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THE FREE FLIGHT RANGE: A TOOL FOR RESEARCH IN THE PHYSICS OF HIGH SPEED FLIGHT

A. C. Charters

General Motors Corporation, Goleta, California

INTRODUCTION

Increase in flight speeds to the velocities of satellites and spacecraft places a new emphasis on the aerophysics rather than on the aerodynamics of flight. The increase in energy of the air flow at these velocities changes the air from a neutral medium to a reacting gas whose composition and physical properties vary from point to point in the flow. Chemical reactions are involved which may not be in thermal equilibrium. Electrical phenomena are also involved because temperatures are high enough to ionize portions of the flow.

This shift in emphasis from aerodynamics to physics has required the development of new experimental techniques. The high energy processes of high speed flight are not ordinarily produced in facilities for subsonic and supersonic testing, and it has been necessary to modify the standard methods of testing and to develop new experimental methods for research in this area. In fact, a single experimental tool, such as the hypersonic wind tunnel, is only suitable for carrying out a limited range of experiments, and a variety of facilities have been developed with each directed toward a particular facet of the physics of high speed flight.

One standard test method, which has been successfully modified for research in these new areas, is the free flight range. The free flight range was originally developed for measurements of the drag and stability of artillery projectiles. In due course, its scope of testing was broadened to include basic configurations, rockets, missiles, and even some aircraft. But the velocities of the tests ran from a few hundred

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1 Head, Flight Physics Section, Defense Systems Division.
to a few thousand fps, covering the region of subsonic and supersonic Mach numbers up to about $M_4$, and the test capabilities of the range were limited accordingly.

The method of testing in the free flight range will be reviewed briefly at this point, because the capability for high speed research proceeds logically from the test technique. In essence, an experiment in the range is a flight test carried out in the laboratory. A sketch of the Physics Range in the Flight Physics Laboratory of the General Motors Corporation's Defense Systems Division in Santa Barbara, Calif., is shown in Fig. 1. The experiment starts with a model of the missile or other object of study. The model is fired from a gun, or suitable launching device, into a long flight-test chamber filled with gas at the pressure and with the composition specified for the test. Records of the model as it flies through the chamber are taken by instruments placed along its trajectory. The aerodynamic quantities of interest are determined from these records.

The instrumentation used depends, of course, on the purpose of the test. For example, if one wishes to measure drag, spark photographs of the model are taken at various places along its trajectory, and the time of each photograph is recorded by a precise chronograph. These records give measurements of time and distance along the trajectory. The velocity, deceleration and drag of the model are determined from them.

Two steps must be taken to modify the range for research in high speed flight. First, the launching velocity must be increased to full-scale flight values. This means that the launcher must have a maximum velocity of 36,000 fps (and preferably higher) if space craft entry is to be studied. Second, new instruments must be devised to measure quantities such as radiation and heat transfer associated with the aerophysics of the flight. As will be explained, this means not only the development of new instruments for the flight test chamber, but also the instrumentation of the model itself for making measurements on the model during its flight and transmitting the in-flight information to receivers stationary in the chamber.

A variety of launchers and a whole new complex of instruments have been invented in response to the need. These have been described in various publications, and it is hardly worth while repeating a listing of them here. Instead, the purpose of this paper is to select one example of a high velocity launcher and one of flight instrumentation and to describe each in sufficient detail for a full understanding of their
design and operation. The choice of example in each case has
been made on the basis of a device which is important, in the
opinion of the author, and which has not yet been covered in
other articles on free flight ranges.

HIGH VELOCITY LAUNCHERS

A test in the free flight range starts with launching the
model. The launcher must be able to accelerate a model of any
specified shape to the velocity desired without damage. Also,
the size of the launcher must be small enough to fit within
the confines of a laboratory.

Consider first the requirement that the model must be accel-
erated to the desired velocity without damage. Experience has
shown that each component part of the model can withstand a
certain stress during the launching. If the stress exceeds
this limit, the component will fail. It can be shown that the
stress on each component is proportional to the stress exerted
on the base of the complete model, or to the base pressure, if
a gas is used to accelerate the model. Consequently, the re-
quirement of launching without damage places a limit on the
maximum value of the base pressure. This value will vary with
the design of the model, but for any particular model ("model"
here includes the sabot) there will be a maximum base pressure
which must not be exceeded.

