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SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

AERODYNAMIC AND ROCKET-EXHAUST HEATING DURING LAUNCH AND ASCENT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion.

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all previously issued monographs in this series can be found on the last page of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will become uniform design requirements for NASA space vehicles.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was A. L. Braslow. The authors were D. E. Walters of McDonnell Douglas Corporation and F. P. Boynton of General Dynamics Corporation. Other individuals assisted in the development and review. In particular, the significant contributions made by D. J. Daniels of McDonnell Douglas Corporation; E. R. Eckert of the University of Minnesota; W. L. Francis of Philco-Ford Corporation; O. M. Hanner and S. Helfman of Martin Marietta Corporation; M. R. Kinsler of North American Rockwell Corporation; L. R. McGimsey of Lockheed Missiles & Space Company; C. R. Mullen of The Boeing Company; A. J. Verble of NASA Marshall Space Flight Center; G. C. Wilson of General Dynamics Corporation; and D. W. Wolsefer of Chrysler Corporation are hereby acknowledged.

Comments concerning the technical content of these monographs will be welcomed by the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RVA), Washington, D. C. 20546.

May 1969

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AERODYNAMIC AND ROCKET-EXHAUST HEATING DURING LAUNCH AND ASCENT

1. INTRODUCTION

Space vehicle structure may be affected significantly by the thermal environment induced during launch and ascent. Elevated temperatures reduce the strength and stiffness of vehicle structure, and thermal gradients produce local increases in stresses and distortions. Improper evaluation of these effects in design can result in structural failure during flight. In addition, heating can induce chemical reactions that degrade the absorptivity and emissivity of surface coatings; this degradation may allow excessive structural temperatures during launch and ascent or later impair the thermal control of vehicle systems during flight.

Sources of heating are external aerodynamic flow, rocket exhausts, solar radiation, structural radiation (or reradiation), and power dissipation from electrical or propulsion components. These sources, coupled with the presence of heat sinks, such as relatively large masses of fluids or structure, determine the vehicle's heat balance and the resultant temperature histories of the structural elements. Although all of these heat sinks and sources must be accounted for in thermal design, the primary sources of heat transfer during the launch-and-ascent phase of flight are external aerodynamic flow and rocket exhausts, the subject of this monograph. For this document, launch and ascent is defined as the period from booster-engine ignition through the boost phase of powered flight.

Aerodynamic heating during launch and ascent results principally from gaseous convection, and depends on the viscous interactions of the atmosphere with the vehicle surfaces. The severity of aerodynamic heating depends on the flight trajectory (velocity, altitude, and angle-of-attack histories); atmospheric variations in temperature and in pressure or density; and vehicle geometry and flow conditions which produce boundary-layer separation, wakes, corner flow, shock impingement, or flow choking.

The source of exhaust-plume heating is the rocket engines, including the main-propulsion, control, ullage, and retro engines. The heating is transmitted to the structure by a combination of convection, particle impingement, and radiation. The severity of plume heating is governed by the vehicle's altitude and velocity, type of propellants, engine-operating parameters (chamber pressure, chamber temperature, and mass flow rates), exhaust-nozzle geometry, engine gimballing, and impingement-surface geometry. Reverse flow induced by interaction of the rocket-exhaust plume with a trailing stage during staging, with the atmosphere (vehicle flow field), or with adjacent plumes in multiple-engine configurations, can produce heating of the base region. Secondary combustion (afterburning) of fuel-rich exhausts at low altitudes contributes significantly to the overall base heating. Base heating during launch also results from plume interactions with the launch pad, which may produce significant amounts of convection and radiation-heat transfer.

All modes of heating (i.e., convection, conduction, and radiation) can be influenced by fluids vented into the external flow. Venting cold gases directly onto hot structure or rocket-exhaust impingement onto cold structure can produce rapid changes in temperature that will result in thermal stresses, physical distortion, and possible structural failure. In addition, the ingestion of hot boundary-layer gases or rocket exhausts can have significant adverse effects on internal components.

Heat transfer during prelaunch, space flight, and entry, and analysis of structural response to heating are under consideration as subjects of separate design criteria monographs. The problem of heating associated with entry from aborted ascent flight will be treated in the monograph on entry heating.

2. STATE OF THE ART

Analytical methods to determine the flow field and aerodynamic heating rates are well developed for both laminar and turbulent flow. Although there is no reliable way to determine whether the boundary-layer flow is laminar or turbulent at the higher altitudes, most of the heating during launch and ascent occurs at low altitudes and high Reynolds numbers where turbulent flow can be assumed with a high degree of confidence. Theoretical methods for predicting perturbed heating (protuberance-induced, separated-flow, and shock-impingement) are not well developed, and experimental data are used. Experimental data also are used extensively for base heating, and to a lesser degree for plume heating (convection, particle impingement, and radiation).

2.1 Aerodynamic Heating

A three-phase computer program is frequently used to calculate aerodynamic-heating conditions during launch and ascent. In the first phase, the inviscid local-flow properties are calculated as time-dependent variables, using the vehicle's velocity, altitude, and angle-of-attack histories in conjunction with a model atmosphere and vehicle geometry. The flow properties of the first phase are then used to calculate heat-transfer parameters in the second phase. The third phase may be a one-, two-, or three-dimensional heat-transfer program utilizing heat-transfer coefficients and recovery temperatures from the second phase to calculate the wall temperature or the temperature history of the structure, or both. Phases two and three are usually combined for iteration because the heat-transfer coefficient is affected by the wall temperature.

In the estimation of heat-transfer parameters for the second phase, existing theoretical methods have been validated by experiment and are adequate for design of clean-body areas. Since most protuberances can be classified by a clean-body shape (i.e., cone, wedge, hemisphere, or cylinder) or by a combination of simple geometries, the theoretical methods are also adequate for protuberance design. For areas adjacent to protuberances, the wake areas downstream of protuberances, shock-impingement areas, and regions of separated or reattaching flows, existing theoretical methods are usually not adequate and experimental data are used.

2.1.1 Flow-Field Determination

An integral part of an aerodynamic-heating analysis is the determination of the inviscid flow field around the vehicle. To define the vehicle flow field at any time requires (1) a trajectory (velocity, altitude, and angle-of-attack history); (2) an atmosphere (pressure or density and temperature); and (3) a knowledge of the vehicle geometry.

