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**AN INTEGRATED APPROACH TO
CONVERSION, VERIFICATION,
VALIDATION AND INTEGRITY OF
AFRL GENERIC ENGINE MODEL
AND SIMULATION (Postprint)**



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An Integrated Approach to Conversion, Verification, Validation and Integrity of AFRL Generic Engine Model and Simulation

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ABSTRACT – Modern airborne weapons systems face increasingly stringent demands for improved performance and lower cost of ownership. The key to attaining the first of these demands is increased sub-systems integration, which leverages improved component performance to make even greater improvements in overall weapons system capability. Research is essential to gaining a fundamental understanding of the behavior and control of these highly integrated systems. Progress towards meeting the affordability demands for these systems is also being closely scrutinized. Recognition and control of ownership costs has become increasingly difficult in the face of increasing systems complexity. It may be possible to reduced the amount of physical engine test required in a typical gas turbine engine development program through the use of simulation and modeling techniques in a virtual engine test cell. However, in order to establish the credibility of a simulation and modeling approach to virtual engine test, carefully documented verification and validation (V&V) activities must be undertaken during model development. V&V is expensive and should be done in an evolutionary process to the extent required to demonstrate fitness of use for the intended purpose of the model. In this paper we discuss the development of a real-time virtual engine simulation model of an augmented, low-bypass turbofan and apply V&V metrics from the literature to assess qualitatively the V&V level achieved with respect to these metrics. We then describe on going efforts that are being applied to improve the V&V status of the model.

Nomenclature

AGEM	=	Augmented Generic Engine Model
FADEC	=	Full Authority Digital Engine Control
GEM	=	Generic Engine Model
HIL	=	Hardware-in-the-loop
HPC	=	High-Pressure Compressor
HPT	=	High-Pressure Turbine
NPSS	=	Numerical Propulsion System Simulation (NASA)
PLA	=	Power Lever Angle
TEDS	=	Turbine Engine Dynamic Simulator
V&V	=	Verification & Validation

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I. Introduction

Modeling and simulation technologies have developed to the point that they provide necessary tools for the engineer designing new weapons systems. Systems are so complex that some element of modeling and simulation is necessary to complete designs. As system complexity continues to increase and system interactions become harder to understand, we believe modeling and simulation will play an increasingly important role. The use of virtual engine testing using modeling and simulation techniques has been suggested by Skira as a means for reducing the required testing while managing acceptable risk in new engine development programs¹. In order for product developers to have the necessary confidence in the answers provided in a system simulation, verification and validation (V&V) are key elements in any simulation model development.

There are several ways to do engine modeling and simulation. Traditional approaches have a long history of development using FORTRAN or other 4th generation languages to calculate thermodynamics cycle parameters associated with the design and performance prediction of gas turbine engines. These cycle decks have been used extensively by developers of gas turbine engines and their customers to understand the behavior of jet engine designs prior to, during, and after the development of the physical engines. Beginning in the mid to late 1990's an effort was undertaken by NASA Glenn Research Center scientists to modernize the way that cycle deck simulations of engine designs are produced. The NASA Numerical Propulsion System Simulation (NPSS) code development effort focused on the use of object-oriented software development practices to develop a very flexible means for capturing the physics of engine components and encapsulating component behavior in configurable, reusable modules². NPSS also contains features for coupling components and completing integrated engine systems designs and automating the test and analysis of these designs. NPSS provides a modern, object-oriented method for producing customer cycle decks that predict engine behavior. In addition to NPSS, MATLAB, Simulink, and associated tools have been applied in the development of detailed, physics-based, turbine engine models capable of execution on real-time hardware simulators³.

NPSS and Simulink based models are complementary in nature. NPSS combines object-oriented techniques for component encapsulation, mechanisms for interconnecting components and establishing communications linkages between the components to perform iterative solutions of coupled systems. Simulink provides an easy-to-use, graphical, modeling and simulation development environment for developing time-based simulations in a broad range of applications. Both NPSS and Simulink are capable of code generation using associated tools. Add-on tools available from the MathWorks, Inc. enable the production of real-time code from Simulink models for execution on specialized, real-time, computing hardware. Turbine engine modeling software for modeling low-bypass ratio, augmented, turbofan engines has been developed for both Simulink and NPSS.