Consider next the requirement that the size of the launcher
be small. It is evident that this requirement will be met if
the base pressure is held at the maximum allowable value
throughout the launching. On this basis the "ideal" launcher
brings the base pressure to this value rapidly and then holds
the base pressure constant throughout the run.

If the base pressure is constant, the square of the velocity
is proportional to the reciprocal of the density of the projec-
tile (the model and its sabot) and directly proportional to
the base pressure and to the length of the launching run in
calibers, according to the following equation

\[ V^2 = \left( \frac{2Ad}{m} \right)_{\text{proj}} p \left( \frac{L}{d} \right)_{\text{gun}} \]

where

\[ V = \text{velocity} \]

\[ A = \text{area of bore (or projectile)} \]
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d = diameter of bore (or projectile)

m = mass of projectile

$p_B$ = pressure (or stress) at base of projectile

L = length of launching run

This equation for the "ideal" launcher is graphed in Figs. 2a, 2b and 2c. The velocity in thousands of feet per second is plotted as ordinate, the length of launching run in diameters as abscissa, and the base pressure in thousands of pounds per square inch as parameter. The graphs differ from one another in the density of the projectile. The cases shown in Fig. 2 are for a spherical projectile with a density of 1 gm/cc in Fig. 2a, 3 gm/cc in Fig. 2b, and 9 gm/cc in Fig. 2c. They cover the range of practical values.

The curve for each base pressure gives the highest velocity obtainable for those projectiles whose strength limits the base pressure to the value defining the curve. Experience has shown that "tough" models can withstand a base pressure of 60 kpsi, and even higher in some cases. On the other hand, experience has also shown that "fragile" models (most models used in aerodynamic experiments belong to this category) can withstand a base pressure of only 20 kpsi, or even less in some cases. Consequently, if we wish to launch aerodynamic models at high velocity, the density of the model must be low and the launching run long. For example, consider a model with the lowest practical density of 1 gm/cc (Fig. 2a) and a base pressure limit of 20 kpsi. If we wish to fire at 40 k fps for studies of atmospheric entry at hyperbolic velocity, maximum base pressure must be maintained for a run of 360 diameters—a long run compared to the 50 caliber length of most military guns (caliber = diameter). These curves point out the second reason for saboting models for high velocity tests—the first reason being to accommodate the shape (external contour) required for aerodynamic tests; namely, to reduce the density of model and sabot. Light plastics, such as nylon and polyethylene, are satisfactory sabot materials, and, if the sabot is large and the model small, the combined density approaches the value of 1 gm/cc. To illustrate by an example to the contrary, suppose one tries to fire a copper sphere from 360 caliber gun and is able to hold the bore pressure at 60 kpsi—a high value. This will reach a velocity of only 26 k fps.

To sustain a moderate driving pressure for a long run is the heart of the launcher problem. From this standpoint, a rocket would appear to be an ideal launching device. Unfortunately,
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a rocket cannot develop high accelerating forces, and such long launching runs are required that the use of a rocket is precluded for launching in the free flight range.

In the author's opinion, the best solution to the launching problem that has been devised so far is the accelerated-reservoir light-gas gun. This launcher is a modification of a piston-compression light-gas gun. It was developed by John S. Curtis of the Ames Research Center, and several light-gas guns of this type are now in use there.

The design of the gun is illustrated by the sketch of the gun's cross-section shown in Fig. 3. The gun consists of a powder chamber, a pump tube, a high pressure coupling, and a launch tube. The high pressure coupling is made from a heavy billet of tough steel. The bore tapers gradually from pump to launch tube. The breech of the launch tube is closed by break valve of special design so that it opens rapidly when the pressure in the pump tube reaches a specified value. Hydrogen is the "light-gas" used. It is compressed by a piston driven down the launch tube with a charge of gun powder. The front part of the piston is made of a plastic material, polyethylene being used by Curtis, so that the front of the piston deforms and follows the contour of the tapered bore as it enters the coupling section.