2.1.1.1 Trajectories

For aerodynamic-heating analyses, two types of trajectories are usually considered: a nominal or performance trajectory and a maximum-heating trajectory. The nominal trajectory is the most probable course a given vehicle will fly to accomplish its mission. A maximum-heating trajectory is a variation of the nominal trajectory that produces a maximum total heat input or a maximum rate of heat input, or both. Generally, for a space vehicle during ascent, the maximum heating rate and maximum total heating trajectories are identical. However, owing to the shape of suborbital trajectories resulting from programmed mission requirements or abort considerations for which both ascent and entry heating must be considered, a given trajectory may produce lower heating rates for a longer period of time, which results in more accumulated heat.

Several methods have been used to evaluate the effects of trajectory parameters on aerodynamic heating. The simplest method is a comparison of the velocity-altitude history. This method is qualitative, and does not account for atmospheric variations or angle of attack. A second method is to calculate flat-plate heating rates or the temperature history of an arbitrary element, or both. In the flat-plate method, atmospheric variations can be accounted for and angle of attack can be included by the assumption that the flat plate is a wedge whose apex angle equals the angle of attack.

This method gives the best quantitative comparison, and can account for boundary-layer transition. Its main disadvantage is its complexity.

A third method that has been used is the aerodynamic heating indicator (AHI). It is derived from the flat-plate heating methods, but essentially weighs only the effects of density ρ and velocity v. The form of the equation used is $\int \left(\rho^{a} v^{b}\right) dt$. For large vehicles, the flow is predominantly turbulent during the period of significant heating, and the approximate relation $\int \left(\rho v^{3}\right) dt$ has been used successfully. Angle-of-attack effects are neglected for trajectories where the angle of attack is less than two degrees during supersonic flight. Where the angle of attack is significant, ρ and v are evaluated as local properties on a wedge whose apex angle equals the angle of attack. Other empirical multipliers are used for relatively small angles, one such multiplier being $\pi/(\pi-2a)$, where a is the angle of attack in radians. Although the AHI is qualitative and there is some disagreement as to its effectiveness in accurately indicating critical heating areas on a vehicle, it has been used successfully in some instances to establish maximum aerodynamic-heating trajectories.

2.1.1.2 Atmospheric Data

Various standard atmospheres have been used in determining a vehicle's flow properties. Reference 1 presents data for a mean latitude for the United States and supplementary data showing latitudinal and seasonal variations; reference 2 contains mean data for Patrick Air Force Base, Florida, applicable to launches from the Eastern Test Range (ETR); and reference 3 includes a condensed version of reference 2, with approximately $\pm 3\ \sigma$ variations in density for launches from ETR.

Atmospheric properties vary seasonally and with geographic location. A standard atmosphere, determined by statistical data compilation, gives mean values and therefore does not give the worst conditions that one can expect to meet with a given probability. Reference 3 gives density variations but not matching temperature data, so standard temperatures are normally used with these density data. The result of this temperature-density combination is a nonstandard atmosphere that does not comply with both the equation of state and the hydrodynamic equation. A realistic atmosphere is required to satisfy both equations. Atmospheric data for the earth and other planets are being gathered continually, and new information is being published as it becomes available. The analyst must ascertain whether he is using the latest data available.

2.1.1.3 Vehicle Geometry

With the trajectory and the atmosphere established, the flow field is determined by the interaction of the free stream with the geometric shape of the vehicle. This is usually accomplished by combining experimental data with the ideal or perfect gas relationships of reference 4. There are so-called exact and approximate analytical methods for determining the pressure distribution over the vehicle. For most aerodynamic-heating analyses, the approximate methods are adequate and much less cumbersome than the so-called exact methods. Reference 5 presents a good discussion of both types of methods and compares analytical (including numerical) methods and experimental data that are applicable to most NASA space vehicles.

2.1.2 Aerodynamic-Heating Methods

Aerodynamic heating during ascent flight occurs predominantly at supersonic and low hypersonic speeds. Numerous analytical methods of calculating aerodynamic heating in this speed range have been documented. Reference 5 provides an excellent review of most methods, with appropriate references for each. It compares methods, states their limitations, and correlates methods with experimental data. The geometries usually considered are spheres, cylinders with longitudinal or cross flow, flat plates, cones, and wedges.

For either laminar or turbulent flow, only two types of theoretical methods are usually required: (1) blunt body or stagnation, and (2) flat plate. Flow near the stagnation point is usually laminar because of the low Reynolds number and favorable pressure gradient.

The most commonly used stagnation-type aerodynamic-heating methods for laminar flow are those of Fay and Riddell, Sibulkin, and Cohen and Reshotko, all of which are reviewed in reference 5. The equations for heat transfer at the stagnation point on a sphere or for the stagnation line on a cylinder differ only by a constant. Stagnation-line heating on a yawed cylinder is usually obtained from an empirical ratio of yawed-to-unyawed heating rates (ref. 5, pp. 122-125).

The most commonly used flat-plate methods for both laminar and turbulent flow are Eckert's reference enthalpy or reference temperature and van Driest's methods. Both are reviewed in reference 5. In addition, the method of Spalding and Chi (ref. 6) is used for turbulent flow. This method was developed for prediction of skin-friction-drag coefficients; it can be adapted to aerodynamic heating with a modified Reynolds analogy that relates skin friction to heat transfer.

Heat transfer to cones is predicted by application of the Reynolds analogy to a corrected flat-plate skin-friction coefficient. The correction is $c_{f,\ \mathrm{cone}} = \sqrt{3}\, c_{f,\ \mathrm{flat\ plate}}$ for laminar flow; and $c_{f,\ \mathrm{cone}} = 2^{\frac{1}{5}}\, c_{f,\ \mathrm{flat\ plate}}$ for turbulent flow. No correction is required to apply flat-plate methods to wedges; however, in applying the flat-plate relations to cones or wedges, the velocity and temperature at the edge of the boundary layer are used.