To mitigate engine and control system development costs and operational costs, the Propulsion Directorate's Turbine Engine Division of the Air Force Research Laboratory has been engaged in the development of real-time, integrated, simulation models of both modern turbine engines and their respective control and health management systems. As a result of this work, a real-time simulation capability called the Turbine Engine Dynamic Simulator (TEDS) has been developed for the purpose of supporting research in advanced turbine engine controls and health management. TEDS, operating as a virtual test cell, enables a user to investigate "what-if" scenarios at a fraction of the cost of an engine test cell or research aircraft. This simulator benefits researchers by offering a shared resource to support advanced controls and health management research in a real-time simulation environment. Non-linear, component-level, engine and engine control models that are physics-based are used to model the operation of a generic, gas turbine engine.

The TEDS virtual test cell is composed of two dSPACE Inc.-based hardware simulators with specialized analog and digital I/O modules for interconnection between simulators or interfacing to external hardware. The function of each simulator is determined by real-time model software compiled on a host PC and downloaded onto the simulator for real-time execution. MathWorks, Inc. MATLAB, Simulink, and Real-Time Workshop with dSPACE, Inc. ControlDesk software running on host computers are used to do rapid system development of real-time models for deployment in the virtual test cell. TEDS simulators have been used to perform real-time simulations of gas turbine engine and engine control systems.

To facilitate turbine engine and control system modeling and simulation, generic engine and control models implemented in Simulink have been developed. The history of this development is briefly described here to set the context for the current work. Dr. Zane Gastineau conducted initial model development for his Ph.D. dissertation in August 1998. His thesis titled, "Robust, Multivariable, Quantitative Design of an Adaptive Model-Based Control for Jet Engines," served as the basis for a generic engine and generic engine control system and led to the development of the concept of a real-time control facility to support real-time modeling and simulation of gas turbine engines³. Later, he established the Intelligent Controls Facility (ICF) with a new program to provide a real-time simulation and analysis platform for the investigation of modern turbine engine and control system behavior. When Dr. Gastineau left AFRL, Scientific Monitoring, Inc (SMI) of Scottsdale, AZ was commissioned to manage the further development of the ICF laboratory and TEDS hardware. SMI also continued development of the generic engine model (GEM), updated the control system model, and developed the hardware components and real-time model development environment for conducting real-time simulations.

Two separate simulation systems are used to provide the high-fidelity, virtual operating environment. The first system simulates the plant, i.e. the engine model, complete with all related sensors and actuators. The second system simulates the engine controls, complete with all logic, switching, inputs and outputs. Data transfer between the two systems is via a set of electrical cables, which carry the actual physical signals that exist in an operating aircraft engine. This architecture resulted in a tool that can be used not only to simulate an engine Full Authority Digital Electronic Control (FADEC), but also to interconnect the real and virtual components of the propulsion systems at will. The versatility of these simulators also allows operational testing of individual engine and control components such as sensors, actuators, and valves. Taken as a whole, TEDS represents a significant improvement in the ability of the Propulsion Directorate to characterize the performance of propulsion systems and components in a timely manner.

The generic engine model (GEM), as developed by SMI, uses a standard thermodynamics package to do engine cycle performance calculations for a two-spool, non-augmented, high-bypass ratio turbofan. The model also includes modules for modeling mechanical shaft dynamics as well as gas dynamics in the engine. These modeling objectives enable GEM to combine both steady-state performance calculations and transient analyses in the same simulation model. Mink lists two goals associated with the development of the generic engine model: 1) To provide a capability for independent testing, V&V of propulsion system components and 2) To provide a non-proprietary model suitable for use by researchers in propulsion systems. The use of real-time hardware with analog sensor interfaces enables the development of hardware-in-the-loop (HIL) testing capabilities⁴.

Mink describes requirements that have been considered in the design and development of the generic engine model, model features, and potential end uses of the generic engine model⁴. Requirements are abbreviated here to facilitate discussions in this paper regarding extensions of the model that are currently underway: 1) Real-time engine simulation, 2) Operation over the entire flight envelope, 3) Accurate steady-state behavior, 4) Credible transient behavior, 5) Easily modified for other engine cycles, 6) Capable of hardware interfacing for testing and validation, 7) Simulated engine sensor measurements, 8) Environment, PLA, and engine load user inputs, and 9) Non-proprietary, accessible model structure.

