Proceedings of ASME FEDSM'00
ASME 2000 Fluids Engineering Division Summer Meeting
June 11-15, 2000, Boston, Massachusetts

2000-FED-11233

THE NPARC ALLIANCE VERIFICATION AND VALIDATION ARCHIVE

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ABSTRACT

The NPARC Alliance (National Project for Applications-oriented Research in CFD) maintains a publically-available, web-based verification and validation archive as part of the development and support of the WIND CFD code. The verification and validation methods used for the cases attempt to follow the policies and guidelines of the ASME and AIAA. The emphasis is on air-breathing propulsion flow fields with Mach numbers ranging from low-subsonic to hypersonic.

NOMENCLATURE

Roman Letters

C	Constant coefficient
E	Error
F_s	Factor of safety
GCI	Grid Convergence Index
N	Number of grid points
f	Solution value
h	Grid spacing
n	Number of grid levels
p	Order of convergence
r	Refinement ratio

Subscripts / Superscripts

$1,2,3$	Value on fine, medium, and coarse grids
$fine$	Fine grid value
$exact$	Exact value

INTRODUCTION

The successful use and acceptance of computational fluid dynamics (CFD) for aerodynamic analysis in the design environment requires the attainment of acceptable levels of credibility of the CFD simulations. Credibility is attained by demonstrating acceptable levels of error and uncertainty. Errors and uncertainty are assessed through verification and validation. Here verification and validation are given distinct meanings. Verification determines if the programming and computational implementations of the conceptual models are correct. Validation determines if the computational simulation agrees with physical reality.

CFD has matured over the last few decades to become a useful tool for aerodynamic design. With this, the accuracy requirements have become greater. Benek et al. (1998) discusses three levels of accuracy for the use of CFD. The first level involves CFD providing qualitative flow field information and requires the least accuracy. The second level involves CFD providing incremental values to baseline flow field properties. Greater accuracy is possible because errors are assumed to partially cancel. The third level involves CFD providing absolute flow field properties.

For supersonic inlet design activities at NASA Glenn, attaining credibility for CFD simulations meant providing flow field properties at that third level. Along with those properties, some measure of the error bounds was desired. These needs have provided additional motivation for the verification and validation described herein.

Verification and validation of CFD codes and simulations has been an important topic of professional discussions and publications (AIAA Journal, 1998) (Roache, 1998). The ASME and American Institute of Aeronautics and Aerospace (AIAA) have each established policies regarding the reporting of CFD results. The AIAA has formulated a guideline for verification and validation of CFD codes and results (AIAA, 1998).

While the importance of verification and validation are recognized, the reality is that these activities often do not receive the proper attention. Developers are under demands to fix bugs in the CFD code or implement new features. Users are under demands to apply the CFD code to a project according to a tight schedule and budget. Users expect the developers to perform the verification and validation and provide them with assurances of accuracy.

One complexity for CFD verification and validation is that CFD can encompass a very large range of fluid flows involving various gases and liquids with various time and spatial scales. Further the CFD code itself may have a multitude of algorithm and model options to solve the same fluid flow. To attempt a complete verification and validation, one usually has to focus on a narrowed flow regime and set of algorithms and models.

The NPARC Alliance (National Project for Applications-oriented Research in CFD) (Matty and Shin, 1997) recognizes the importance of verification and validation for CFD, as well as, the difficulties mentioned above. From its inception, the Alliance has attempted to address these issues and provide a public forum.

The NPARC Alliance was formed in 1993 by the USAF Arnold Engineering Development Center (AEDC) and the NASA Glenn Research Center (GRC) in response to requests from goverment, industry, and academia for a formal organization for the support, development, and validation of a common CFD code. The Internet web site of the NPARC Alliance is **www.arnold.af.mil/nparc**. The Alliance is open to participation by all entities in the United States.

