Computational Requirements for Hypersonic Flight Performance Estimates

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Among the many new hypervelocity vehicles being considered for development, the air-breathing, single-stage-to-orbit transatmospheric vehicles and aeroassisted orbital-transfer vehicles are going to be designed largely by computational fluid dynamics (CFD). (The nomenclature of CFD is used to encompass a range of related areas such as computational aerodynamics, combustion, rarified gas dynamics, and computational aerothermodynamics.) Errors in CFD, flight-performance estimates, and, consequently, in the specifications for these vehicles need to be sufficiently small to achieve the design goals set for the vehicles. At present, the credibility of the CFD technology, in general, is poor when different forms of the Navier-Stokes equations are used for estimating critical design-performance quantities. To improve this credibility, a procedure is presented. This procedure introduces the phrase "programmatic research," the CFD design technology development triad and "code certification." Programmatic research emphasizes performance estimates. In turn, performance estimation requirements largely determine the computational requirements. This triad uses the systems approach (a characteristic of programmatic research) to create a strong interaction between CFD, design, ground-based testing, and flight testing. Code certification can bring order into the process of establishing the credibility of computer codes by insuring compliance to specific requirements. These requirements are primarily set by design sensitivities, physical/chemical realities, and computational sensitivities. Ground-based experiments and flight tests principally help to establish the credibility of CFD results. However, risks are associated with CFD performance estimates mainly because of a lack of quality test data, inadequate modeling of physics and chemistry, and a lack of a satisfactory level of numerical accuracy. These risks need to be estimated with an uncertainty analysis. The preceding procedure is applicable to all speed regimes, not only to the hypersonic speed regime.

Introduction

AFTER a comparative lull in the 1970s, there is now a strong demand to develop hypersonic technology for proposed new space missions requiring vehicles with improved performance, such as transatmospheric vehicles (TAV), entry vehicles, and aeroassisted orbital-transfer vehicles (AOTV). This demand has come about because the hypervelocity flight experience with the Space Shuttle and Apollo missions, and several planetary probes, has been limited. The National Aero-Space Plane (NASP), horizontal takeoff and landing (HOTOL) launch vehicle, SÄNGER, HERMES, HOPE, and the aeroassisted flight experiment (AFE) vehicle are examples of new types of vehicles.

Among all these vehicles, the need for development of hypersonic technology is the greatest for the NASP. It is going to be largely designed by CFD because of aeropropulsion issues that cannot be duplicated in ground-based facilities. Reusable AOTVs also depend mainly on CFD because of chemical exchange processes that cannot be simulated in ground-based facilities. Limitations of these facilities place a major responsibility on the discipline of CFD. The objective of this paper is to suggest a way for meeting this responsibility. The computational requirements for hypersonic flight performance estimates are discussed, and a procedure for fulfilling these requirements is outlined.

Technology development is "the systematic use of the knowledge and understanding gained from scientific research directed toward the production of useful materials, devices, or methods, including design and construction of prototypes and demonstration processes."[1] Technology development is a product of programmatic research and applied research. These types of research differ from basic research, fundamental research, exploratory research, and industrial research (see Table 1). (Although it is customary to broadly classify research into basic and applied areas, the classification in Table 1 is based on the specific motivation of the research.) When a specific program involves conceptual, preliminary, and technology demonstration design (or final design), etc., and it is also constrained with cost and time, it is primarily programmatic research that leads to the development of the enabling technology.

There are three main characteristics of this programmatic research (see Fig. 1). First, it is focused research directed toward achieving the objectives of a mission. Second, because of the emphasis on achieving these objectives, this research is conducted with a top-down approach. Third, programmatic research is conducted in a framework of the systems approach. That is, different technologies/disciplines interact strongly to seek the required knowledge. To a large extent, this type of research is exemplified by the research pursued in the NASP program. In the development of a technology, programmatic research is generally more effective and efficient than applied research. This is because the latter type of research is primarily characterized by limited focus, a bottom-up approach, and weak interactions between different technologies or scientific disciplines.

The objectives of a hypervelocity mission are likely to be achieved if errors are sufficiently small in estimation of flight performance and, consequently, in specifications for the vehicle. CFD research and technology development efforts for design applications therefore must emphasize the end result: flight performance estimates. This emphasis necessitates the top-down approach, focused research, and the systems approach. That is, the development of the CFD design technol-

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Table 1 Types of research

	Basic	Fundamental	Exploratory	Applied	Programmatic	Industrial
Time required to show industrial utility	None	None	None	>8 years	4–8 years	0–3 years
Motivation	Seek knowledge for the sake of knowledge	Seek useful knowledge	Identify perceived usefulness	Pursue specific practical objectives	Systematically seek and use knowledge for a mission	Achieve economic benefits and meet demand
				Perceived crisis and profit		
Institution	Universities (low cost) Laboratories (high cost)			Laboratories and universities	Industry and laboratories	Industry

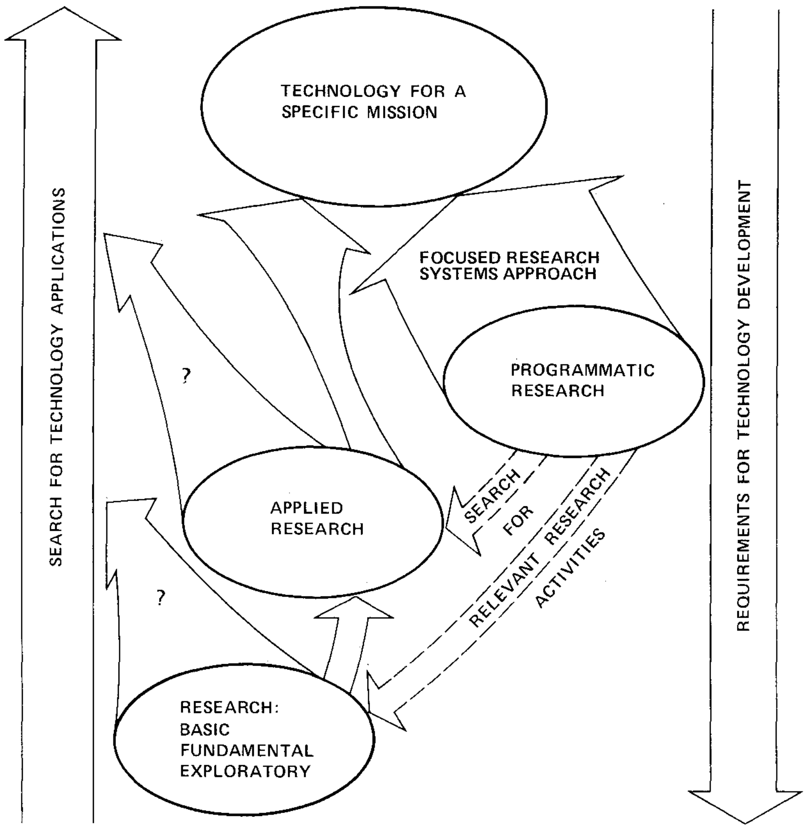

Fig. 1 Programmatic research vs applied research for technology development.

ogy requires the programmatic type of research, whether or not it is associated with a program. Here the system approach requires a strong interaction between the following technologies with CFD: design, ground-based testing, and flight testing (see Fig. 2).