2.1.3 Boundary-Layer Transition

Even though aerodynamic-heating methods for both laminar and turbulent flows are well developed for the range of conditions important to ascent flight, boundary-layer transition cannot be predicted with a high degree of certainty. This is because the factors that affect transition are difficult to evaluate. These factors include Reynolds number, Mach number, pressure distribution, shock waves, nose bluntness, two- and three-dimensional roughness elements, surface-to-stream temperature ratio, and injection of fluids into the boundary layer. Discussion of these factors and their interrelationships can be found in section 2.3.1 of reference 5 and in reference 7.

In practice, transition for ascent flight is usually assumed to occur at a Reynolds number Re_x based on surface distance from the stagnation point and local flow conditions ranging from 0.5×10^6 to 1.0×10^6. The use of a transition Reynolds number in this range will normally give a conservative estimate of heating rates.

2.1.4 Protuberance Heating, Separated Flow, and Localized Disturbances

As mentioned in Section 2.1, most protuberances are classified as general clean-body shapes for analysis. The theoretical methods for clean-body heating (Sec. 2.1.2) are therefore also applicable for protuberance heating. These methods are not used for areas adjacent to protuberances, wake areas, separated or attaching flows, shock impingement, or other regions of disturbed flow. Experimental data are used to define the magnitude of heating in these regions.

Examples of experimental data on heat transfer in perturbed flow regions may be found in references 8 to 18. References 8 to 13 present heat-transfer data around and downstream (wake) of various shaped protuberances. The data, presented as ratios of protuberance-induced heat-transfer coefficient to flat-plate heat-transfer coefficient, were obtained for turbulent flow at three Mach numbers ranging from approximately 2.5 to 4.5. References 8 to 13 also describe the effects of external stringers on flat-plate heating, as well as their effects on protuberance-induced heating and wake heating. Data and correlations with theory for heating on a swept cylinder in the region of flow interference with a wedge are given in reference 14. This particular reference is quite limited in applicability, since the tests reported were conducted at a single Mach number of 8. Results of an experimental investigation of heat transfer at Mach 6 in separated flow regions created by steps and wedges are described in reference 15. A comprehensive review of analytical methods and pertinent experimental data for predicting heat transfer in separated flow and reattachment regions is given in reference 16. The review includes data on forward- and aft-facing steps, compression and expansion corners, blunt bodies, cavities, and shock-wave boundary-layer interactions. A less extensive discussion and some empirically determined factors for estimating heating rates in separated and attaching flows are contained in reference 5. A comprehensive bibliography on flow separation, including tables that aid in the selection of data for various flow and geometric configurations, is contained in reference 17; empirical data on heating rates associated with boundary-layer separation induced by exhaust plumes are given in reference 18.

Other perturbing influences on heat transfer are produced by geometric and thermal discontinuities. These discontinuities can be grouped into three general categories: compression corners, expansion corners, and nonisothermal-wall effects. The first two are almost always combined with the third since they produce discontinuities in heating rates resulting in temperature discontinuities in the direction of flow. Nonisothermal-wall effects can, of course, occur independent of geometry as the flow passes over areas with large heat sinks (as fuel and oxidizer tanks).

It is common practice to assume an isothermal wall, which results in overpredicting heat rates downstream of a cold wall and at the beginning of a compression surface, and underpredicting them on the initial portion of a cold surface. No failures have been attributed to nonisothermal-wall effects; nonetheless, nonisothermal-wall effects are included in heat-transfer calculations to increase accuracy when there are large variations in wall temperature. This problem is discussed in references 19 and 20. The former discusses all three discontinuities and includes a computer program for heat-transfer calculation; the latter gives a simplified method for treating temperature discontinuities that is amenable to hand calculations.

2.1.5 Venting

Venting of propellants or ullage gases into the boundary layer may significantly influence heat transfer by physically altering flow properties or by inducing combustion. Venting of the normally inert gases from interstage compartments is usually not a significant influence if the vents are properly sized and located.

The venting of noncombustible ullage gases does not normally influence heat transfer significantly unless the flow rates are sufficient to produce flow separation or shock waves. If the flow rate is sufficient, the vented flow can alter the flow characteristics of the oncoming stream over a large region, and the effect requires experimental data for evaluation.

For multistage vehicles, the venting of hydrogen from fuel tanks on upper stages is the most probable source of a combustible mixture in the boundary layer, although vented hydrogen does not usually ignite at altitudes above 15 km. Methods of calculating combustible-mixture ratios or the possibility that a combustible mixture may become ignited are not well developed or readily available. Analyses produce evaluations that can only be described as estimates. Reference 21 discusses hydrogen venting and the analysis of heat transfer resulting from burning in a boundary layer.

2.2 Rocket-Exhaust Plume Heating

As a general rule, it is more difficult to predict heating rates from rocket exhaust plumes than heating rates from the external air stream. Not only is the plume flow field often extremely complicated, but heating by modes other than convection (particle impingement and radiation) can be significant. The problem of prediction becomes particularly acute for heating in the base region of vehicles with clustered engines, where plume-plume and plume-atmosphere interactions produce a very complex recirculatory flow. It is convenient, though arbitrary, to separate heating by direct plume impingement from heating by base recirculation in this and subsequent discussions. To some extent this separates problems where wholly or substantially analytical procedures can often be used for design purposes from problems where an extensive test program is imperative.

The high temperatures and large optical densities of some plumes result in appreciable radiative heating rates. Radiation is usually more important in base heating than in direct impingement. Predictions of radiative heating rates can be either good or poor, depending on how well the flow field properties are known.

An accurate description of the plume flow field is necessary for all analytical predictions, and is often helpful in interpreting or extrapolating test data. A brief appraisal of available procedures for computing flow fields is thus given first, and then methods of establishing design heating rates are discussed.

2.2.1 Flow-Field Determination

For analytical predictions, it is first necessary to determine the chemical composition and state properties of the combustion products for the wide range of flow conditions from the combustion chamber to the highly expanded plume boundary. Computer programs are generally required. Reference 22 describes a program which calculates the properties of a reacting mixture of perfect gases and condensed species both at the specified combustion chamber pressure and composition (mixture ratio) and at isentropically expanded conditions assuming either frozen or shifting equilibrium. Computer programs for one-dimensional finite-rate expansions (e.g., ref. 23) are also available. The accuracy of combustion-product property calculations depends upon how well the mixing of fuel and oxidizer is known, and upon the accuracy to which properties of the individual product species is known.