The Alliance produced several versions of the NPARC code from 1993 to 1996 (NPARC Alliance, 1996). The Boeing Company joined the Alliance, and in 1998, the WIND code (Bush, Power, and Towne, 1998) was initially released, replacing the NPARC code. Currently version 3.0 of WIND is available. The WIND code is distributed free-of-charge as a national resource. The Internet web site for the WIND code is **www.grc.nasa.gov/www/winddocs**.

The NPARC Alliance has traditionally focused on air-breathing, propulsion-related flow fields, especially those of inlets and nozzles, as well as, complete airframes. The Mach number range of the flows can vary from low subsonic to hypersonic. The development of the capabilities of NPARC and WIND have reflected this emphasis. The WIND code solves the compressible, Reynolds-averaged, Navier-Stokes equations for steady-state and unsteady flows. The flow is typically turbulent and modeled with the Spalart-Allmaras or Menter SST models, among others. Various equations of state allow fluids ranging from incompressible fluids with constant properties, perfect gases, to high-temperature gas flows with chemical reactions. The equations are solved on multi-zone, structured grids, which may be overlapping.

The three main tasks of the NPARC Alliance are *Support*, *Development*, and *Verification and Validation*. The Support Team coordinates the release of the software, provides training, assists users in its application, and resolves problems. The Development Team coordinates enhancements to the code and establishes directions for the future development of the code. The Verification and Validation Team coordinates the verification and validation activities of the Alliance.

The primary objective of the NPARC verification and validation effort is to provide WIND developers and users with assurances of the quality of the code. The range of flow fields of interest to the Alliance and the capabilities of the WIND code influence the Alliance's choice of flow fields examined during the verification and validation activities. The verification and validation efforts also support users by providing examples on the usage of the WIND code.

Since the Alliance is open to national entities, the verification and validation efforts are also open. The Alliance has developed a publically-available web site that publishes the results of the verification and validation efforts. The Internet web site is **www.grc.nasa.gov/www/wind/valid**. Contained within the web site is an Archive of cases that examine various flow fields and apply the methods of verification and validation.

While the web site and Archive primarily serve members of the NPARC Alliance, it has also become a resource for the CFD community world-wide. The authors have received e-mail messages from CFD researchers and users throughout the world asking about information within the web site. Usage statistics indicate an active browsing of the site. The Alliance welcomes this and hopes the web site is a useful resource.

The following sections provide background on the approach of the NPARC Alliance towards CFD verification and validation. Central to this are the distinctions between verification and validation. The content of the web site is described with emphasis on the verification, validation, and example cases of the Archive. The discussions provide a broad overview of the Archive and includes comments on our experiences which might be useful to others involved in verification and validation. Specific information on the results from the cases is left to the detailed and dynamic environment of the web pages.

TERMINOLOGY

The terms *uncertainty*, *error*, *verification*, and *validation* have been used above. We now present the formal definitions of each term. These definitions are taken from the "Guide for the Verification and Validation of Computational Fluid Dynamics Simulations" (AIAA, 1998).

Uncertainty is defined as

> *A potential deficiency in any phase or activity of the modeling process that is due to the lack of knowledge.*

A key word is "potential", which indicates that deficiencies may or may not exist. "Lack of knowledge" has primarily to do with lack of knowledge about the physical processes that go into building the model. The WIND code implements several physical models for the flow equations, gas properties, boundary conditions, and turbulence models. The uncertainty may be quantifiable, but if not, it should at least be stated that uncertainties exist. Uncertainty may be determined through validation involving comparison with "real-world" phenomena.

Error is defined as

> *A recoqnizable deficiency in any phase or activity of modeling and simulation that is not due to lack of knowledge.*

This definition implies that the deficiency is identifiable upon examination. The primary errors in CFD are *discretization*, *programming*, *round-off*, and *usage* errors. Discretization errors are those errors that occur from the representation of the governing flow equations and other physical models as algebraic expressions in space and time. Programming errors are "bugs", i.e. mistakes made in programming or writing the code. Programming errors should be addressed by the developer and are discovered by reviewing the lines of code and systematically performing verification studies of the entire code and individual subprograms. Computer round-off errors are not generally significant on modern computers since storage of numbers is fairly accurate. Usage errors are due to the application of the code in a less-than-accurate or improper manner.