Development based on these requirements has resulted in an extremely flexible design that has been and is currently being used in several capacities for HIL testing. The generic model features a 0-D model of the thermodynamics associated with an engine cycle. It is physics-based and component-based so that parts of the model may be reused in other engine simulation and modeling experiments. Model behavior may be customized by tuning any of over 100,000 data points (including component map points, geometry, and other parameters) in the underlying MATLAB workspace.

Since its completion, a number of possible uses for the generic engine model have been suggested including suggestions in Ref. 4. These include: 1) V&V of actuators, engine controllers, and advanced control algorithms, 2) Integration of the generic engine model with models of other propulsion system components, 3) Evaluation of engine health management algorithms, 4) Engine performance trending, and 5) Parameter fitting for specific engine types. When considering new potential uses of the modeling and simulation technology it is important to quantify assumptions that can be made in considering the new use and balance the need for V&V steps during the development and the risk associated with not performing V&V steps.

Although GEM is a powerful research tool, there are several aspects of the model which make it difficult to apply in applications listed above. The model features a comprehensive set of subsystem components that are available for reuse. However, these components have not been delivered in library

form, making their reuse more difficult. Common subsystems are reused within the model. However, in many cases slight variations on the subsystem components are required in each application. A library structure with more complete encapsulation of component parameters is required to make the components more easily reused. Documentation regarding the use of components including underlying assumptions of the design is in progress and has recently become available. V&V efforts of GEM have been limited and informal due to time and budget constraints.

The risks associated with limited V&V activity have been deemed acceptable in terms of the original intended uses of the GEM, which are to provide a reasonable model for HIL testing and provide a non-proprietary model for researchers. However, in considering more advanced uses of the model, a more formal V&V process must be completed. Methods for tuning model parameters for matching specific engine behavior are not fully documented and the degree to which derivatives of GEM can be used to model individual engine behavior have not been completely quantified. The original generic engine design assumed subsonic operation, and associated assumptions must be revisited prior to using the model in applications involving modern fighter engines that operate in flight envelopes including supersonic Mach numbers.

There is currently interest in extending GEM for use in modeling augmented low-bypass turbofan engines of the type used in tactical fighter aircraft with the intent of testing uses described above. In order to realize this goal, several obstacles must be overcome. This paper serves several purposes: 1) To outline required modifications and conversion procedures for reuse of generic engine components, 2) To present a self-assessment of the current generic model V&V maturity in terms of published DoD measures for modeling and simulation, 3) To describe the need for and suggest steps to be taken toward a more formal V&V process, 4) To outline steps required to enhance the reusability of individual generic engine components, and 5) To present the current status of this project and enumerate lessons learned through this process.

II. Generic Engine Model Conversion

The Augmented Generic Engine Model (AGEM) is an extension of previous GEM work that is under development for 0-D, off-design, steady-state and transient cycle performance analysis of an augmented, low-bypass ratio fighter aircraft engine. The Simulink model of the AGEM in its early stages of conversion is shown in Figure 1. Examples of military engines that fit this class include the General Electric F110 and Pratt & Whitney F100 engines. For the purposes of this study we are choosing to narrow the focus of intended uses for AGEM to the following: 1) To capture non-proprietary physics and design aspects of military engines to an extent that goes beyond that available in other more traditional means in an easily understood, self-contained format for use by propulsion system researchers, 2) As a basis for simulating variation in performance both across engines of the same type and of an individual engine at various stages of its operational life, 3) As a basis for the development and testing of advanced control system algorithms, and 4) As a basis for understanding complex, multidisciplinary interactions embedded in the physics of propulsion system design. Each of these uses has a direct impact on our ability to demonstrate the utility of modeling and simulation in propulsion system design. A tool that is suitable for each of these four uses can be instrumental in exploring the next generation of engine control algorithms and lead to health management solutions that accomplish our goal for reducing total cost of ownership in future propulsion system designs. The risk associated with each of these intended uses is low to medium. However, in order for propulsion systems engineers to have the confidence to use results of these types of simulation experiments, a more formally documented V&V effort is necessary.