For accurate plume calculations, the variation of flow properties across the nozzle exit plane must be included. This variation can be quite significant for contoured nozzles. A numerical (method of characteristics or finite-difference) computation of the nozzle flow field, starting from initial conditions at the nozzle throat, can be used to determine the exit-plane conditions. For axially symmetric nozzles, references 24 and 25 are examples of single-phase flow programs; reference 26 presents references to two-phase flow programs and compares experimental results with predictions. Procedures for determining the three-dimensional flow fields in nozzles without axial symmetry have recently been developed (ref. 27). The Interagency Chemical Rocket Propulsion Group's recommended procedures for calculating delivered engine performance (ref. 28) are generally suitable for determining exit-plane properties in liquid-propellant engines.

Methods for computing flow fields of axially symmetric exhaust plumes with or without a coaxial free stream are well developed (refs. 24 to 26) except for the recirculation region. A computer program based on a numerical procedure is usually required for the supersonic portion of the flow, where the calculation can be started at the nozzle exit plane; external or imbedded subsonic regions in the flow are adequately treated by approximate techniques. The effects of the external flow field on the plume should be considered at low altitudes where its dynamic pressure affects the plume structure, and mixing and secondary combustion (afterburning) can occur. The altitude above which the external flow field can be neglected depends upon the specific problem and the given nozzle and engine parameters, but is usually greater than 60 km. The region of mixing and secondary combustion at the plume-atmosphere interface (shear layer) heats the vehicle structure primarily by radiation. Finite-difference procedures for evaluating this part of the flow field are available (ref. 29).

Satisfactory methods for calculating three-dimensional plume flow fields without axial symmetry have not yet been developed. For example, there are no satisfactory methods for determining flow fields for plumes from symmetric nozzles into noncoaxial external streams, plumes from asymmetric nozzles, and plumes from clusters of engines. Attempts at "exact" calculations (e.g., refs. 30 and 31) have not been satisfactory, and it is common practice to employ approximate procedures based on axially symmetric calculations for analytical estimates. In general, test programs must be relied upon for thermal-design data for three-dimensional exhaust plumes without axial symmetry.

Reference 32 presents an up-to-date review of methods available for computing exhaust-plume flow fields.

2.2.2 Plume Impingement

Portions of the vehicle structure which lie within the exhaust plume are heated by gaseous convection, particle impingement, and (to a usually lesser degree) by radiation. The dominant mode of heating depends upon the position of the surface in the plume and the propellants employed. For positions close to the centerline of the plume of an engine using a metallized solid propellant, metal-oxide particle impingement heating may greatly exceed the other modes. Near the boundaries of highly expanded gas-particle plumes, and in most liquid-propellant engine plumes, only convection may require consideration. Radiation is seldom the dominant mode except in special locations, such as in a very tenuous region of a hot, optically dense plume.

Convective heat transfer is calculated by applying the same methods used for aerodynamic heating, using flow properties derived from the flow field calculation and normal or oblique shock relations, as appropriate, at the surface. The accuracy of these calculations depends on how well the plume flow has been described, in addition to the accuracy of the heat flux prediction procedures themselves. Predictions may be as good as ±10%.

Heat transfer by particle impingement has not been as thoroughly examined as convective heating, and predictions should currently be considered less accurate. Analysts generally proceed by first computing the local particle flux density and properties, using either the numerical procedures of reference 26 or approximate techniques, and then applying an "accommodation coefficient" to determine the heat flux to a surface. Recent test data (ref. 33) suggest this to be a conservative practice if the usual assumption of inelastic impact is employed. Reference 34 uses an accommodation coefficient of 0.25 to 0.3 to correlate measured heating rates.

Even when relatively accurate analyses of plume-impingement heating are possible, experimental confirmation is usually obtained.

2.2.3 Radiation

Computational procedures for determining radiative heat transfer from exhaust plumes have advanced rapidly in the last few years. Reference 35 contains a comprehensive review of thermal radiation from both liquid- and solid-propellant rocket exhaust. In general, analyses of radiation from nonscattering media (i.e., those not containing highly reflective particles, such as $A\ell_2O_3$) are more accurate than those involving scattering. In either case, however, the local radiative heating can be rather sensitive to the details of the flow field (particularly the temperature distribution) and predictions are thus dependent upon flow field accuracy.

While convective heating often scales in a simple fashion with vehicle size, radiative heating scales in a complicated manner except in a few, essentially trivial, situations. The scaling of radiation between systems of similar geometry and optical properties, but greatly differing sizes, generally requires separate complete computations for each system.

2.2.4 Base Heating

Gaseous convection and radiation are the dominant modes for heating in the base region of a vehicle. Secondary combustion of fuel-rich exhaust gases, either along the plume boundary or in the recirculation zone, increases the heating rates at low altitudes. Radiation and convection from plume gases "splashing" from the launch pad can be significant at liftoff.

There is no satisfactory analytical procedure for determining the base-region flow fields of realistic launch vehicles to the accuracy needed for heat transfer analyses because of the geometrical complexity of the flow patterns resulting from plume interactions with the atmosphere, adjacent plumes, and vehicle structure. Current analytical methods are based on empirical correlations of test data and are limited to configurations similar to those tested. Design data are usually obtained from specifically designed test programs or from existing experimental data.

The influence of the launch pad on base heating depends upon flame-deflector geometry and whether the deflector operates dry or water-cooled.

Reference 36 contains a good description of base-flow characteristics of clustered engines and the influence of various engine and geometrical parameters; reference 37 summarizes design experience on several multiengine Saturn stages; and reference 38 gives the thermal data obtained from several flights of the Saturn I Block I booster, together with an acceptable method of correlating flight data with data from small-scale hot-flow tests. The most promising procedures now available for obtaining base heating design information were developed too recently to have been incorporated in *a priori* design decisions on the current generation of launch vehicles, so that extensive confirmatory data are not available. Fair to good agreement has been demonstrated with a limited number of test flights.

2.2.5 Venting and Staging

The location of engine-compartment vents influences the base pressure and therefore the base-heating rates. Venting of combustibles (propellants or very fuel-rich turbine exhausts) into the base region at low altitudes can significantly increase base heating. As in other base-heating problems, design data must be obtained from experiments.