Errors can be *acknowledged* or *unacknowledged*. Acknowledged errors include round-off and discretization errors. Procedures exist for identifying them and possibly removing them. Otherwise they can remain in the code with their error estimated and listed. Unacknowledged errors include programming and usage errors. There are no set procedures for finding them and they may continue within the code or simulation.

This discussion of errors assumes that the simulation has reached *iterative convergence* such that the deficiencies or variations are not due to improper iterative convergence.

Verification is defined as

> *The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.*

Verification has also been described as "solving the equations right". It is intended to concern itself more with mathematics rather than engineering. Verification methods can be used to expose discretization and programming errors. Roache (1998) differentiates between "verification of a code" and "verification of a calculation". A grid convergence study, discussed below, is a useful method for verification. The Archive contains *verification cases* that examine the verification of the WIND code.

Validation is defined as

> *The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.*

Validation has also been described as "solving the right equations". It is not possible to validate an entire CFD code. One can only validate the code for a specific range of applications for which there are experimental data. The Archive contains *validation cases* that examine the validation of the WIND code.

NPARC POLICIES

The NPARC Alliance sets policies and plans to formulate an approach towards verification and validation. This is done at an annual two-day workshop which produces the NPARC Alliance Policy and Plans document (NPARC Alliance, 1999).

Central to the policy is the understanding that verification and validation are on-going activities. The scope of the WIND code is large and the dynamic nature of the code development leads to the dynamic nature of verification and validation. The web site adapts well to this environment.

The Alliance attempts to follow the guidelines published by the AIAA (AIAA, 1998) and adhere to the policies of the ASME and AIAA in reporting CFD results. Further, at NASA Glenn, we adhere to internal procedures on software verification and validation developed for ISO 9001 certification.

The Alliance has the policy of providing support to users. This includes providing within the Archive examples of the usage of the WIND code and associated utilities.

The Alliance has policies guiding the documentation of the methods and results of the verification and validation activities. The documentation is published on the web site.

OVERVIEW OF THE WEB SITE

The Internet address of the NPARC Verification and Validation web site is **www.grc.nasa.gov/www/wind/valid**. The central feature of the site is an Archive of verification, validation, and example cases. The coordinators of the verification and validation effort are listed. The site also contains background information on verification and validation, which includes a glossary, bibliography, and the policies and plans for the current fiscal year.

The site provides information on the methods of verification and validation that are used within the Archive. These methods are primarily from the AIAA (1998) and Roache (1998). They include methods for estimating errors and order-of-accuracy, evaluating and reporting grid convergence, presenting experimental and computational data, and documenting verification and validation results.

A "lessons learned" page is available for the posting of small bits of information learned during the application of WIND that are not documented in the user's guide.

The site has a page of links to other web sites which contain CFD verification and validation information. Included are sites listing experimental results and computational results. The list is fairly short - an indication of limited on-line information.

The primary content of the web site is the Archive of verification, validation, and example cases. The next sections provide some details on these cases. Information on the cases is obtained from listings of abstracts and cross-reference tables, which allow the matching of cases with specific WIND features that are examined within each case. Access to the information in the Archive is completely public. Users of WIND can download all the files needed to run WIND for a case. Those not using WIND, can download geometry, grids, and experimental or analytic data for their verification and validation activities.

ARCHIVE CASES AND STUDIES

The Archive consists of cases. Each *case* of the Archive corresponds to a specific geometry or physical configuration (i.e. ONERA M6 wing). A case is catagorized according to the basis of the data to which the CFD results are compared. A *verification case* uses analytic or numeric data as its basis of comparison. A *validation case* uses experimental data as its basis of comparison. An *example case* has no data and serves only to demonstrate some aspect of the usage of WIND. The example case may involve a hypothetical geometry and flow condition to demonstrate a particular feature in WIND.