Physical and Chemical Phenomena

The characteristics of the hypersonic environment around a vehicle depend on the vehicle and its flight trajectory. The NASP is a single-stage-to-orbit (SSTO) TAV with air-breathing propulsion. This plane uses scramjets for an extended period of hypervelocity flight to orbital speed. Much of the forebody of this vehicle is used to condition the air going into the engine, and the afterbody is part of the exhaust nozzle for the engine. The entry corridor of this vehicle is similar to the Space Shuttle entry trajectory, but this vehicle flies at a much lower altitude for nearly its entire ascent trajectory. The following are the principal phenomena taking place during this flight: strong shock waves, viscous/inviscid interactions, shock boundary-layer interactions, transition, turbulence, relaminarization, thermochemical equilibrium, chemical nonequilibrium, thermal nonequilibrium, combustion, mixing, radiation, surface catalyticity, and departures from continuum flow. On the other hand, an AOTV uses aerodynamic forces produced by grazing passes through the upper atmosphere to achieve the transition to a different orbit by deceleration or directional change. As it grazes the upper atmosphere, much of the flow surrounding the vehicle is in thermochemical nonequilibrium and most of the preceding phenomena are expected.

Requirements for Performance Estimates

To effectively use CFD in design, particularly for estimating performance quantities, the following items need to be considered: credibility of CFD, design sensitivities, test uncertainties, risk assessment, and consistency in determination. Performance estimates introduce requirements related to these items. These requirements (Fig. 3) are stated and briefly explained below. How these requirements can be fulfilled is discussed in the following sections with a few examples.

First, the CFD flight-performance estimates need to be credible. This requirement is satisfied by the use of "certified" codes, duplication of flight physics/chemistry, and by insuring a high level of numerical accuracy. (The word "certified" will be explained subsequently.) Note that establishment of this credibility lends credence to engineering methods that are improved by corresponding CFD methods. Second, it is necessary for computational fluid dynamicists to know how accurately performance quantities need to be estimated. This requirement is satisfied by quantifying the sensitivity of specifications for the aircraft to performance quantities and the sensitivity of performance quantities to computational errors. An example of specification is the takeoff gross weight. Third, the uncertainties of test data must be taken into account while ascertaining how well codes can predict test data. Test uncertainties involve instrumentation errors, flow composition and quality, and deviation from flight physics/chemistry in the case of ground-based tests. Fourth, safety factors to be used in design resulting from errors in estimated performance quantities are required. These factors are determined by the assessment of the CFD risk associated with the estimated performance quantities. This assessment requires identification of avoidable and unavoidable risks and quantification of these risks for the purpose of determining these factors. Fifth, the consistency condition requires that the designers, computational fluid dynamicists, and experimenters (people conducting ground-based experiments and flight tests are grouped together, and are called experimenters) use the same methodology for estimating performance quantities. (Nothing more will be said about this requirement, as it is an obvious one.)

CFD Design Technology Development

In the 1970s and the first half of the 1980s, the emphasis was on developing CFD design technology for transport planes, and applied research activities in CFD were focused on issues related to computations of transonic flows. The status of CFD method developments and applications has been reported and suggested by a few, recent reports.[2-6] These references indicate, in general terms, what CFD can and cannot do in aeronautics.

The state of the art is such that numerical solutions of different forms of the Navier-Stokes equations have poor credibility, in general, for estimating critical design-performance quantities. A number of factors have caused this low credibility rating: a lack of understanding or inappropriate modeling of the physics/chemistry, inadequate numerical accuracy, limited availability of quality test data, limited computer resources, a lack of code certification (defined below), and improper use of developed computer codes. Therefore, the following questions arise: How can this credibility be improved? How should research in CFD be conducted for design applications?

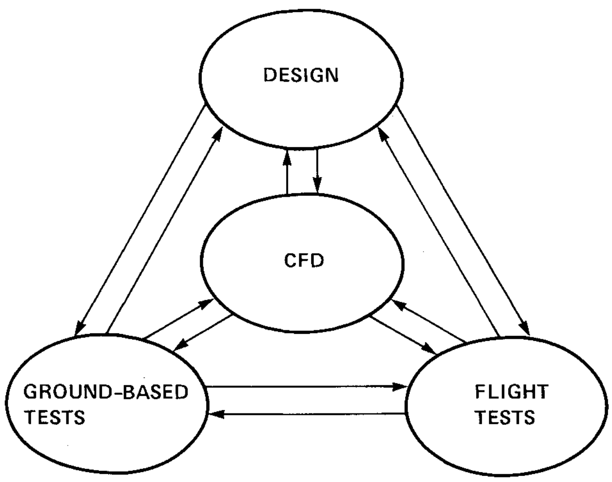

Fig. 2 The systems approach for CFD design technology development.

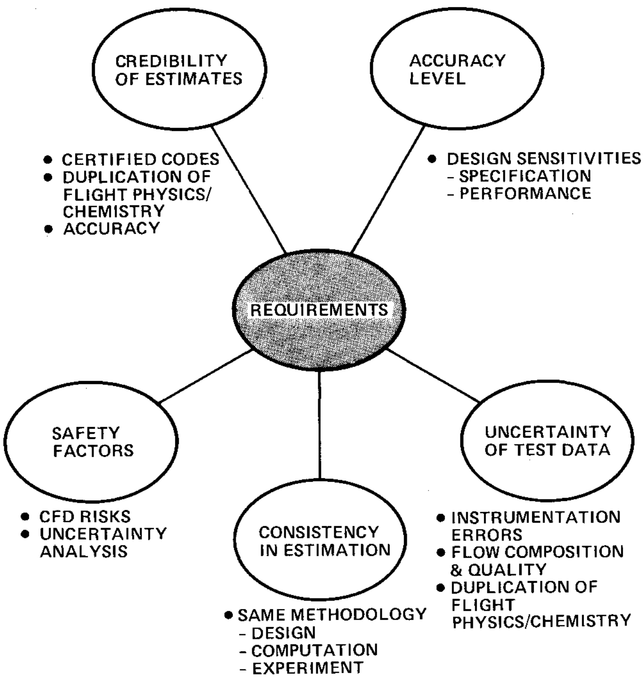

Fig. 3 Requirements for performance estimates.