We recognize that no model will completely capture the behavior of an actual engine. Engine manufacturers and others (e.g. Ref. 4) have produced cycle deck models that are suitable for many of the purposes above. However, there are three features of GEM and AGEM that distinguish them from others. First, AGEM and GEM capture detailed graphical representations that are easily extended from a course model to a more refined model in an evolutionary development process. Second, both are capable of execution in real-time hardware with analog sensor interfaces. This feature enables HIL testing of advanced control concepts. Finally, the development environment for working with models is widely available and quickly understood. In order to establish credible operation for these uses we have adopted the same requirements that were established for the original GEM (see Section I). The AGEM leverages

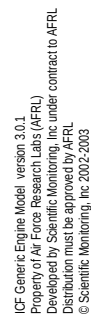


Figure 1: Augmented Generic Engine Model

work done to date in generic engine modeling by using the components developed for the non-augmented engine.

The modeling assumptions used in the original GEM⁴ are inherited in AGEM. Major engine components modeled include inlet, fan, compressor, combustor, high- and low-pressure turbines, mixer, bypass duct, afterburner, nozzle, cooling elements, auxiliary gear boxes and fuel metering equipment. Of these, the afterburner is a new component that is based loosely on the original GEM combustor module. The GEM fan model is implemented as separate fan hub and fan tip modules driving the core flow and bypass-flow streams, respectively. We include a single element for modeling the fan as a complete unit and follow this with a flow splitter that splits out the core and bypass flow streams from the main gas stream. The gas path flow connections between major engine components include mass flow rate, total temperature and pressure, static pressure and fuel-air ratio. JANAF thermodynamics tables are used in both GEM and AGEM, and local Reynolds corrections are employed (see Ref. 4). We assume that component maps, steady-state and transient cycle decks, length and volume data are available for V&V of the AGEM model.

The incorporation of turbomachinery map data into the MATLAB workspace is a significant part of the tuning process required to match AGEM performance with data for a specific engine. AGEM is a low-bypass ratio turbofan engine model. Separate map data for the fan hub and fan tip regions is not available for at least one of the intended engine models of interest. GEM includes both hub and tip region models for more precise modeling of core and bypass flows through the fan. In the absence of both hub and tip region flow data, average maps over the entire flow region are used, and the division of the incoming stream into core and bypass streams is accomplished using a splitter modeling element. This approach is consistent with one of the NPSS models with which we wish to compare results. Our conversion process adds the splitter element and provides a means for handling both methods, depending on availability of map data. Turbomachinery component map data that is required for model conversion and tuning includes maps for the fan, high-pressure compressor, and high- and low-pressure turbines. Both GEM and AGEM contain hooks for including inlet guide vane and variable stator vane sensitivities to adjust the component map look-up table data.

Many of the parameters that are required to tune individual engine component models to specific operational and performance characteristics are collected into a single complex data structure that is stored within the MATLAB workspace. The model references these parameters at run-time. Parameters include characteristic lengths, volumes, moments of inertia, design constants, efficiencies, etc. Values for these tuning parameters must be determined from engine design documentation, experimentation, or other simulation models. In previous work, NPSS simulation models have been used to determine sets of these parameters. We continue to use this approach to determine reasonable parameter values for those parameters that can not be determined directly. For initial model conversion work, reasonable estimates based on propulsion system engineering principles can be used to determine many of the workspace parameter values. More detailed tuning is required later to more closely match transient response characteristics of particular engines under study.

GEM contains hooks for additional engine control signal inputs that were not required for previous applications. These include inlet guide vane control, variable stator vane control, nozzle area control, bleeds and auxiliary components. The addition of an afterburner requires an additional fuel control input and pumping/fuel metering component. The performance of the engine is highly dependent on the control system used to provide signals for these inputs. For the purposes of this study, we assume that control schedules are available for simulation test cases so that the controller behavior can be decoupled from the engine in determining AGEM performance. Control schedules can be provided in several ways: 1) From the original design documentation and 2) From experimental results using a customer deck, an NPSS model or recorded data from physical tests.

For use of GEM components in the AGEM model there are several areas where the component models must change and be re-verified. GEM assumed low Mach number operation and we require AGEM to operate at supersonic speeds. Modeling equations in the inlet and exhaust nozzle component models require modification. The AGEM afterburner component is based on GEM combustor, which includes subsystems for modeling orifice flow and pressure loss associated with the dome and liner panels typical of a main combustor. These subsystems are not used in the afterburner configuration.