A case contains one or more studies. Each *study* represents a set of one or more simulations of the case. Studies within a case can differ according to the creator, grids, flow conditions, code version, code, and intent. The intent of the study may be verification, validation, example, or check. A *verification study* applies the verification methods such as a grid convergence study while comparing the CFD results to analytic or numeric data. A *validation study* compares the CFD results to experimental data. An *example study* provides a step-by-step tutorial which demonstrates some aspect of usage of the WIND code. A *check study* is used by developers to examine some aspect of the operation of the WIND code during code development and contains only the minimum required files and documentation.

Table 1 presents the structure of cases and studies with regard to which type of studies can exist within each type of case. A verification case may contain verification, example, or check studies. A validation case may also contain a verification study. An example of this is the RAE 2822 airfoil verification study to be described below.

It is possible that a single study may be a combination of study types. For example, a study can be a verification or validation study, as well as, an example and check study. Example and check studies can overlap. For example, a validation study may also be fairly detailed as to provide a clear example on the usage of WIND, as well as, used by a developer to check the operation of the WIND code after a modification.

Table 1. Structure of cases and studies.

Verification case	
	Verification study
	Example study
	Check study
Validation case	
	Validation study
	Verification study
	Example study
	Check study
Example case	
	Example study
	Check study

VERIFICATION ASSESSMENT

The methods used in the Archive to perform verification studies are now discussed. Much of the material is from the AIAA guidelines (AIAA, 1998) and the book by Roache (1998). Verification examines 1) if the computational models are the correct implementation of the conceptual models, and 2) if the resulting code can be properly used for an analysis. The strategy is to identify and quantify the errors in the code and the solution. Thus, the two aspects of verification are the *verification of a code* and the *verification of a calculation*.

Verification of a code involves *error evaluation*, that is, looking for bugs, incorrect implementations of conceptual models, and other errors in the coding. This is typically done by the developers prior to release of the code. First, *consistency checks* are performed which examine basic relationships expected in the solutions (i.e. mass conservation). Then the code is used to simulate a suite of verification cases. A grid convergence study should be conducted to bring out potential errors. All the options of the code should be examined. This becomes more complicated as the number of options available within a CFD code increase. Identifying and quantifying each type of error is important because errors can interact and cancel each other - leading to erroneous conclusions.

Verification of a calculation involves *error estimation*, that is, determining the accuracy of a calculation and putting an error band on the final quantity. The approach is to peform a grid convergence study and determine the observed order of convergence, grid convergence indices (GCI), and report on error bands.

A grid convergence study is a method for determining the "ordered" discretization error in a CFD simulation and involves performing the simulation on two or more successively finer grids. The method results in an error band on the computational result which indicates the possible difference between the discrete and continuum value.

Assessing the accuracy of codes and calculations requires that the grid is sufficiently refined such that the solution is in the asymptotic range of convergence, which is the range in which the discretization error reduces asymptotically with decreasing grid size.

The easiest approach for generating the series of grids is to obtain the "coarse" grid by using every other grid point in each coordinate direction of the "fine" grid. This can be continued to create additional levels of coarser grids. In generating the fine grid, one must build in the n levels of coarser grids by making sure that the number of grid points in each coordinate direction N satisfies the the relation $N = 2^n m + 1$, where m is an integer.

The WIND code has a grid sequencing control that solves the solution on the coarser grid without having to change the grid input file, boundary condition settings, or the input data file. Further, the converged solution on the coarser grid then can be used directly as the initial solution on the finer grid. This option was initially created to speed up convergence of solutions; however, it can also be used effectively for a grid convergence study.

It is not necessary to halve the number of grid points to obtain the coarser grid (Roache, 1998). Non-integer grid refinement or coarsening can be used. This may be desired since halving a grid may put the solution out of the asymptotic range. Non-integer grid refinement or coarsening will require the generation of a new grid. It is important to maintain the same relative grid generation parameters as the original grid. The grid refinement ratio should be a minimum of $r \geq 1.1$ to allow the discretization error to be differentiated from other error sources.