The gun is operated in such a manner that the front face of the piston approaches the tapered bore of the coupling as the pressure of the hydrogen in the pump reaches the value specified for the base pressure. The brake valve opens, and the model starts its launching run. The main mass of the piston continues to move forward with its velocity maintained by its inertia, but the velocity of the front face increases as it moves into the tapered bore. The front face of the piston accelerates because the material of the piston is relatively incompressible and continuity requires that the velocity of the piston's material must increase at every point in the tapered bore for the product of velocity with cross-section area to remain constant (similar to the flow of an incompressible fluid in a convergent channel). This rapid thrust forward of the piston's front face produces a correspondingly rapid compression of the hydrogen in the coupling section as the launching cycle continues. This rise of pressure in the coupling, and hence at the breech of the launch tube, is transmitted by pressure waves down the launch tube from its breech to the base of the model. At the same time, the acceleration of the hydrogen flowing into the launch tube demands a pressure gradient with the pressure falling from breech to model. If the gun is operated just right, the rise in breech pressure will

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just counteract the fall in pressure from breech to model and the base pressure will hold constant for the run. In fact, the gun is designed and operated to accomplish this purpose.

A complete solution of the operation of the accelerated-reservoir light-gas gun has been carried out by Curtis. The analysis is quite complicated, and details will not be given here. A full account is given in his report (to be published shortly).

The most critical feature of the gun's operation is the variation in the breech pressure required to hold the base pressure constant. This particular phase of the operation can be solved as a discrete problem by itself if one assumes that the pressure at the base of the projectile remains constant and that the flow of hydrogen into the launch tube is entropic. The results of this analysis give the pressure at the breech of the launch tube which the pump must deliver in order to maintain a constant base pressure.

The solution of the launching cycle is carried out by the method of characteristics. The characteristic diagram for a typical case is shown in Fig. 4. Distance in feet is plotted as ordinate and time in microseconds as abcissa. The initial conditions are listed in the legend. Since the base pressure, the diameter of the bore and the weight of the model are given, the trajectory of the model is determined and is the basis for the construction of the characteristic net. The trajectory is the heavy line forming the envelope at the left and top of the characteristic net. The analysis for this case has been carried out for a total time of 400 microseconds, corresponding to a launching run of 506 calibers and a muzzle velocity of 48,500 fps.

At each point in the net, the P waves proceed to the right of the point and the Q waves to the left. Recalling that a horizontal slope of a Q wave means that the velocity of the flow equals the local value of the speed of sound, one sees that the flow of hydrogen becomes supersonic soon after the start. The change in breech pressure is carried through the flow to the projectile by the P waves. These traverse the flow at the speed of sound relative to the flow, and a significant time is required for traversing the distance from the

2The author is indebted to David Benepe and Kenneth Vincent for carrying out this analysis. Mr. Benepe is a research scientist with the Santa Barbara Laboratories of the General Motors Corporation's Defense Systems Division.

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breech to the projectile, which time becomes longer and longer as the distance increases with the run of the model. In this case, the last P wave to reach the model leaves the breech at a time of 200 microsec. about one half the total run time. The value $1/2$ is representative, and as a rough rule of thumb, only the first part of the pressure pulse in the pump tube which lasts for about one half the total launch time is effective in accelerating the model.

The variation in breech pressure determined by this characteristic solution is shown in Fig. 5. The pressure in thousands of pounds per square inch is plotted as ordinate, and the time in microseconds as abcissa. The breech pressure rises smoothly but at an ever increasing rate from the 20,000 psi at the start of the launching run to 300,000 psi at 200 microsec—the last effective time. This variation in breech pressure is required to keep the base pressure constant for the particular conditions of this firing.

In operating the gun the velocity of the pump piston and the convergence of the tapered bore in the coupling are adjusted to produce a variation in breech pressure which approximates the ideal variation of the analysis. Of course, the real variation in pressure will never be exactly that required by theory, but Curtis' calculations show that even a simple conical taper gives a good first approximation to the ideal.