Recently, a new era of computational hypersonic aerodynamics has begun. For the airbreathing SSTO TAVs, and AOTVs, primarily some form of the Navier-Stokes equations and higher-order equations are required. Another question that arises is the following: How should the necessary CFD technology be developed for use by the hypervelocity vehicle designers?

In the past, the following four similar models have been formulated showing how computational design capability is developed through different phases with increasing levels of payoff.

1) The National Research Council (NRC) model I[2] considers three stages in a development cycle for a major computational capability for aircraft design. A research stage (conception, algorithms, pioneering applications); a development stage (assembly technology components, user requirements, engineering applications); and a usage stage (mature design capability, technology realization, and innovative usage).

2) The NRC model II[3] considers five phases in the CFD development cycle (Fig. 4). The first phase is the development of enabling technology. In the second phase, capabilities and limitations of technology are understood through demonstrations. The third phase is called "putting it all together." The fourth phase is learning to use CFD effectively. The last phase produces a mature capability. This capability is generally expected to produce codes that can be routinely used by designers in complex design applications.[7]

3) Based on the role of ground-based experiments in developing CFD, three types of codes are identified (Fig. 5): research, pilot, and production codes (for design).[8] Research codes are developed into pilot codes, which in turn are developed into production codes.

4) The evolution of CFD design methodology[9] has four parts: algorithm development (basic research, pilot applications, numerical experiments); pioneering implementations (intensive programming, solution checkout, convergence studies, experimental correlations, empirical improvements); technology development (trial applications, feedback to devel-

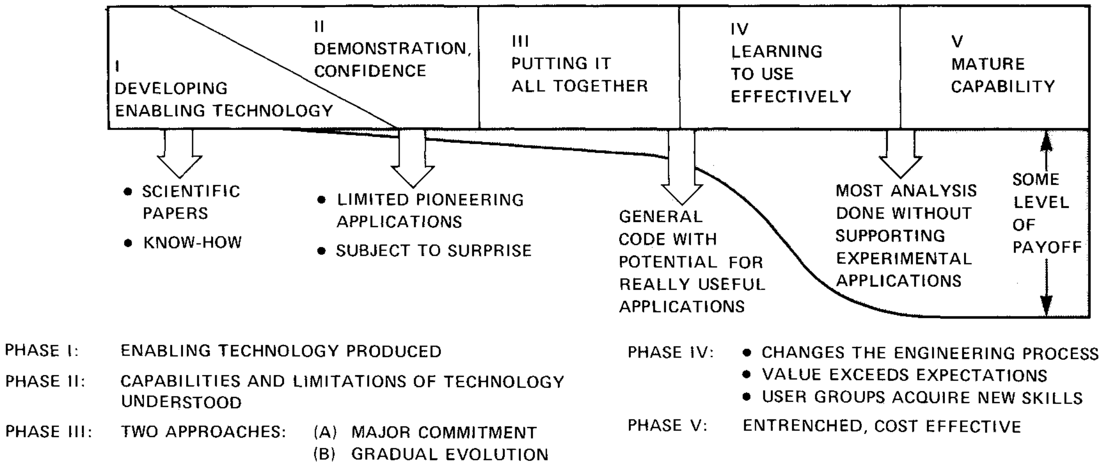

Fig. 4 The CFD development cycle[3] (courtesy of Aeronautics and Space Engineering Board, National Research Council).

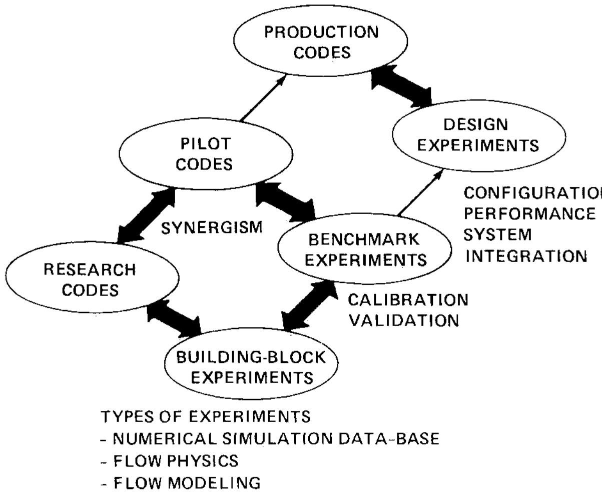

Fig. 5 Role of experiment in developing CFD.[8]

opers, design and test); and project usage (product applications, feedback to developers).

Models 1 and 2 produce a general code with potential for useful applications. These models generally result in a designer's "toolset"[7] (model 2, phase 5). Just as it is difficult, if not impossible, to develop a practical, universal turbulence model, the development of a general code is not possible or practical. This is likely to be the case until comprehensive knowledge-based systems have been developed.[10,11] As for the present and foreseeable future, generically developed computational Navier-Stokes technology is not applicable with confidence, for example, to the B-2 or B-767 aircraft without tailoring this technology for these aircraft. CFD technology developed for the design of the F-16 aircraft is not appropriate for the design of the X-30 aircraft, and vice versa. Although both air-breathing SSTO TAVs and AOTVs are hypervelocity vehicles, they require different CFD design technologies. However, the CFD technology developed for the L1011 aircraft is applicable to the DC-10 aircraft. Essentially, the design requirements of different types of aircraft are different, necessitating different computational requirements.

Model 3 appropriately emphasizes the role of experiments in CFD technology development. This model explicitly considers interactions between CFD and ground-based experiments.[8] These interactions are essential for developing confidence in CFD technology. Only recently some examples of such interactions have occurred. However, the following are shortcomings of this model. First, building-block and benchmark experiments are appropriate in ground-based facilities, but not in flight tests. Such tests involving design experiments are not considered. Second, there is a synergism between research codes, pilot codes, building-block experiments, and benchmark experiments, but this synergism does not include production codes and design experiments. Consequently, this model does not explicitly account for new, or combinations of, phenomena associated with a design and its mission in developing research codes and pilot codes. Pilot codes develop into production codes. There is no feedback from production codes to pilot codes. (Note the directions of the arrows in Fig. 5.) In addition to these shortcomings, the word "calibration" when used in this model does not mean the same thing as when used to define "CFD code calibration" by an ad hoc committee on CFD Validation of the Aeronautics Advisory Committee of NASA.[7] Design-like geometries are not considered in benchmark experiments.