The *order of grid convergence* is the order p in the relationship between the grid spacing h and the solution error E, which is the difference between the discrete solution $f(h)$ and the exact solution f_{exact},

$$E = f(h) - f_{exact} = Ch^p + \text{H.O.T.} \tag{1}$$

where C is a coefficient. A "second-order" solution would have $p = 2$. The asymptotic range has been reached when the coefficient C has reached a constant value.

WIND uses numerical algorithms that provide a *theoretical order of convergence* from 1 to 4; however, the boundary conditions, numerical models, and grid will reduce this order so that the *observed order of convergence* will likely be lower.

The order of convergence p can be evaluated using the solutions at three grid levels with constant grid refinement ratio r,

$$p = \ln\left(\frac{f_3 - f_2}{f_2 - f_1}\right) / \ln(r). \tag{2}$$

Richardson extrapolation is a method for obtaining a higher-order estimate of the continuum value (value at zero grid spacing) of the solution f from a series of lower-order discrete values. A generalized Richardson extrapolation can be expressed for a non-integer refinement ratio r and order of convergence p as

$$f_{h=0} \cong f_1 + \frac{f_1 - f_2}{r^p - 1} \tag{3}$$

where solutions f_1 and f_2 are computed on two grids of spacing h_1 and h_2, respectively, with h_1 being the finer spacing.

Roache (1998) proposed a grid convergence index (GCI) to provide a consistent manner of reporting the results of grid convergence studies and perhaps provide an error band on the grid convergence. The GCI can be computed using two levels of grid; however, three levels are recommended in order to accurately estimate the order of convergence and to check that the solutions are within the asymptotic range of convergence. The GCI is based upon a grid convergence error estimator derived from the Richardson extrapolation. The idea is to approximately relate the results from any grid convergence test to the expected results from a grid doubling using a second-order method. The GCI is a measure of the percentage difference of the computed value from the value of the asymptotic numerical value; it approximates an error band. It also indicates how much the solution would change with further refinement of the grid.

The GCI on the fine grid h_1 is defined as

$$\text{GCI}_{fine} = \frac{F_s \left| (f_2 - f_1) / f_1 \right|}{(r^p - 1)} \tag{4}$$

where F_s is a factor of safety. The refinement may be spatial or temporal. The factor of safety is recommended to be $F_s = 3.0$ for comparisons of two grids and $F_s = 1.25$ for three or more grids. The higher factor of safety is recommended for reporting purposes and is quite conservative of the actual errors.

The use of the above relations within a grid convergence study is demonstrated for a CFD simulation of the Mach 2.35 flow through a supersonic diffuser. The objective was to evaluate the pressure recovery at the outflow of the diffuser. The flow field was computed on three grids, each with twice the number of grid points in each coordinate direction such that the grid refinement ratio was $r = 2$. Table 2 reports the values of pressure recovery on each grid. Each simulation was checked for acceptable iterative convergence. The column indicated by "spacing" is the spacing normalized by the spacing of the finest grid.

Table 2. Grid convergence study example.

Grid	Normalized Grid Spacing	Recovery
1	1	0.97050
2	2	0.96854
3	4	0.96178

Figure 1 shows the plot of pressure recoveries with varying grid spacings. As the grid spacing was reduced, the pressure recoveries approached an asymptotic zero-grid spacing value.

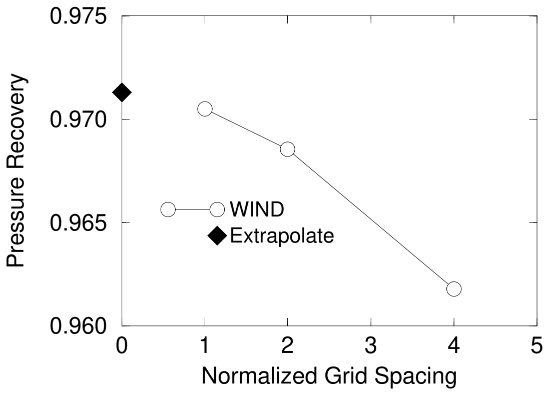

Figure 1. The pressure recoveries for the supersonic diffuser.