It is significant that the breech pressure rises to a maximum of 300,000 psi in order to maintain the base pressure constant at 20,000 psi. This is the price required to accelerate the hydrogen as well as the model. Of course, the purpose of using hydrogen, the gas with the lowest molecular weight, is to keep this price as low as possible. For the same reason, the total quantity of hydrogen loaded in the gun is kept to a minimum, just sufficient for the launching.

The experience with accelerated reservoir guns at the Ames Research Center has been very satisfactory. This gun has proven to be a reliable, accurate launching device for firing models in the range of 20,000 to 30,000 fps. The velocity of a shot can be predicted to about 1,000 fps, and the erosion of the gun barrel is surprisingly small, even at 30,000 fps, thereby greatly increasing the gun's utility. The highest velocity to date is 31,500 fps with a 0.23-in. diameter model weighing 0.1 gram.

The velocity of 31,500 fps, high as it is, should not be regarded as a limit. Further increases in speed should be possible by improving the design of the coupling section,
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increasing the compression ratio of the hydrogen, and heating
the initial charge of hydrogen prior to firing. It is reason-
able to suppose that the maximum velocity finally achieved with
this gun will exceed the present record of 31,500 fps, even for
fragile aerodynamic models and almost surely for simpler pro-
jectiles which can be made strong and tough to withstand higher
base pressures.

HEAT TRANSFER MEASUREMENTS IN THE FREE FLIGHT RANGE

Experiments in the free flight range are made on a model in
free flight--the basis of the experimental technique. However,
until very recently the model itself has been a passive ele-
ment in experiments, and all measurements have been made with
instruments external to the model, that is with stationary in-
struments placed along the flight test chamber. Some physical
quantities can be determined directly from these external
measurements. For example, the wave patterns in the flow, the
boundary layer, and the wake appear straight off in the spark
photographs. Other physical quantities must be determined in-
directly. For example, the drag is determined from records of
time and distance along the mode's trajectory (together with
measurements of certain other physical quantities).

The use of external instrumentation has been dictated by
necessity rather than choice. In measuring the drag, the ex-
perimenter would prefer to record the drag force directly
through an accelerometer in the model rather than determining
the force from a double differentiation of the time-distance
measurements. The need for instrumented models has long been
recognized, and the development of model telementry has been
an objective of range experimenters for many years. Unfor-
tunately, the launching forces are large, and the size of the
model is small. These are difficult obstacles to overcome,
and, in fact, a completely satisfactory solution to the prob-
lem of instrumenting the model still lies in the future, de-
spite recent advances in technology.

The demands on the range instrumentation have increased with
the advent of high velocity research, because the scope of
measurements to be made in the range has broadened. There are
new quantities to be measured, quantities associated with the
aerophysics in addition to the aerodynamics of the flight.
Some of these new quantities can readily be measured by new
types of external instruments. For example, the luminosity in
the flow surrounding the model can be measured by photo-
electric apparatus focused on the trajectory. But other aero-
physics quantities cannot be measured by external instruments.
Perhaps a more accurate statement would be that their
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measurement has defied the ingenuity of the experimenter so far, but, in any case, as a practical matter, the problem of developing active instrumentation in the model can no longer be avoided if the free flight range is to develop its full potential as a tool for research in the physics of high speed flight.

Measurement of the stagnation point heating is the example chosen for this paper. Heating at the stagnation point plays a vital role in the performance of all bodies in high speed flight, as is well known, and any facility doing research in this field must be capable of measuring it. Some early attempts were made to record stagnation point heating entirely by external observations but were abandoned after initial failures. The issue seemed clear--the model's role must be changed from a passive to an active one, if measurements of this quantity were to succeed.

In 1956 (approximately), H. Julian Allen of the Ames Research Center conceived a new technique for instrumenting the model which provided the key for the solution to this problem. His technique was developed by the staff of the HBR Branch at Ames and applied in due course to measurements of the stagnation point heating of spheres in air and carbon dioxide at velocities up to 20,000 fps. This development will be described briefly in this section. But it should be remarked parenthetically that the underlying purpose of this section is to illustrate this new trend in the instrumentation of free flight ranges.

