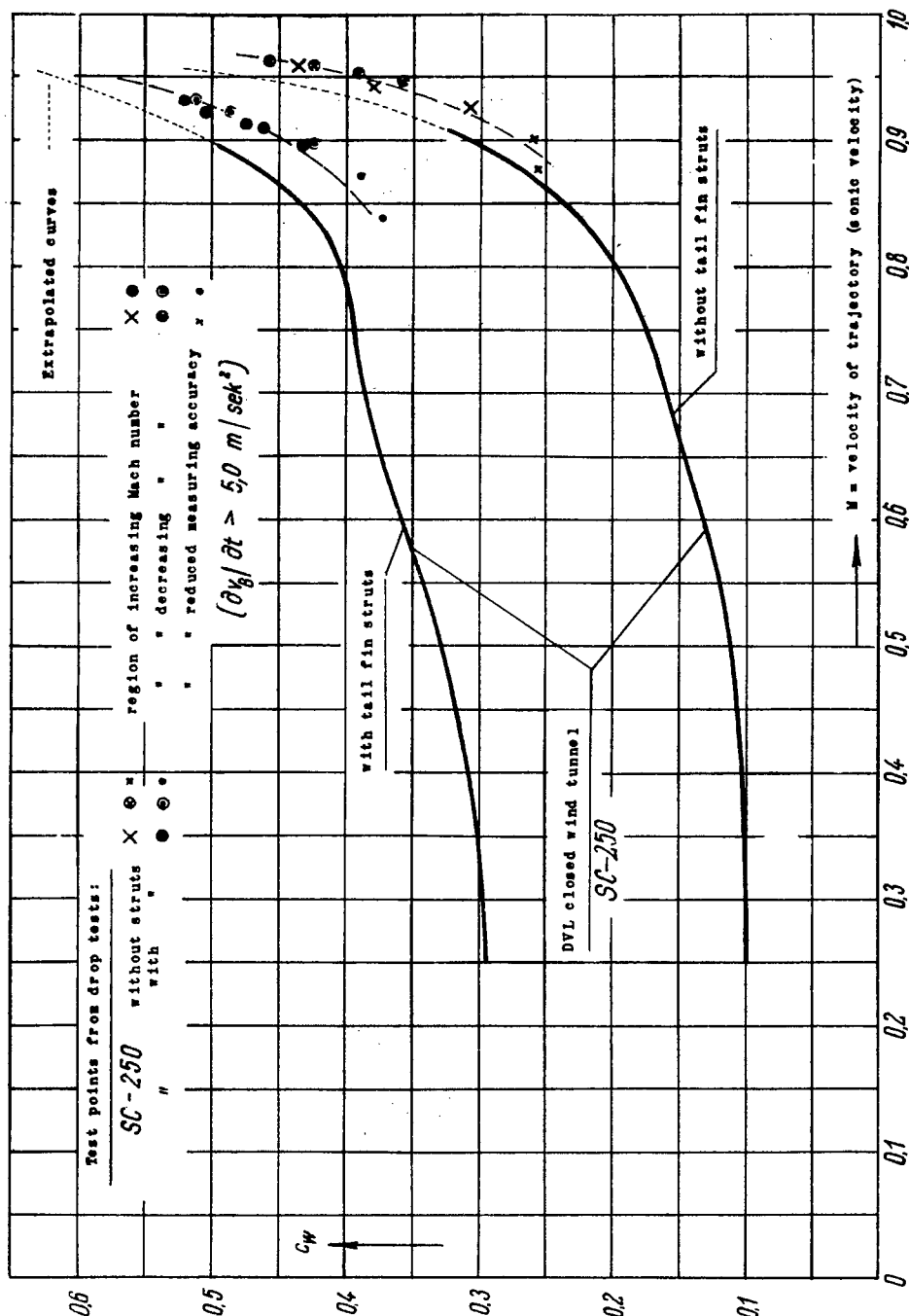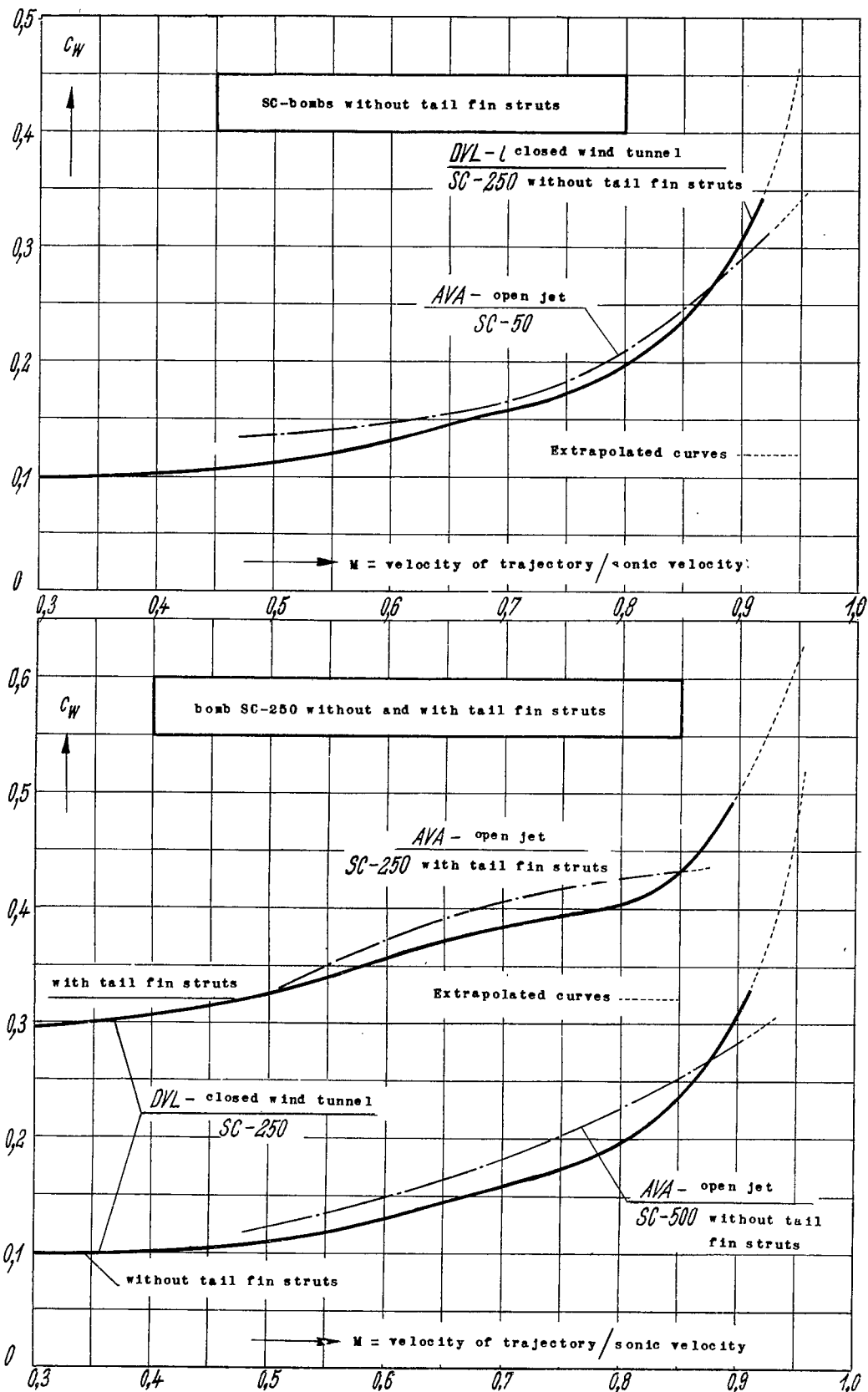
Figure 3.- Comparison of the drag coefficients obtained from wind tunnel and release experiments for the bomb SC-250 with and without tail fin struts for various Mach numbers.

Drag coefficient $\qquad c_w = \dfrac{W}{\rho/2\,V^2\,F}$

Bomb frontal area $\qquad F = \dfrac{\pi}{4}\,D^2$

Mach number $\qquad M = \dfrac{\text{Trajectory speed}}{\text{Sonic speed}}$

Figure 4.- Comparison of bomb drag coefficients from measurements in the closed DVL wind tunnel and the open jet, AVA-Gottingen.