Plume-impingement heating during staging is in principle no different from other cases of plume impingement, and the same predictive techniques can often be employed (with a proper accounting for the surface's exposure to different parts of the plume as separation proceeds). High heating rates may occur for short periods of time, and the heating can affect previously unexposed structure; electrical, hydraulic, and pneumatic system components; and thermal-control surfaces. These surfaces may be contaminated, eroded, or even destroyed by the plume. Analysis of some complicated situations which may arise on staging (such as "fire-in-the-hole") is not sufficiently accurate, and test data are required for design predictions.

2.3 Tests

Two types of tests are conducted to determine aerodynamic and rocket-exhaust-plume heat transfer: (1) free-flight tests and (2) captive tests in wind tunnels, vacuum chambers, or other ground facilities. Captive tests are usually conducted on reduced-scale models or on mockups using full-scale rocket-engine hardware. Free-flight tests are usually full scale; however, free-flight testing of small-scale models is by no means unusual, and a considerable amount of aerodynamic-heating data has been obtained in this way. Testing techniques, facilities, and instrumentation for determining heating rates are well developed.

2.3.1 Aerodynamic Heating

Methods for obtaining aerodynamic-heating data are well developed. Many facilities, both government and privately owned, are available, and have been used to obtain aerodynamic-heating data. Three types of ground facilities are normally used: continuous and blowdown wind tunnels and shock tubes. The facility selection is usually made by considering the critical flow parameters to be duplicated and the estimated requirement for data accuracy.

Free-flight data are obtained for general geometric shapes on small- or full-scale vehicles. Small-scale models may be made so as to reduce three-dimensional conduction effects and provide straightforward reduction of temperature data to obtain heating rates. This is seldom the case for full-scale flight vehicles where installation requirements and conduction effects may produce significant differences between the sensor output and the true structural temperature. In full-scale flight, therefore, measurement of heat flux provides better-quality, more readily reduced data than does measurement of temperature. Reference 5 compiles data from a number of full-scale flight vehicles and gives a good description of the problems encountered. Thin skin models have been used extensively for wind-tunnel and small-scale free-flight testing with satisfactory results.

2.3.2 Exhaust-Plume Heating

Analysis of plume heating has had a relatively short development period, so significant advances in testing techniques and instrumentation should be expected. Engineering data have been obtained for a variety of test conditions and are referenced in the following paragraphs. Both sub- and full-scale tests have been performed with satisfactory results. Also, both short- and long-duration tests have been used satisfactorily.

2.3.2.1 Direct Plume Impingement and Radiation

Test methods and instrumentation are generally adequate to obtain flow-field pressures, densities, and heat-transfer data. For small control- and retrorockets, data are usually obtained from full-scale firings. For larger engines at high altitudes, ambient-pressure excursions in the test chamber are difficult to control, so either small-scale models or short-duration techniques are employed.

Convection and total heating rates may be obtained directly from calorimeters or indirectly from temperature measurements. Convection is usually determined by subtracting radiation-heating rates (obtained from radiometers) from total heating rates. For design purposes, it is usually not necessary to distinguish between particle-impingement and gaseous-convection heating; however, under some circumstances this distinction may be necessary for scaling the test results. References 39 and 40 summarize test methods and instrumentation of recent rocket-exhaust-impingement tests; references 34 and 35 give detailed studies of thermal radiation and particle impingement for rocket exhausts, including test methods and results.

2.3.2.2 Base Heating

Since the convection and radiation-induced base-heating rates may depend on altitude as well as on the geometric and operating characteristics of the engine, tests are frequently conducted to simulate a wide range of altitudes. At lower altitudes, the external flow field of the vehicle is important, and data are usually obtained on small hot-flow models in a wind tunnel. The venting of combustibles into the base region is included when applicable. Usually, the external flow-field effects become negligible somewhere in the band of operational altitude from 60 to 90 km, and tests can therefore be conducted in a vacuum chamber.

Testing techniques, facilities, and instrumentation are generally adequate for obtaining design data. Many tests have been conducted on multiengine configurations. Although the effects of scale modeling on base flow and heat transfer are not completely understood, successful correlations of test and flight data have been obtained (ref 38). Recent tests and testing techniques are reviewed in references 37 and 40 to 42. Other data obtained on launch vehicles developed for military applications are reported in classified literature.

2.3.3 Venting

Testing methods that adequately describe venting-induced phenomena are complex, since reduced scale testing requires a compromise between the simulation of chemical-reaction parameters and aerodynamic parameters.

Methods of testing for combustible mixtures are reasonably well developed, but theoretical methods must be used to interpret the results. One method (ref. 43) utilizes temperature measurements to obtain the enthalpy of the mixture and calculated-mixture ratios from the initial enthalpies of the two gases. Another method (ref. 44) utilizes a tracer-gas technique with concentration measurements made by a gas chromatograph. Here, theory is used to relate volumetric-mixture ratios in air of the tracer gas to the actual gas under consideration. The estimated accuracy of the method of reference 44 is ±20%, which may be good enough for most engineering applications. Both methods are theoretically sound, but no correlation with flight data has been attempted. At this time, there is no valid reason to favor either method.

3. CRITERIA

3.1 General

The heating imposed on a space vehicle by external flow fields during launch and ascent shall be adequately accounted for in the design evaluation of stresses, deflections, and structural materials and coatings.

3.2 Guides for Compliance

3.2.1 Analysis

To ensure that the aerodynamic and rocket-exhaust plume heating is properly determined, analyses shall, as a minimum, account for the following:

Aerodynamic Heating

- Heating rates and total heating for all maximum aerodynamic-heating trajectories based on at least 3-σ dispersions of performance and atmospheric parameters.
- Sufficient points along the trajectory to define the aerodynamic heating and structural temperature history.
- The effects of vehicle geometry and any local flow perturbations.
- The effects of venting fluids into the boundary layer.
- The effects of ingesting hot boundary-layer gases or the exhausts of control, ullage, retro, or main engines.

Rocket-Exhaust Plume Heating

- The influence of vehicle external flow field, nozzle configuration, propellant composition, and chamber pressure.

- The effects of local geometry and upstream geometry.
- The effects of base geometry and engine gimballing.
- The effects of secondary combustion and other chemical reactions.
- The effects of the adjacent launch pad structure.
- The effects of base or engine-compartment venting.