The basic scheme of measurement is as follows: The heat at the stagnation point warms a calorimeter, and its rise in temperature activates a thermocouple. The thermocouple's current generates an electric field, which is recorded by receiving stations along the trajectory in the flight test chamber. In the strictest sense, therefore, the model has been instrumented with a telemetering unit, although, as will be seen, the unit is a very simple one.

A cross section through the instrumented model is shown in Fig. 6. The hemisphere is the head of the model, the cone its base, the direction of flight to the left. A thin, copper cap forms the calorimeter. This cap, a constantan rod, and a coil coaxial with the model complete the thermocouple circuit. The cold junction, buried deep in the body, stays cold by thermal inertia. The hot junction, however, rises in temperature with the copper cap and produces the electrical potential for the thermocouple current. The thermocouple current flowing through the coil generates a dipolar magnetic field, as though the
model were magnetized along its axis. The strength of this magnetic field is proportional to the temperature of the copper cap, and, hence, to the total heat transferred to the cap during the model's flight through the flight-test chamber up to the observing station.

The magnetic field of the model is recorded by firing the model through a stationary, pick-up coil. The experimental setup is shown in Fig. 7. The output of the stationary receiving coil is recorded by a cathode-ray oscilloscope, a typical record being shown at upper right. The voltage in the pickup coil is proportional to the rate of change of magnetic flux through the coil (which accounts for the characteristic shape shown in the illustration), and the peak voltage is proportional to the product of the velocity of the model and the temperature of the cap. Consequently, if the velocity is measured, the temperature of the cap at the instant that the model passes through the coil may be determined from this record. In practice a series of coils are placed at various distances along the length of the flight test chamber, and their combined records determine the total heat transfer as a function of distance along the flight path. Differentiation of these total heat transfer measurements then gives the heat transfer rate, the quantity desired.

Measurements of the heat transfer rate in air were made in the Hypervelocity Ballistic Range at the Ames Research Center at velocities up to 18,000 fps, and the results are shown in Fig. 8 (Fig. 5 of NASA TN D-777). The heat transfer rate in Btu/ft²-sec is plotted as ordinate; the velocity in thousands of feet per second as abscissa. The HBR data (circles) are compared with two theories and with shock tube results (squares). It should be noted that the accuracy of range and shock tube measurements are comparable. Furthermore, the range and shock tube experiments both agree with the theory indicating the reliability of the experimental data, since the theory is believed to be well established for this case.

Measurements of heat transfer in carbon dioxide were also made in the HBR, and the results are shown in Fig. 9. The range data are compared with shock tube results and with rough theoretical estimates. Here, again, the agreement between range, shock-tube, and theory is satisfactory.

In commenting on this development, one should note that the highest velocity rounds were fired with an acceleration of greater than $10^5$ g. Also, the diameter of the models was 0.22 in. Consequently, it is clear that the Ames development is a good start toward overcoming the barriers of launching.
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acceleration and size in the development of instrumented models for the free flight range.

TEST CAPABILITY OF FREE FLIGHT RANGE

A spacecraft encounters difficulty on its return to Earth because it enters the atmosphere at high velocity. The situation is further complicated by the extremes of density encountered during the entry. In a word, velocity and density are the controlling variables. Size is important and must be taken into account in analyzing the aerophysics of entry. But size is not a critical variable in the sense that velocity and density are.

If one looks at laboratory experiments in the same light, the test capability of the free flight range is measured by the velocities of its guns and the capacity of its vacuum pumps. The point is that significant and critical experiments can be made if the velocity and density are right even though the size of the model is small compared to its full-scale prototype. As these experiments improve our knowledge of the physics, it will be possible to derive scaling laws for extrapolating the results obtained with small models to the flight performance of the full-scale vehicle.

The velocity-density region covered in the range is compared in Fig. 10 with the values of these quantities along the entry trajectories of two vehicles being developed by the NASA for manned space flight: Mercury, a near-Earth satellite, and Apollo, a craft for a voyage to the moon. The altitude is plotted as ordinate, and the velocity as abcissa. The solid lines mark out the velocities and chamber pressures presently available in the Physics Range at the Santa Barbara Laboratory of the General Motors Corporation is Defense Systems Division; the dotted lines mark the boundaries which are expected to be reached in the future. Figure 10 shows that all of the Mercury entry and much of the Apollo entry are within the current capabilities of the Physics Range. If launcher developments go as planned, all of the Apollo entry will be within the capability of the Physics Range in the future.