Model 4 comes somewhat close to being a useful model for developing CFD technology for design. There are two specific drawbacks of this model.[9] First, much more research and development need to be done to transfer the relevant CFD methods and codes developed by research activities conducted in parts 1 and 2 into a technology that is useful to the designers. Second, the understanding of design-related physical insight, mathematical formulations, and engineering methods is generally weak among computational fluid dynamicists. The effects of these drawbacks can be substantially reduced if the designers are made full partners in the CFD design technology development process.

The successful use of a technology in developing a product is the ultimate proof of the utility of research ideas on which this technology is based. During the first half of the CFD design technology development process of the preceding models, the design aspects of an aerospace vehicle are not considered. Therefore, only a few research ideas conceived in this half are actually utilized during the second half when these aspects are addressed. In model 1, design requirements are considered in stage 2. Model 2 does not specifically address design issues, but it expects that the outcome of the process is for the designers. In model 3, the last phase introduces design. In model 4, part 3 first pays attention to the design. Thus, there is inefficiency in developing the preceding technology with the bottom-up approach followed in these models (see Fig. 2). This inefficiency can be practically eliminated with the top-down approach.

Considering the definition of technology development in the Introduction, CFD design technology development begins with the knowledge and understanding gained from (basic, fundamental, exploratory, and to a large extent applied) research, rather than with basic research. Essentially, this definition suggests that the first half of the process depicted in the preceding models is not a part of this technology development process. In addition to the knowledge and understanding already available, there may be a need for further programmatic research that would lead to the development of the required technology.

A new model is proposed for developing CFD technology for design applications (see Fig. 6). The computational fluid dynamicists, experimenters, and designers formulate requirements for this technology and develop it. First, this approach explicitly considers possible vehicle designs right from the beginning of the development process. Specific designs, relevant physics/chemistry, design sensitivities, analytical and engineering methods, numerical accuracy, and programming logic guide the choice and development of CFD methods and codes. Second, both ground-based and flight tests are integral parts of the CFD design technology development process. The credibility of this technology is to a great extent dependent on design-related tests. With respect to the comparison of computed results and experimental data, there are three levels of certification: building-block and benchmark experiments, design-like experiments, and flight tests. Third, the designers use the available codes while this technology is being developed; they provide feedback to the computational fluid dynamicists for making it effective and useful; and they (along with computational fluid dynamicists) interact with the experimenters.

The preceding CFD design technology development triad forces strong interactions among computational fluid dynamicists, designers, and experimenters. It emphasizes focused research for achieving the ultimate purpose (top-down requirement) of developing this technology; namely, estimation of performance quantities.

Code Certification

One of the following phrases, "code validation," "code calibration," or "code verification," is often used in a discussion of a CFD code. These phrases mean different things to different people. Sometimes these phrases have been used interchangeably. At times, the purpose of the activities associated with these phrases is to verify physics rather than to verify a computational tool trying to represent the physics. Also, these phrases have been loosely used to describe a procedure of comparison, primarily between computed results and experimental data. But the intent firstly should be to convey either a process of establishing the credibility or the determination of the degree of credibility of the code.

Sometimes, based only on limited evidence and without indicating whether the level of agreement between computed results and experimental data is acceptable or not, the code is declared to be a validated/calibrated/verified code. Further, if users decide to use, for example, the validated code, they still have to convince themselves that the code is validated, and frequently they are unable to do so.

Recently, an ad hoc committee on CFD Validation of the Aeronautics Advisory Committee of NASA defined the first two of these phrases[7] as follows:

CFD Code Validation: Detailed surface and flowfield comparisons with experimental data to verify the code's ability to accurately model the critical physics of the flow. Validation can occur only when the accuracy and limitations of the experimental data are known and thoroughly understood and when the accuracy and limitations of the code's numerical algorithms, grid-density effects, and physical basis are equally known and understood over a range of specified parameters.

CFD Code Calibration: The comparison of CFD code results with experimental data for realistic geometries that are similar to the ones of design interest, (this comparison is) made in order to provide a measure of the code's capability to predict specific parameters that are of importance to the design objectives without necessarily verifying that all the features of the flow are correctly modeled.

The preceding definitions are explained, and a CFD validation philosophy is presented by Bradley.[7] As will be explained, these definitions need to be modified. Further, these definitions by themselves are not enough. There has to be an agreed-

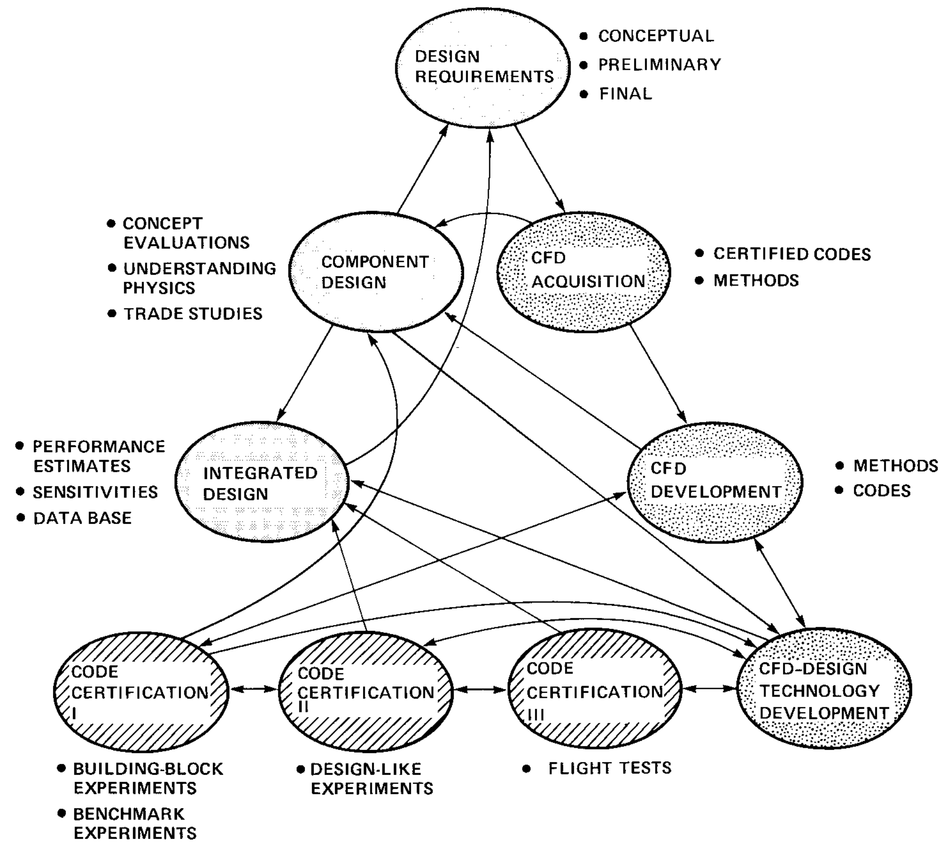

Fig. 6 The CFD design technology development triad.

upon comprehensive and systematic process to insure and improve the credibility of the computed results, and consequently that of the corresponding computer code, and to establish the limits of its application.