Equation 2 was applied to calculate the observed order of convergence as $p = 1.79$. The theoretical order of convergence was $p = 2.0$. The difference can be attributed to grid stretching, grid quality, non-linearities in the solution, presence of shocks, turbulence modeling, and perhaps other factors. Richardson's extrapolation was applied using the two finest grids with Eq. 3 to obtain an estimate of the value of the pressure recovery at zero grid spacing, which yields, $f_{h=0} = 0.97130$. This is plotted in Fig. 1 as the extrapolate.

The grid convergence index for the fine grid solution was calculated from Eq. 4 to be $GCI_{fine} = 0.103083\%$ using a factor of safety of $F_S = 1.25$. This variation is quite low. It was also determined that all three grids were in the asymptotic range of convergence.

Based on this study we could say that the pressure recovery for the supersonic diffuser is estimated to be 0.97130 with an error band of 0.103%.

One useful method of verification is comparing the results from two CFD codes. However, verification is not a democratic activity. While a reasonably close aggreement is encouraging, it is not sufficient to ensure verification. Highest encouragement comes when the results from two codes agree, but they differ signficantly in their approaches and algorithms (i.e. finite-volume density-based method versus a finite-element pressure-based method). However, disagreement in the results may be confounded by the different approachs or algorithms. The Archive contains several studies involving comparison between the WIND and NPARC codes. As part of the check process, the newer version of the WIND code is often compared to earlier versions of WIND.

VERIFICATION CASES AND STUDIES

The verification cases and studies contained within the Archive are listed in Table 3 and are reviewed below. Detailed discussion of the cases and studies is deferred to the web site.

Table 3. Verification cases and studies.

Normal Shock at Mach 1.3
Oblique Shock on 15^o Wedge at Mach 2.5
Conical Shock on 10^o Cone at Mach 2.35
Prandtl-Meyer 15^o Centered Expansion at Mach 2.5
Oblique Shock on 15^o Wedge at Mach 2.5
15^o Ramp at Mach 7.0 with Laminar Flow
Cylinder at Mach 8 in Laminar Flow
Blasius Laminar Flat Plate
RAE 2822 Airfoil at Mach 0.3 and $\alpha = 0^o$
ONERA M6 Wing at Mach 0.3 and $\alpha = 0^o$
Sod's Shock Tube
Standing Shock
Annular Duct
Square Jet Injection

Several of the verification cases involve steady-state, inviscid supersonic flow of a perfect-gas for which the analytic solution is well-known from any text on gas dynamics (Anderson, 1982). Examples include normal, oblique, and conical shocks and Prandtl-Meyer centered expansions. Such simple geometries and solutions are indicative of basic code capabilities.

The Blasius solution for the incompressible, laminar boundary layer on a flat plate (White, 1974) is a classic verification case that brings out errors in the laminar viscous terms.

Classic inviscid aerodynamics indicates that inviscid, shock-free flow over a closed body should result in zero drag. This can be used for verification. In the Archive, the RAE 2822 airfoil and the ONERA M6 wing were simulated under such conditions and produced drag values that are essentially zero. Since the ONERA M6 wing uses a symmetric airfoil, the lift was also zero. Note that these *verification studies* fall under their respective *validation cases.*

Analytic solutions exist for unsteady, one-dimensional, inviscid flow (Anderson, 1982). Sod's shock tube problem is a classic verification case. It has been used to demonstrate the ability of codes to capture shocks, slip discontinuities, and expansions in a time-accurate manner.

Other verification tests can be performed that are not specific to a particular case. For example, one can check the conservation of mass, momentum, and energy in the solution. For inlet and duct flows, one common test is whether the mass flow is conserved through the duct. Errors in obtaining conservation are one indication of overall error in the results.

Verification can examine the operation of specific code features. For example, WIND has a subsonic "arbitrary" inflow boundary condition which allows a user to specify inflow total pressure, total temperature, and flow angles. Such inflows are common in the analysis of propulsion systems. A simple verification case is the injection of a square jet into a square domain. For different conditions one can verify that the correct inflow conditions are imposed by simply examining the conditions during the simulation.