Another comparison of range capability and flight performance of the same vehicles is made in Fig. 11 on the basis of Reynolds and Mach numbers. The Reynolds number is plotted as ordinate, and the Mach number as abcissa. Again, the solid and dotted curves mark out the current and future test regions of the Physics Range. It should be noted that the Reynolds number boundary increases with Mach number—an important advantage for the free flight range method. Again, all of the
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Mercury entry is covered by the current capability of the range, but the increase in velocity planned for the future is needed to bring the largest part of the Apollo entry into the range's test region. This is further evidence of the importance of the launcher to the free flight range.

CONCLUDING REMARKS

In conclusion, it is well to mention another method of extending the free flight range's capability for high velocity research. The flight test chamber need not be a tank filled with still gas. Rather, it can be the working section of a wind tunnel. In this way, advantage can be taken of the properties of the flow in the wind tunnel in order to produce special test conditions which would be difficult to realize in a simple, pressure-controlled chamber. The method of testing is the same as in the standard free flight range, with the difference that the model is fired into the wind tunnel's working section against the direction of the air flow. Records are taken of the model's flight as it passes through the working section, just as they are in the flight test chamber.

The range of variation in density can be made dynamic to simulate a complete entry of a vehicle through the Earth's atmosphere. The flight test chamber in this experiment is replaced by the working section of a hypersonic wind tunnel designed to give an exponential variation of density similar to that of the Earth's atmosphere. The range of Mach number can be extended by using a wind tunnel with a cold flow so that the speed of sound in the flow is low. An ordinary supersonic wind tunnel operating at Mach number 2 or 3 serves nicely for this purpose, if provided with a long working section. The range in velocity can be increased through the use of a wind tunnel with a high velocity flow in its working section. A shock tube wind tunnel has been used for this purpose, since a flow with a velocity of 15,000 fps can be generated without undue difficulty.

In summary, a light-gas gun has been developed for launching aerodynamic models at velocities up to 30,000 fps and improvements are being made which are expected to increase this limit. Models have been instrumented for in-flight measurements of heat transfer and flown successfully; models with more complex instrumentation for other in-flight measurements are being developed. The test capability of the range can be extended by replacing the flight test chamber with the working sections of supersonic, hypersonic, and shock tube wind tunnels. All these factors combine to make the free flight range a versatile, reliable tool for research in the physics of high speed flight.
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Free Flight Ranges


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High Velocity Launchers


Aerophysics Measurements in Free Flight Ranges


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Combined Range-Wind Tunnel Facilities


Fig. 2 Velocity trajectories for constant base pressure.
2a) Density of spherical projectile equals 1 gm/cc.
2b) Density of spherical projectile equals 3 gm/cc.
2c) Density of spherical projectile equals 9 gm/cc.
Fig. 3 Accelerated reservoir light-gas gun.

\[ P_b = \text{CONSTANT} \times 20 \text{ KPSI} \]
\[ P_i = 44.7 \text{ PSI} \]
\[ T_i = 520 \text{°R} \]
\[ W_p = \text{QI GRAM} \]
\[ V_i = 400 \times 48,500 \text{ FT/SEC} \]
\[ d = 0.23 \text{ IN} \]

Fig. 4 Characteristics solution for launching cycle of constant base pressure, isentropic light-gas gun.
Fig. 5 Variation in launch tube breech pressure required for constant base pressure, isentropic launch cycle.

Fig. 6 Instrumented model for in-flight measurement of stagnation point heat transfer.
Fig. 7 Experimental set-up for free flight range telemetry of stagnation point heat transfer.
Fig. 8
Stagnation point heat transfer rate in air.

Fig. 9
Stagnation point heat transfer rate in carbon dioxide.
Fig. 10 Velocity-altitude test region of GMC/DSD Physics Range.

Fig. 11 Aerodynamic test region of GMC/DSD Physics Range in terms of Mach and Reynolds numbers.