3.2.2 Tests

When analysis indicates a critical effect of aerodynamic or rocket-exhaust plume heating on design, and when existing experimental information is not applicable to the design configuration or operational conditions, tests shall be conducted for evaluation of the external heating sources in at least the following areas:

- Areas adjacent to protuberances.
- Wake areas downstream of protuberances.
- Separated flow and reattachment areas.
- Shock-wave impingement areas.
- Areas of base heating.
- Areas subjected to three-dimensional exhaust plumes or to plume impingement.

4. RECOMMENDED PRACTICES

The design evaluation of stresses, deflections, and structural materials and coatings requires a determination of the temperature history of the structural elements and development of a heat balance among the various heat sources and sinks identified in Section 1. The following practices are recommended for the determination of the external aerodynamic and rocket-exhaust plume heating, the primary sources of heat transfer during launch and ascent.

4.1 Aerodynamic Heating

4.1.1 Flow-Field Determination

Local flow properties, determined from trajectory and atmospheric data and vehicle geometry, should be established to compute heat-transfer parameters. When conservative analytical methods produce results that have a severe impact on design, the flow field or the heating rates, or both, should be determined from experimental data.

4.1.1.1 Determination of Thermal-Design Trajectory

It is recommended that a thermal-design (maximum-heating) trajectory be developed for the maximum-performance ascent mission. This should provide adequate thermal inputs for all missions. The primary control over the severity of aerodynamic heating is the pitch program: the earlier pitch is initiated, and the greater the pitch rate, the more severe the aerodynamic heating usually becomes.

To establish the trajectory, changes in aerodynamic heating produced by the following vehicle and aerodynamic characteristics should be evaluated:

- Thrust.
- Thrust misalignment.
- Specific impulse.
- Propellant loading (or density).
- Vehicle's dry weight and moments of inertia.
- Normal force.
- Axial force.
- Center of gravity.
- Center of pressure.
- Control system.
- Atmospheric density.
- Winds.

Either the AHI or the summation of flat-plate convective heating rates is recommended for a preliminary evaluation of acceptable changes in these characteristics, but critical heating areas should be examined in more detail before the final design is completed. Only variations ($3\ \sigma$ or those corresponding to the reliability and confidence level specified for a given vehicle) which give increases in heating are considered in establishing the maximum-heating trajectory. The increase caused by each characteristic is combined by the root-sum-square method to obtain the total increase. Then, to obtain the value to be used in the final trajectory, the deviation of each characteristic is multiplied by the ratio of the increased heating due to the change in characteristic to the total heat increase.

Flat-plate heating and the AHI may also be used to compare the heating severity of different trajectories. If a given vehicle is designed for one trajectory, a comparison of the AHI or a summation of flat-plate heating will show whether another trajectory is acceptable. In either case, the trajectory having the higher numerical total is the more severe trajectory, and the history of the heating parameter used should be plotted and compared. If there are appreciable differences in the time history, even though the totals come to the same value, rigorous thermal analyses should be performed on critical sections of the vehicle to ascertain the actual thermal effects of the trajectory. Any method of comparison except rigorous thermal analyses must rely heavily on the judgment of the person making the comparison.

4.1.1.2 Definition of Thermal History

For an adequate definition of the thermal history, a sufficient number of time points (usually at 5- to 10-sec intervals) must be chosen to cover the critical flight periods. For areas of a vehicle that are initially at ambient temperature, the subsonic portion of flight results in negligible heating; in fact, subsonic flight usually results in cooling. As the vehicle attains supersonic speed, the heating rates increase rapidly, and maximum heating usually occurs between Mach 2 and Mach 3.

Aerodynamic loads are usually maximum (maximum αq) during transonic or low supersonic flight, at which time room-temperature properties can be used for structural analysis. The maximum heating rate that produces large thermal gradients occurs when aerodynamic loads are smaller but acceleration has increased, thus giving a possible critical condition. The next critical condition usually occurs at main engine cutoff, when both temperature and acceleration are maximum. For small solid-propellant vehicles, maximum dynamic pressure and maximum temperature may occur at nearly the same time.

The same atmospheric data should be used for thermal analyses as for the thermal-design trajectory. The latest data available should be used for all launch areas (including any on other planets). For launches from ETR, the $+3\ \sigma$ density and standard temperature given in reference 3 are recommended. Free-stream pressure should be calculated from density and temperature by the equation of state. The supplements to the U.S. Standard Atmosphere (ref. 1) supply data for latitudinal and seasonal variations that should be used for locations in the United States other than ETR.

4.1.2 Effects of Vehicle Geometry

The methods presented in Section 2.1.2 are acceptable for determining the aerodynamic heating for attached flow conditions over clean-body shapes. The complete geometry forward of the point of interest should be accounted for, as recommended in reference 5. Where doubt exists as to the precise method to follow, a conservative approach should be used (e.g., a weaker shock or a higher local pressure will normally result in increased heating downstream of the shock).

4.1.2.1 Boundary-Layer Transition

In the absence of a method to determine boundary-layer transition with confidence, the use of a critical Reynolds number (based on surface distance from the stagnation point and local flow conditions Re_X) of 5×10^5 is recommended. Although some flight data have indicated laminar flow at Reynolds numbers greater than 10^6, the use of a larger value for design predictions cannot be recommended for all designs with a reasonable degree of confidence. It should be noted that protuberances can cause premature transition with higher heating rates at positions forward of $Re_X = 5 \times 10^5$; however, an assumption of fully turbulent flow throughout flight does not always give conservative results. Near the forward stagnation point, where Reynolds numbers may be relatively small, this assumption could result in underpredicted heating rates. For Reynolds numbers lower than approximately 10^4, laminar-heating rates exceed turbulent-heating rates, and should be used.

4.1.2.2 Protuberance Heating, Separated Flow, and Localized Disturbances

In most instances, a protuberance can be classified as a sphere, cone, wedge, or cylinder, and thus be analyzed by the standard aerodynamic-heating methods described in Section 2.1.2. These methods should be employed particularly for the forebody. Depending on the geometry of the protuberance, other areas may be influenced by such factors as shock interaction, shock impingement, or separated flow, and thus require experimental data. Reference 13 presents a method for analyzing protuberances which will account for submergence in a turbulent boundary layer. The method and correlations with test data are presented for protuberances having conical forebodies and afterbodies and cylindrical centerbodies. The basic method should be applicable to other generalized shapes; however, it should be used for preliminary design only, and be verified by experimental data for final design.