VALIDATION ASSESSMENT

Validation examines if the conceptual and computational models as implemented into the CFD code and computational simulation agree with the real world as observed through experiments. The accuracy required in the validation assessment is dependent on the desired use of the CFD code. A building-block approach is followed in performing the validation assessment. The approach consists of a series of cases involving successively more complex flow physics, geometry, and interactions. The next paragraphs discuss these different types of cases.

Unit cases involve simple geometry, one element of the complex flow physics, and one relevant flow feature. An example is the measurement of a turbulent boundary layer over a flat plate. The experimental data set contains detailed data collected with high accuracy. The boundary conditions and initial conditions are accurately measured.

Benchmark cases involve fairly simple hardware representing a key feature of the system. The flow field contains only two separate flow features of the flow physics which are likely coupled. An example is a shock / boundary layer interaction. The experimental data set is extensive in scope and uncertainties are low; however, some measurements, such as, initial and boundary conditions, may not have been collected.

Subsystem cases involve geometry of a component of a complete system. The geometry may have been simplified. The flow physics of the complete system may be well represented; but the level of coupling between flow phenomena is typically reduced. An example is the ONERA M6 wing. The exact inflow conditions may not be matched. The quality and quantity of the experimental data set may not be as extensive as the benchmark cases.

Complete system case involves the geometry of the actual hardware and the complete flow physics. All of the relevant flow features are present. An example is the MADIC 3D nozzle case. Less detailed data are collected since the emphasis is on system evaluation. Uncertainties on initial and boundary conditions may be large.

VALIDATION CASES AND STUDIES

The validation cases and studies contained within the NPARC Verification and Validation Archive are listed in Table 4 and are reviewed below. Detailed discussion of the cases and studies is deferred to the web site.

Table 4. Validation cases and studies.

Flat Plate in Turbulent Flow at Mach 0.2
Flat Plate in Turbulent Flow at Mach 4.5
Driver-Seegmiller Backward-Facing Step
Backward-Facing Step in Supersonic Flow
RAE 2822 Transonic Airfoil
Onera M6 Wing
S-Duct
Fraser Conical Diffuser
Sajben Transonic Diffuser
Supersonic Axisymmetric Jet
Ejector Nozzle
MADIC 2D Boattail Nozzle
MADIC 3D Boattail Nozzle
Supersonic Unsteady Shock Validation Experiment (SUNVE)

The cases in Table 4 reflect the emphasis of the Archive on air-breathing propulsion. The Archive attempts to span Mach numbers ranging from low subsonic to hypersonic. Turbulent flow over a flat plate is a basic flow. The turbulent flow over backward-facing step examines fundamental properties of separation and the ability of turbulence models to capture separation.

A couple of external flows are the RAE 2822 airfoil and ONERA M6 wing, which are classics in CFD validation. A review of the 1999 AIAA CFD Conference yielded approximately 13 papers using these two cases. Numerous researchers have browsed the Archive for information on these cases. Both cases contain the verification studies mentioned above.

The S-duct, Fraser conical diffuser, and Sajben transonic diffusers are fundamental duct flows. Nozzle and jet flows are represented by the supersonic axisymmetric jet, ejector nozzle, and MADIC boattail nozzle cases. The MADIC 3D boattail nozzle case represents the most complex case within the Archive (McClure and Heikkinen, 2000).

Several of the cases and studies contain computational results from the NPARC code. This allows comparison with another CFD code using slightly different algorithms. It is also a check on whether the Alliance is providing an improved CFD capability with WIND relative to NPARC.

The NPARC Alliance validation effort has an experimental component with the Supersonic UNsteady Shock Validation Experiment (SUNVE), which is discussed via the NPARC Verification and Validation web site.

EXAMPLE CASES AND STUDIES

The example cases and studies contained within the Archive are listed in Table 5 and are reviewed below. Detailed discussion of the cases and studies is deferred to the web site.

Table 5. Example cases and studies.