III. Importance of V&V

Many issues surrounding the application of modeling and simulation as analysis and design tools have been discussed in the literature. Among these, V&V have been recognized as key factors in the acceptance and usage of results from simulation experiments for supporting design decisions. Volumes have been written stressing the importance of incorporating formal V&V processes into the design process for newly developed modeling and simulation tools. For simulation models developed for execution in software code, verification of the model coding entails the process of guaranteeing that the code has been implemented correctly according to design. Validation refers to the process of guaranteeing that the simulation model design and underlying assumptions are correct with respect to intended uses of the model. Accreditation of the model certifies that the model is suitable for use in the intended application. A detailed discussion on the topics of model verification, validation and accreditation can be found in any number of standard texts available in modeling and simulation. The text by Law and Kelton is one such example⁵.

V&V efforts, although required for confident use of a model, are expensive. The developer of a model and the ultimate users of the model must reach a decision regarding the risk of using simulation results as a basis for design decisions and balance this risk against the level of effort and expense deemed appropriate for V&V of the model. At the same time, it is recognized that the least expensive modeling and simulation effort uses the simplest model possible to produce the required data to make the decisions that a designer needs in order to implement a design. In cases where cost is a primary consideration and it is difficult to assess the level of effort required in a model development effort, an evolutionary process that combines both model development and V&V efforts to develop simulation models at increasing levels of detail is often useful. In this setting, it is possible to quantify levels of V&V efforts that correspond to cost associated with the effort. We believe that a qualitative assessment of V&V efforts for AGEM provides confidence that the model is suitable for use in desired applications of the model and that continuous improvement with respect to levels of V&V. We adopt a framework as described by Logan and Nitta⁶ for assessing the extent to which a simulation model has been verified and validated in order to reduce the subjectivity associated with V&V and match expense with amount of effort required to solve the problem. A self-assessment using the framework quantifies (although subjectively) the current level and provides a path for evolutionary improvement toward a goal that balances the level achieved and the expense required to achieve it. In the next section, the framework is described. We then apply this framework to assess our work on AGEM and describe goals for evolutionary improvement with respect to the framework.

A. Assessment Frameworks

Logan and Nitta have discussed at length in their work the use of both qualitative and quantitative meters (or instruments) for measuring levels of V&V for a simulation model^{6,7,8}. Even though there is still a certain amount of subjectivity associated with a qualitative assessment of the V&V status of a simulation model, the VER meter for measuring verification maturity and the VAL meter for measuring validation maturity are useful for assessing V&V status of simulation models. Both meters measure maturity on a 0-10 scale with low values representing low levels of V&V status and inexpensive to achieve. The scales that have been developed provide a means for measuring level of effort and can be used as a basis for accreditation or measurement toward that end. Simulation analysts trade off expense of the V&V process with risk associated with use of the simulation models for their intended purpose and relate these with levels on the V&V meters. In this section, we describe the VER and VAL qualitative scales that are described by Logan and Nitta. We then perform a self-assessment of the AGEM model and discuss its readiness for the intended applications that were enumerated in Section I. Finally, we describe an approach taken to perform V&V for AGEM and relate this approach to the V&V scales.

Both the VER and the VAL meters describe levels of maturity in terms of four ranges as shown in Tables 1 and 2, respectively. The factors associated with each of the ranges are shown. The verification levels are measured with respect to each self-contained code unit associated with a model. The first maturity level, Level 1, requires that basic software quality engineering practices, including version control, are followed in the development and maintenance of the code and that basic documentation exists that describes assumptions, limitations and usage of code modules. The transition from Level 1 to Level 2 on the VER meter involves the construction of a basic verification suite that is used to demonstrate that each code module calculates the correct answer with respect to the model design documents. To achieve Level 3

on the VER meter, performance of code modules with respect to the established verification suite must be documented. Level 4 requires that combinations of code modules used in conjunction with the model produce the correct answer. Verification with respect to AGEM is concerned with the ability of the model to correctly calculate intended results given input and parameter values that bound the modeling problem.