The following observations relate to the preceding definition of code validation. 1) It sets forth a stringent requirement for a code to be a validated code. 2) None of the existing Navier-Stokes codes is a validated code by this definition. 3) Different utilities of the code have different requirements. Acceptable accuracy and limitations, usually, depend on these requirements. 4) This definition considers a range of specified parameters but not a range of specified body shapes or geometries.

The following observations relate to the preceding definition of code calibration. 1) The phrase "to provide a measure of the code's capability to predict" is not quantified. A measure by itself is not enough. Is the measure going to remain the same, either over a range of specified parameters or when actual design geometry is considered? 2) By this definition, any comparison between computed results and experimental data for a design-like geometry results in a calibrated code! 3) Although it is not explicitly mentioned, it appears that design-like geometries are partial geometries of a complete design.[7] 4) The restriction on design-like geometries is limiting the role of code calibration.

No one seems to have defined code verification. Blottner[12] has implied that verification of a code is "to convince the user that the code is accurately solving the given physical problem."

Some concerns regarding the preceding definitions follow. 1) Suppose there are validated/calibrated/verified codes. When these codes are put together in a CFD design technology, there is still a need to establish the credibility of this technology. 2) These definitions do not consider how to gain confidence in a code if there are no experimental data (ground-based or flight). 3) Apart from these definitions, no standard exists to suggest what activities need to be carried out to establish the credibility of a code, how these activities are conducted, who should conduct them, or how to document the outcome of these activities, and so forth. 4) If a code is claimed to be validated/calibrated/verified without either fulfilling some generally accepted standard or independently verifying this claim, it cannot be taken seriously. 5) Mistakes in computer codes may have serious and costly consequences. No provision is made in the aforementioned definitions to check the logic of the code, which entails the following items: whether computer instructions do correspond to mathematical models representing physical phenomena, and whether the algorithm of the code is appropriate to execute these instructions, numerical methods, input/output instructions, and so forth.

The previous observations and concerns suggest the establishment of a standard. The primary purpose of the standard is to guide the process of establishing the credibility of a code. This process is called code certification,[13] and it is defined here as the process of evaluating a computer code in terms of its logic, numerics, physics/chemistry, and the results, to insure compliance with specific requirements.

This choice of the word "certification" is appropriate because in the aerospace industry it is customary to certify reliability and limits of applicability. Examples of certification are flight certification, structural certification, etc. In contrast to the definitions of code validation, code calibration, and code verification, the definition of code certification separates the process and the requirements for establishing credibility and limits of applicability of a code. These requirements may change, but the process is the same. The requirements are determined by the computational fluid dynamicists, designers, and experimenters. Once a code has been certified, the designers, who are the customers, can use it confidently.

Five example sets of code certification requirements along with the range of applicability will be presented in this paper. While maintaining the essence of the aforementioned definitions of code validation and code calibration, they are modified and presented in terms of requirements. Further, two additional sets of requirements are introduced, keeping in mind that the focus of CFD design computations is on performance estimates. Also one other set of requirements is presented to cover the situation when there is a lack of sufficient and necessary experimental data. Actually, each set contains a partial set of requirements. What needs to be done to complete these requirements is discussed subsequently.

Validated Code

A code is said to be validated if the following conditions are met. 1) A comparison of computed, detailed surface and flowfield data with experimental data shows that the code is able to accurately model the critical physics/chemistry of flow. 2) The accuracy and limitations of the experimental data are known and are thoroughly understood. 3) The accuracy and limitation of the code's numerical algorithms, grid-density effects, convergence effects, and physical/chemical basis are known and are thoroughly understood. The range of applicability of the validated code depends on the range of flow parameters and/or body shapes for which the code has been validated.

Design-Validated Code

A code is said to be design-validated if the following conditions are met. 1) A comparison of computed, performance quantities with experimental performance data shows that the code is able to accurately predict these quantities. 2) The accuracy and limitations of the experimental performance data are known and are thoroughly understood. 3) With respect to performance quantities, the accuracy and limitation of the code's numerical algorithms, grid-density effects, convergence effects, and physical/chemical basis are known and are thoroughly understood. The range of applicability of the design-validated code depends on the range of flow parameters and/or body shapes for which the code has been validated.

Calibrated Code

A code is said to be calibrated if significant, computed results agree with corresponding experimental data, with or without adjustment of computational (physical/chemical and/or numerical) parameters for achieving this agreement, and without necessarily verifying that all other features of the flow are predicted accurately. The range of applicability of the calibrated code is fixed by the similarity of body shapes and flow physics/chemistry to those existing during the calibration process. The code is calibrated only for the computed quantities that were calibrated with experimental data.

Design-Calibrated Code

A code is said to be design calibrated if computed performance quantities agree with corresponding experimental estimates, with or without adjustment of computational (physical/chemical and/or numerical) parameters for achieving this agreement, and without necessarily verifying that all other features of the flow are predicted accurately. The range of applicability of the design-calibrated code is fixed by the similarity of body shapes and flow physics/chemistry to those existing during the calibration process. The code is calibrated only for the computed performance estimates that were calibrated with experimental data.

Method-Confident Code

A certification by computer simulation experiments is achieved if the following conditions are satisfied. 1) A systematic determination of numerical accuracy of performance quantities is carried out. 2) The computed physics/chemistry is qualitatively satisfactory. 3) A part of physics/chemistry modeled in the code has been verified by ground-based and flight

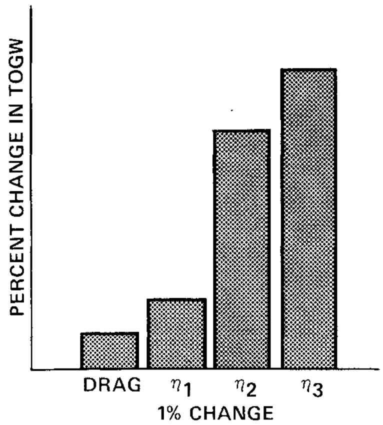

Fig. 7 Performance sensitivities to takeoff gross weight.