NLR Airfoil with Flap
Incompressible Flow in a Cavity
15^o Ramp at Mach 7.0 with Laminar Flow
RAE 2822 Transonic Airfoil
Onera M6 Wing
S-Duct
Supersonic Axisymmetric Jet
Sod's Shock Tube

Most of the cases and studies listed in Table 5 are within the respective verification or validation cases and studies rather individual example cases or studies. They contain step-by-step instructions for performimg the simulation using WIND. In addition, they demonstrate the use of the GMAN pre-processor and CFPOST post-processor along with several other NPARC Alliance utility programs. These cases and studies are part of a training program offered by the Alliance.

The case involving the NLR airfoil with a flap is a two-element airfoil in which the flap grid overlaps the airfoil grid. Step-by-step instructions on cutting the hole and applying fringe boundary conditions for overlapped grids are included. The case involving a 15^o ramp at Mach 7.0 with laminar flow demonstrates the use of various gas and chemistry models to model high-temperature air properties. The case involving a cavity demonstrates the use of a moving wall. The case involving the shock tube demonstrates the application of WIND to unsteady flow simulation. The other studies listed in Table 5 have been discussed previously and are listed here to indicate that they contain step-by-step instructions.

CHECK STUDIES

Currently, there are no individual check studies. The existing studies in the Archive also serve as check studies. A developer takes the files from an existing study and runs WIND for a certain number of iterations. The convergence and flow field is examined for differences. The performance and solution should remain fixed, if not improved. The developer then evaluates any differences and makes necessary corrections.

CONCLUDING REMARKS

The NPARC Alliance recognizes the importance of verification and validation within CFD and provides a publically-available, web-based Verification and Validation Archive. The efforts are ongoing and improvements are planned, including: greater use of verification methods, improved reporting of experimental error bars, improved archiving of experimental data, and the addition of more cases involving chemistry.

While the emphasis of the Archive is on demonstrating the usage and accuracy of the WIND code, the world-wide CFD community is welcome to use this resource. The Archive could be strengthened if results from other CFD codes were also published on the web site, and the Alliance is open to such submittals. Further, the Alliance welcomes comments and assistance in improving the Archive.

ACKNOWLEDGMENT

The authors would like to thank members of the NPARC Alliance who have contributed material to the Archive.

REFERENCES

AIAA, 1998, “Guide for the Verification and Validation of Computational Fluid Dynamics Simulations,” AIAA G-077-1998.

AIAA Journal, 1998, “Special Section: Credible Computational Fluid Dynamics Simulation,” *AIAA Journal*, Vol. 36, No. 5, pp. 665-764.

Anderson, J.D., 1982, *Modern Compressible Flow: With Historical Perspective.* McGraw-Hill, New York.

Benek, J.A., Kraft, E.M., and Lauer, R.F., 1998, “Validation Issues for Engine - Airframe Integration,” *AIAA Journal*, Vol. 36, No. 5, pp. 759-764.

Bush, R.H., Power, G.D., and Towne, C.E., 1998, “WIND: The Production Flow Solver of the NPARC Alliance”, AIAA-98-0387.

Matty, J.J. and Shin, J., 1997, ”The NPARC Alliance: A Progress Report.” AIAA-97-3353.

McClure, M. and Heikkinen, B., 2000, “Applications of the WIND Code to Aeropropulsion Testing”, AIAA-2000-0745.

NPARC Alliance, 1996, “NPARC Version 3.0 User's Manual”.

NPARC Alliance, 1999, “NPARC Alliance Policies and Plans”.

Power, G.D. and Underwood, M.L., 1999, “WIND 2.0: Progress on an Applications-Oriented CFD Code”, AIAA-99-3212.

Roache, P.J., 1998, *Verification and Validation in Computational Science and Engineering*, Hermosa Publishers, Albuquerque, New Mexico.

Tatum, K.E. and Slater, J.W., 1999, “The Validation Archive of the NPARC Alliance”, AIAA 99-0747.

White, F.M., 1974, *Viscous Fluid Flow*, McGraw-Hill, Inc., New York.