References 8 to 18 contain experimental data that can be used to predict heating rates in perturbed flow regions; Section 2.1.4 gives a brief description of the data available in these references and their applicability.

4.1.3 Effects of Venting Fluids

Fuel and oxidizer vents should be on opposite sides of all vehicle stages to reduce the possibility of the presence of a combustible mixture in the boundary layer. In any case, when combustibles are to be vented, this possibility should be investigated. Calculations to determine mixture ratios and combustible heat inputs may be made by the method described in reference 21. The possibility of adverse chemical reactions with the structure, insulation, or other thermal control surfaces should also be investigated and corrective action taken as required.

4.1.4 Effects of Ingesting Hot Gases

Compartment vents should be designed or located to prevent ingestion of hot boundary-layer gases and the exhausts of control, ullage, retro, or main engines. If this is not possible, the vent may be treated as an orifice to determine flow rates. Heating rates to internal components and structure may then be determined as a plume heating problem for the internally expanding plume.

4.2 Rocket-Exhaust Plume Heating

The vehicle designer should recognize that the current state of development of plume-heating predictive techniques is uneven, with some problems being readily susceptible to analytical treatment and others requiring considerable experimental testing before satisfactory predictions can be made. The pace of plume heating research and development is also uneven, since research efforts in this field are generally stimulated by specific vehicle development problems. In this situation, where rapid advancements in predictive techniques may occur during a vehicle development program, the designer must make certain that his procedures are up to date. In particular, it is in the determination of base heating that available procedures are most cumbersome and least satisfactory, and further development should be expected when the proper stimulus arises.

In many situations, it may appear that a specific plume heating problem is so complicated or depends upon so many different vehicle or thrust-chamber parameters that only crude approximate procedures should be employed for heating estimates. This is sometimes but by no means always true. Even in situations where knowledge of relevant parameters is incomplete, and where the absolute accuracy of sophisticated analytical procedures is modest, such procedures may yet be of considerable use. In interpreting test data, in assessing the effects of scaling from model tests to the vehicle, and in examining the sensitivity of heating rates to variations in designs and operating conditions, the analyst often obtains considerable insight by examining quantitatively and in detail a problem which at first glance appears too complex or too vaguely formulated to warrant detailed studies.

4.2.1 Plume Impingement

In order to account for the influences of the vehicle flow field (external pressure and Mach number), nozzle configuration (expansion ratio and contour), propellant composition (which determines combustion temperature and combustion-product composition), and chamber pressure, the flow properties in a plume (and if necessary in the nozzle) should be determined analytically from an appropriate numerical solution. Properties in the immediate vicinity of the surfaces impinged upon should be determined from the local plume properties and either Newtonian relationships or appropriate shock equations. The state properties of plume constituents entering the calculation should be realistically chosen. For some cases a constant specific heat value based on nozzle-exit properties is acceptable, while in others the inclusion of a variable specific heat and chemical reaction effects may be necessary. If there is not a clear choice, the properties giving the more conservative heating rates (usually equilibrium flow) should be employed.

Calculations of convective heat transfer to a surface should be made with the techniques used for aerodynamic heating. Surfaces with a complex geometry should be analyzed as a collection of simple shapes. Where necessary, effects of transition, separation, and shielding should be included as described in Section 4.1. A characteristic length for calculations involving a surface not entirely immersed in the plume should be selected conservatively. The Knudsen number used in rarefied-flow heating calculations for a surface over which this quantity varies appreciably should also be chosen to predict conservative heat fluxes. The procedures used on Saturn-class vehicles, reviewed in reference 40, are generally acceptable.

When appreciable amounts of particles are present in the exhaust products, the contribution of particle impingement to the overall heat transfer should be included. The flux of particles to the surface should be established from the flow field solution, and the energy transfer should be computed with effective accommodation coefficients that agree with test data (refs. 33 and 34). When insufficient data exist, the assumption of perfect accommodation will produce conservative heating rates. Acceptable treatments of the particle-impingement problem are presented in references 34 and 40.

4.2.2 Radiation

The procedures described in reference 35 are currently the most satisfactory for analyses of radiative heat transfer from exhaust plumes. Many of the optical-property data needed for these calculations are also summarized or referenced there. The use of these procedures, together with carefully computed or measured flow-field data, is recommended for design calculations. Approximate "effective emittance" calculations have been employed in most previous vehicle designs; these are now outdated, although they may be of use in preliminary design studies where accuracy is not as important as in later stages of design.

4.2.3 Base Heating

Base heating data for preliminary design can sometimes be obtained from flight data on other launch vehicles having similar configurations to those being considered. Data for detailed design should include the effects of base geometry, engine gimballing, base pressure, altitude, propellant composition, and secondary combustion, and these data should be obtained from test programs. Model test in wind tunnels or high-altitude simulation facilities, followed by careful scaling of the data, should be used to obtain design information for the early research and development vehicles. The best currently available scaling procedures still result in rather large uncertainties for full-scale heat fluxes. While it is difficult to place quantitative limits on these uncertainties, it seems clear that errors by a factor of about 2 can occur in some situations. It is therefore good practice to overdesign the heat shield of the early vehicles and to remove any excessive shielding from subsequent articles as full-scale data become available.

Data on full-scale vehicles can be obtained both from flight tests and (for first stages) from static firings, which are usually conducted as part of the vehicle development program. Some care must be taken in applying static-firing data alone, since experience with the current generation of launch vehicles has shown that heating rates are not necessarily greatest at liftoff. Furthermore, they are likely to reproduce actual liftoff heating rates only if the surrounding structure and flame deflectors are very much like those of the launch pad. The best use of static-firing data is as a test of predictive techniques and scaling procedures.

Base heating on upper stages is usually a lesser problem than on first stages. On single-engine H_2-O_2 stages, base heating is very low; on some multiengine configurations, significant heating (primarily convective) may occur. For vehicles where base heating is expected, design data should be obtained from model and flight tests, as discussed above.