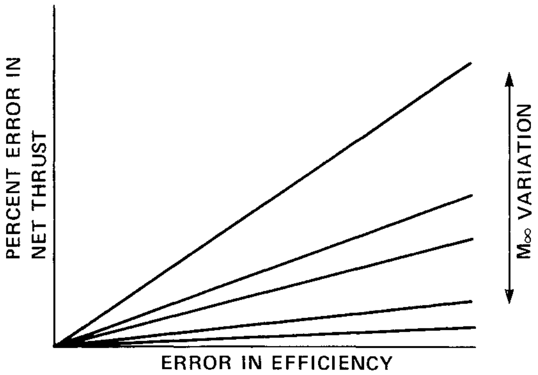

Fig. 8 Sensitivity of component performance to overall performance.

experiments, limited to this physics/chemistry. The range of applicability of the method-confident code is fixed by the similarity of physics/chemistry and body shapes.

In case it is not possible to compare computed results with experimental data, then the certification is done by the method-confident requirements. There are two aspects of a method, numerics and physics/chemistry. On the whole, there is more understanding about numerics than about physics/chemistry. The strategy is to "cut the losses," whenever possible. Confidence is gained in a code by a rigorous requirement of numerical accuracy and a circumstantial evidence concerning the appropriateness of the physics/chemistry that is modeled in a code. With requirements 1 and 2 of the method-confident code, only requirement 3 of a design-validated code is essentially satisfied. An example of requirement 3 of method-confident certification is the following: The ground-based facilities are limited for duplicating the hypervelocity flight conditions. If a code has been certified with the data from a ground-based facility, it may be applied to flight conditions, provided that some of the critical physics/chemistry is the same in the experiment and in flight and that other critical physics/chemistry not duplicated in the facility appears to be acceptable for flight conditions.

A computer code may be certified by another certified code. But a comparison of results of different, uncertified codes solving the same governing equations and the same physical problem does not necessarily establish confidence in any one of these codes. All of them may produce similar or different results. Similar results may all be erroneous. Further, a certified code has a domain of applicability. If such a domain is not established, but isolated "point" checks (in terms of flow parameters and body shapes) are made, then the code is labeled as a point-certified code.

Mainly, two important types of requirements are not listed in the preceding sets of requirements: logic and level of accuracy. The requirements of logic, in part, depend on the types of applications. In the development of CFD design technology, the requirements concerning the acceptable level of accuracy are determined by the designers, experimenters, and computational fluid dynamicists for that type of application. Further, both sets of requirements may change somewhat as one proceeds from a conceptual design, to a preliminary design, to a final design of a new type of vehicle. Note that once the CFD design technology has been developed for this vehicle, it is, essentially, the appropriate technology for this type of vehicle.

Development of a standard for certification of application codes used in the aerospace industry is recommended. This standard would provide guidelines for code certification in terms of how to set up and upgrade requirements, what activities should be conducted for certification, who should conduct these activities, documentation of outcomes of activities, and so forth. This standard may be developed by considering the standard that is formulated for guiding the "verification and validation" of scientific and engineering computer programs for the nuclear industry.[14]

Design Sensitivities

The specification of a vehicle in terms of takeoff gross weight (TOGW), trajectory, speed, etc., depends on performance quantities such as those associated with external aerodynamics, aerothermodynamics, stability and control, and propulsion. Because the errors in performance quantities change the specifications for the vehicle, design sensitivities provide requirements for the acceptable level of accuracy of performance estimates. Some of these requirements for code certification are presented here.

As an illustration, consider the design of an SSTO air-breathing TAV. The TOGW depends on performance estimates (such as the vehicle drag and the performance of the inlet, the combustor, and the nozzle). An error of 1% in these estimates at some point along the trajectory can be translated into some percentage of change in the TOGW, as illustrated in

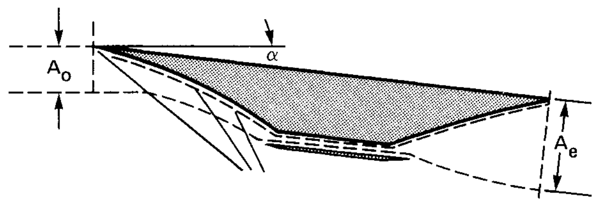

Fig. 9 Control boundary for force accounting.

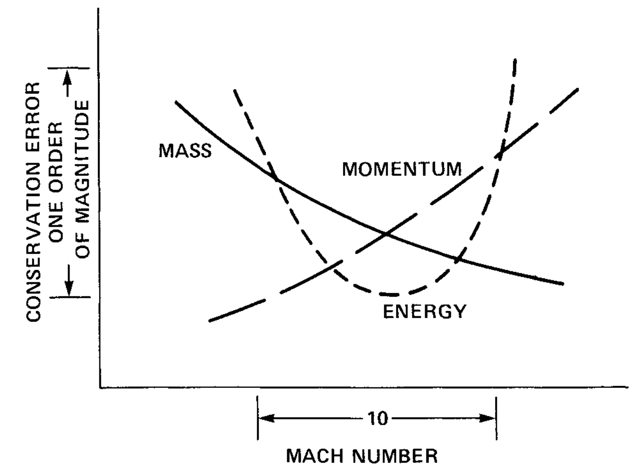

Fig. 10 Variation of conservation error with Mach number.

Fig. 7. (Figure 7, and others like it in this section, are hypothetical figures.) The designer may require that the TOGW should not change by more than 5%. It is then possible to determine the level of accuracy required for the computation of drag and propulsion performance estimates. (Note that, in a related discussion, Gregory[15] has analyzed the first-order gross weight ratios and associated sensitivites by using a blend of the rocket equation and the Breguet range equation.) This process of determining sensitivities may be repeated at different points along the trajectory (Fig. 8).

The propulsive forces are deduced with the aid of one or more momentum equations. A fluid control boundary is selected such that some part of the boundary is in contact with the physical surfaces upon which the fluid is exerting force (Fig. 9). The momentum through parts of the control boundary that are not in contact with surfaces needs to be computed accurately, otherwise, the propulsive forces would be in error. Since the computation of momentum depends on mass and energy equations of the Navier-Stokes equations, an accurate solution of the latter set of equations is required such that all the conservative variables are conserved. The level of conservation required and that achieved with a computer code may vary along the flight trajectory. Further, the level of conservation achieved for mass may differ from that achieved for momentum and energy (see Fig. 10).