4.2.4 Venting

Venting of fuel-rich turbine exhausts or of raw fuel directly into the base region should be strictly avoided.

4.3 TESTS

The test environment should simulate the critical flow parameters for the expected environment of the flight vehicle. Analyses should be performed to determine the sensor type and attachment procedures which best satisfy the environment and accuracy requirements for amplitude and response.

4.3.1 Aerodynamic Heating

When tests are required to evaluate aerodynamic-heating effects on areas adjacent to or downstream from protuberances, separated flow regions and reattachment areas, shock-wave impingement areas, or on geometries for which existing analytical methods may not be adequate, the test should be conducted in facilities capable of producing the local Mach number and Reynolds number. The model to be tested should duplicate the actual geometry of the design being considered, and should be as large as possible to ensure maximum accuracy of heating measurements. In many cases, however, it will not be possible to duplicate Re_x at the lower Mach numbers. When Re_x cannot be duplicated, the heat-transfer data should be normalized to obtain the Stanton number, C_H, for a given Mach number and at least three values of Re_x. To ensure a degree of conservatism, caution should be exercised in the extrapolation of data. Specifically, the range of Re_x should be chosen to ensure that laminar data are not extrapolated into the turbulent regime, or vice versa. References 8 to 15 present acceptable testing methods and instrumentation.

References 43 and 44 present test data and two different techniques that may be used for measuring mixing rates and concentrations of gases vented into flowing streams. The external-flow parameters to be duplicated are the local Mach number and the local Reynolds number. The mass flow rate-per-unit area (ρv) of the vented gas should be duplicated.

4.3.2 Exhaust-Plume Heating

The accuracy in predicting plume heating (impingement, radiation, and base heating) varies between 10% and about 100%, depending upon the particular problem. Tests are desirable in most cases and are mandatory for base heating, where predictive procedures rely upon experimental data. Since the detailed vehicle geometry affects the heating to a marked degree, tests should be conducted on the specific geometries being considered. Plume testing is difficult and requires careful attention to experimental technique in order to obtain meaningful results. Since local plume heating rates can vary rapidly as test conditions are changed, preliminary analytical studies to select conditions, measurement points, and instrumentation ranges are recommended.

In all plume testing, simulation of the nozzle-exit-plane flow conditions and the critical flow conditions induced by the external stream and the surrounding vehicle structure is required. Simulation of the interaction between the vehicle's external flow field and the plume is necessary for testing plume heating below about 60 km altitude. Above 90 km altitude, high-vacuum facilities are needed; the required back pressure depends upon the particular heating problem. Between 60 and 90 km altitude, consideration should be given to the need for simulating external flow-field effects. With an external flow field, the stream Mach number and the ratio of plume-exit to free-stream total pressure should be reproduced. The plume and free-stream total temperatures usually need not be simulated exactly, although exact simulation is desirable if possible. In tests in which the free stream is simulated, the plume and free-stream specific-heat ratio should be simulated. Useful information can be obtained by comparing cold- and hot-flow tests.

It is usually not possible to simulate plume composition exactly, especially the important particulate constituents such as soot concentrations and their distributions. Thus, where radiative heat fluxes are a significant contribution to the overall plume impingement effects, it is important to formulate a test program which will produce conservative but realistic design information. The methods and instrumentation of references 34, 39, and 40 should be used for tests of plume impingement; the remarks in Section 4.3.1 are also applicable here.

The procedures described in reference 41 are generally acceptable for base heating tests. Such tests should be conducted over a range of external pressure which simulates the range of operational altitudes of the vehicle. The minimum number of test altitudes depends upon the design problem. References 36 and 45 contain a good description of the effects of altitude on base heating; they should be referred to in the determination of the number of tests required. Reference 38 describes acceptable test procedures and instrumentation for flight vehicles and presents base heating data as a function of altitude on recent flights; reference 42 describes recently developed procedures that are acceptable for investigating base flow fields in model tests, as well as measured data.

Straightforward procedures can be used to scale convective base heating rates, since Reynolds number is the principal scaling parameter. However, if appreciable secondary combustion occurs in the base region, the scaling problem can be more complicated. Scaling of radiative contributions to base heating is very complicated. The only generally applicable scaling procedure is to investigate the model flow field in detail, as well as the radiative heat-transfer rates, scale up the flow field (accounting for any local differences in composition between the model and the vehicle flows), and recompute the radiation for the full-scale situation using the methods of reference 35. Any realistic simulation of radiative heating rates in model tests must be regarded as fortuitous. In the absence of complete information on the effects of scale on base heating rates, the vehicle designer should employ conservative approximations in scaling the model results.

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SP-8001	(Structures)	Buffeting During Launch and Exit, May 1964
SP-8002	(Structures)	Flight-Loads Measurements During Launch and Exit, December 1964
SP-8003	(Structures)	Flutter, Buzz, and Divergence, July 1964
SP-8004	(Structures)	Panel Flutter, May 1965
SP-8005	(Environment)	Solar Electromagnetic Radiation, June 1965
SP-8006	(Structures)	Local Steady Aerodynamic Loads During Launch and Exit, May 1965
SP-8007	(Structures)	Buckling of Thin-Walled Circular Cylinders, September 1965 Revised August 1968
SP-8008	(Structures)	Prelaunch Ground Wind Loads, November 1965
SP-8009	(Structures)	Propellant Slosh Loads, August 1968
SP-8010	(Environment)	Models of Mars Atmosphere (1967), May 1968
SP-8011	(Environment)	Models of Venus Atmosphere (1968), September 1968
SP-8012	(Structures)	Natural Vibration Modal Analysis, September 1968
SP-8013	(Environment)	Meteoroid Environment Model – 1969 (Near Earth to Lunar Surface), March 1969
SP-8014	(Structures)	Entry Thermal Protection, August 1968
SP-8015	(Guidance and Control)	Guidance and Navigation for Entry Vehicles, November 1968
SP-8016	(Guidance and Control)	Effects of Structural Flexibility on Spacecraft Control Systems, April 1969
SP-8017	(Environment)	Magnetic Fields – Earth and Extraterrestrial, March 1969
SP-8018	(Guidance and Control)	Spacecraft Magnetic Torques, March 1969
SP-8019	(Structures)	Buckling of Thin-Walled Truncated Cones, September 1968

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