A design consideration of an air-breathing TAV is the amount of air mass captured by the inlet of the scramjet engine. The performance of the engine is highly sensitive to this mass capture. A computer code that does not conserve mass to a level required by the designer, when the flow is computed from the nose of the vehicle through the engine, is obviously not acceptable. A possible effect of mass conservation error on the efficiency of a propulsive component is illustrated in Fig. 11. On the other hand, the conservation of mass should not be so crucial if surface heat transfer is of concern to the designer.

Nose-to-tail computations of flows past and through an air-breathing TAV are conducted by breaking up the whole computation domain into a number of small manageable domains. The requirement for conservation variables across boundaries of computational domains is as essential as it is within each domain.

Because conservative variables must be conserved, a requirement arises for choosing a computer code or a numerical method for computing propulsive performance quantities. The error in conservation of mass is higher for codes using finite-difference techniques than for those using finite-volume procedures. Apparently this is because the finite-volume grid system is better suited for conserving conservation quantities than are finite-difference grid systems.[16] In the limit of the spatial grid size going to zero, a consistent discretization, either a finite difference or a finite volume, would not have any conservation errors. In practice, this limit cannot be taken. The strategy in development of CFD design technology is to cut the losses whenever possible. Just as it is preferable to use affordable, higher-order numerical methods rather than lower-order methods and to use conservative-law rather than nonconservative-law forms of governing equations, the design requirements suggest the use of finite-volume grid systems.

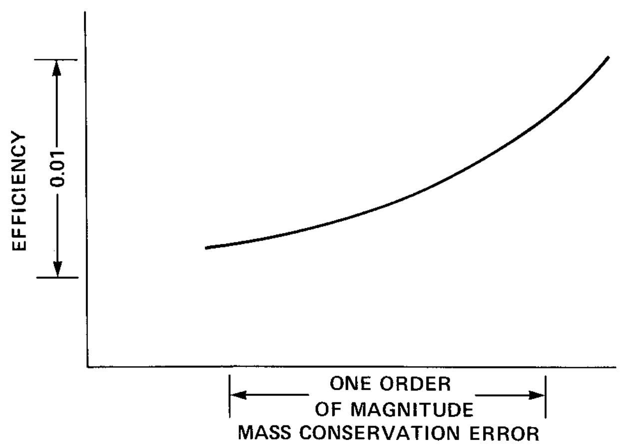

Fig. 11 Sensitivity of mass conservation error to a performance estimate.

For a given grid system, conservation checks and the level of error in conserved variables provide a measure of the quality of results. But computed performance quantities need to be independent of the grid system. This is another example of computational sensitivity. The acceptable degree of grid dependence is again dictated by design requirements.

On the other hand, the AOTVs will use aerodynamic characteristics to execute orbital maneuvers and to reduce the amount of propellant required to make orbital changes. These maneuvers take place in a severe aerothermodynamic environment. Accurate computations of these characteristics and environments are major design requirements. In particular, the trim angle and pitching-moment coefficient will determine the stability and control needs of these vehicles, and the surface temperatures will fix the structural requirements and payload. Sensitivities of these quantities to numerical errors and physical modeling error, and consequently to gross weight, can be determined to establish the code certification requirements, just as previously illustrated.

Ground-Based Experiments

The objectives for conducting tests may be one of the following: 1) understanding of physics and chemistry, 2) concept verification, 3) design data, 4) exploratory, 5) code certification, or 6) a combination of these objectives. The quality and quantity of data required depend on the objective. From the point of view of CFD, the interest is in data for code certification and understanding of phenomena.

A code certification activity can be carried out properly if the following conditions are met. 1) Flow quantities at the boundaries of the computational domain are available. 2) Relevant and sufficient quantities of qualitative and quantitative data are taken. 3) A data uncertainty (bias and precision) analysis is carried out. 4) Relevant performance quantities are measured in design-like experiments. 5) The same model is tested, and the same types of data are collected, in at least two different facilities. 6) Power-on tests are required when appropriate. 7) Redundant data are available. 8) Independent evaluation (certification) of the quality of data is done. In item 2, the relevancy and sufficiency are determined by the code certification requirements. Fulfillment of these requirements would generally necessitate nonintrusive flowfield measurements and flow visualization.

The computational fluid dynamicists often certify codes by comparing pressure distributions from experiments with those from computations. Certification based primarily on this requirement is not satisfactory because these distributions are relatively easy to predict. On the other hand, when the experimenters conduct experiments for code certification, often sufficient data are not collected, and the uncertainty of these data is not determined.

Until recently, there has been poor interaction between computational fluid dynamicists and experimenters. There are a number of ways the computational fluid dynamicists can assist the experimenters. The qualitative (and possibly quantitative) design of model support and other devices and their interference effects can be obtained with CFD. The computational fluid dynamicists can help determine the type, quality, and quantity of data for code certification. The experimental flowfields can be computed before conducting the tests so that instruments for measurements may be properly placed. Pretest computations can make the experimental test matrix more relevant and less of a "fishing expedition." Further, computed results can help to fill gaps in the experimental data base. This

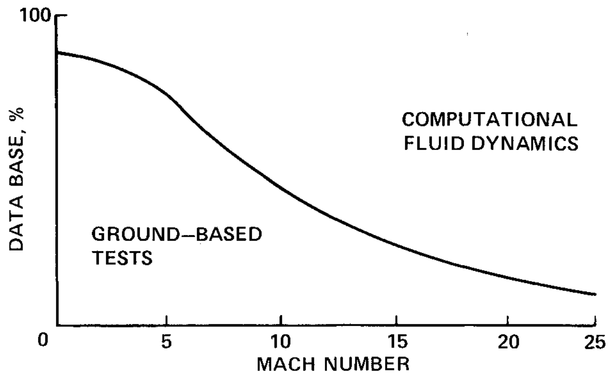

Fig. 12 Role of CFD vis-à-vis ground-based tests.

augmented data base is useful, for example, when some quantities are to be integrated over some experimental domain in which sufficient data are not available. Apart from providing data for code certification, the experimenters can specify certification requirements regarding what phenomena are to be expected in computations.

Because of differences in physics and chemistry between flight and ground-based tests, the shortcomings of ground-based tests must be identified and quantified. For example, it must be established which of the flight phenomena are not going to be simulated in the ground-based facility; and it must be ascertained what simulation requirements are fully, partially, or not met along the flight trajectory.

In a NRC report,[17] three types of fluid flow testing in the regime above Mach 8 to 10 are identified along with their simulation requirements and current limitations of simulations in general. Aerodynamic testing requires reproduction of force coefficient, pressure, and heating distribution. The simulation method duplicates Mach number and Reynolds number and it relaxes the temperature effect. The facility concerns are real-gas effects, flow equilibrium, and scaling. Aerothermal testing requires duplication of heating rates and full-size hardware. The simulation method duplicates total pressure and temperature, and it relaxes the Mach number effect. The facility concerns are flow composition, test methods, and measurements. Aeropropulsion testing requires conditions for proper chemical reactions, mixing, boundary layers, shocks, and full-size hardware. The simulation method duplicates pressure, temperature, Mach number, and velocity scale. The facility concerns are pressure, size, power, flow composition, test methods, and measurements. There is, therefore, a lack of adequate facilities to simulate fully the hypervelocity flight flows to provide data for code certification.

For air-breathing TAVs, the primary limitation of ground-based testing is that the complete verification of CFD thrust estimates is not feasible. Further, realistic test results for a scramjet engine can be obtained only with full-scale model because the burning length is a significant engine parameter. Currently, such results are not feasible to obtain. At hypervelocities and in low-density environments, the AOTVs experience a combination of nonequilibrium flow effects and high shock layer temperatures resulting in ionization, radiative heating, and wall catalysis effects. These effects cannot be duplicated in current or presently planned ground-based facilities. On the other hand, the primary limitation of CFD is that it is dependent on appropriate modeling of the physics/chemistry of the boundary layer, mixing, and combustion.

The role of CFD vis-a-vis ground testing for the design of an air-breathing TAV appears as follows (see Fig. 12). In the low-speed regime ($0 < M_\infty \leq 3$), ground testing will play a major role. In the midspeed regime ($3 < M_\infty \leq 8$), both ground testing and CFD will play important roles, with the former having a larger share. In the high-speed regime ($M_\infty > 8$), CFD will play a major role. However, the design of an AOTV depends largely on CFD.

Considering a likely flight trajectory of an air-breathing TAV and the capability and limitation of ground-based testing, it appears that code certification (in the absence of flight tests) must meet the requirements of design calibration below $M_\infty = M_{dc}$ and above this Mach number, the requirements of the method-confident code up to M_{oe}, corresponding to the orbital entry. However, the level of confidence in a code would decrease from M_{dc} to M_{oe} because less and less of requirement 2 of the method-confident code would be obvious, and less and less physics/chemistry modeled in the code would be verified (requirement 3). "Sufficient" confidence would be possible only up to $M_\infty = M_{mc}$, beyond which confidence in the code would be built by flight tests. Actual values of these Mach numbers will depend on the design of the vehicle, its trajectory, and what ground-based tests have been conducted to certify codes.

Flight Tests

The ultimate certification of CFD codes for both air-breathing TAVs and AOTVs will come from flight tests. In the case of TAVs, it would come during flight certification; whereas for AOTVs it would come initially during the AFE.

An incremental expansion of the flight envelope of a TAV will verify CFD performance estimates, and consequently certify CFD codes, and at the same time certify the vehicle and establish the confidence in the design. These dual purposes may be achieved as follows. First, the flight-testing envelope is expanded up to a Mach number for which there is a high level of confidence in CFD (say $M_\infty = 5$), and CFD performance estimates and/or flowfields are verified up to this Mach number. Second, the flight envelope is expanded beyond $M_\infty = 5$ incrementally (say $\Delta M_\infty \approx 0.5 - 2$) by determining CFD solutions and then verifying them with flight test data. If verification is not satisfactory, the CFD method is improved, and again solutions are obtained. If the CFD method cannot be improved and if *unfavorable* divergence develops between flight test data and CFD results, the flight envelope is not further expanded and the design is changed. This process is continued until the aforementioned purposes are achieved.

To carry out the preceding flight-test plan for code certification, the design of the TAV must include necessary instrumentation at appropriate locations for obtaining data. All experimental requirements, except item 5, listed in the previous section for conducting a code certification activity are also applicable to flight tests.

The AFE is planned early in the 1990s to gather data for code certification and verification of thermochemical closure models used in codes.

Risk Assessment

The decision to embark on Phase III of the NASP Program and the execution of a flight-test program with reasonable safety require an assessment of risk in estimation of performance quantities and X-30 specifications. This assessment requires identification of avoidable and unavoidable risks. The risks are different in different Mach number regimes. The boundaries of these regimes are defined by some significant change in the flow physics/chemistry. The minimum number of regimes is three: low speed, midspeed, and high speed. The quantification of risks is done with an uncertainty analysis.

There are two types of technical risks. First, there is uncertainty of technical maturity, which entails new concepts, incomplete developments, and lack of integration of new concepts with other existing concepts. Second, there is uncertainty in achieving, which concerns specified technical performance, and operational satisfaction. These types of uncertainty arise when code certification requirements are not completely fulfilled.

The identification of risks and estimating/quantifying them in terms of uncertainty help to determine the probability of success of the mission, margin of safety to be built into the design, and how to expand the flight envelope during flight certification. Sensitivities of performance estimates to numerical and physical/chemical modeling errors are needed, and the uncertainty analysis incorporating these sensitivities is required for estimating risks.

Concluding Remarks

The development of CFD design technology requires programmatic research, characterized by the top-down approach, focused research, and the systems approach. This type of research is generally more effective and efficient than applied research, which is characterized by the bottom-up approach, limited focus, and weak interactions between different technologies or disciplines.

In a broad sense, computational requirements for design performance estimates are the following: credibility of computations, the acceptable level of accuracy, the uncertainty of test data, safety factors, and consistency in determination. The key characteristic of a majority of these requirements is sensitivity. The presented vision of the CFD design technology development triad is essential in fulfilling these requirements. This triad brings together different technologies, CFD, design, and testing (ground-based and flight). The process of establishing the credibility of a CFD code is called code certification, which insures compliance with specific requirements.

In spite of the limitations of the experimental data, designers have been able to design aircraft flying at subsonic, transonic, and supersonic speeds. In the same sense, a design-specific computational technology developed with programmatic research can be used in the design of hypervelocity vehicles.

The days of demonstrations of the Navier-Stokes capability for designs with a limited establishment of the credibility for the results are coming to an end. It has become relatively easy to present such demonstrations. The challenge is to predict the performance quantities to a level of accuracy required for design purposes and to understand and quantify limitations of these predictions, if any. The NASP program and the great interest in AOTVs provide excellent opportunities for facing this challenge.

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