Table 1: Verification (VER) Meter Levels and Factors

Level 1	0.0-1.5	
		Code is named and has user documentation
		Version control mechanisms are in place to track changes
		Software quality engineering principles used in development
		Extensive code coverage regression
Level 2	1.5-3.5	
		Basic verification suite has been developed to verify code
Level 3	3.5-7.5	
		Most code elements have been verified with verification suite
Level 4	7.5-10.0	
		Most couplings between code elements have been verified
		Method of Manufactured Solutions (MMS)

The VAL meter factors shown in Table 2 show a similar progression in maturity based on the factors that are satisfied by a simulation model associated with a given application of the model. Validation with respect to the AGEM model is concerned with the ability of a given set of model parameters applied with the verified model to match results expected in given applications. The first validation level, Level 1, requires that the simulation runs to completion and output signals of the model are reasonable. To progress to Level 2 of validation, steady-state and transient solutions for a single application are reasonable, and slight changes in model inputs or parameters produce changes in the output solutions that are in the correct direction. In Level 3 of the validation meter, several instances of the model have been tested, validation of component subsystems has been checked, and composability of the subsystems has been established. Steady-state operation of the model has been established throughout operational regimes of the model. In the highest level of the VAL meter scale, Level 4, quantitative statements regarding the accuracy of the model with respect to the modeled system have been made, and sensitivity and uncertainty analyses have been performed and documented.

Table 2: Validation (VAL) Meter Levels and Factors

Level 1	0.0-3.0	
		Runs the first time step
		Runs desired model to completion
		Obtains an answer
		Is calibrated for the intended application
Level 2	3.0-5.5	
		Solution validated in time space and iterative domains
		Sensitivities are qualitatively correct
Level 3	5.5-7.5	
		Integral validation to more than one system level test
		Hierarchical validation to numerous subsystem tests
		Integral or hierarchical validation across different systems
		Quantitative validation over range of experimental data
Level 4	7.5-9.9	
		Predictive validation bound assessed
		All uncertainty terms quantified
		Validated sensitivity slopes

B. AGEM V&V Approach

V&V of simulation models depends on a comparison between data collected from simulation results using the developed model and data collected from the system that the model represents. In the case of turbine engine simulation, this is particularly difficult to do. The cost to perform a system validation using engine test data at multiple operating points throughout the flight envelope to achieve a validation meter reading of 5.5-7.5 on the VAL scale (Table 2) has been prohibitive. However, the required data collection and processing off-wing may be possible with updated storage and processing capability, on-board in the controller, and better logistical infrastructure. An alternative for validation against actual engine data involves the use of more accurate simulation data to validate AGEM. Although this is less meaningful than the use of physical data for validation, it is still important for several reasons. It quantifies the ability of AGEM to represent behavior of multiple engine types and helps us characterize design space that AGEM can represent. It also establishes techniques that can be used for validation purposes when better performance data becomes available. It is with these goals in mind that we establish the approach described in this section for V&V of the AGEM model.

The data management associated with the development of V&V test sets and the analysis of results is an important consideration. There are two aspects that must be developed. These include 1) A means for organizing the large amount of data required to set up and run V&V test cases, 2) The storage of data from each of the tests models that are being compared, and 3) An infrastructure for automating the generation of AGEM and other data from each of the models under test that correspond to each of the test cases.

The Hierarchical Data Format, version 5 (HDF5)⁹ is a modern data file format that is supported within the scientific computing community for storing multiple data sets consisting variable containers of possibly varying types in a hierarchical (tree-like) structure. HDF5 provides a way to store V&V data sets that is independent of modeling architecture. Interfaces exist for writing data to HDF5 files from MATLAB, NPSS, modern 4th generation languages, such as FORTRAN, C, and C++, and modern interpreted languages. We use HDF5 file formats to catalog data sets used in model verification suites, validation test data, and model output data for validating models. Tools that compare structured data in several HDF5 files can be used to assign quantitative V&V measures to a particular model using automated model test procedures.

Several sources of data for AGEM V&V are assumed. The use of data from different sources at various levels of fidelity helps us to assess the generic representation capability of AGEM. Examples of sources for readily accessible design and performance data include data contained as a case study in the text of Ref. 10, the accompanying software design tools, and other off-the-shelf tools such as GASTURB¹¹. These tools are independent of NPSS tools that have been used in original verification efforts associated with GEM. The use of these tools in the first stage of a V&V process facilitates an initial independent assessment and preliminary sensitivity analysis that is necessary to increase confidence in AGEM capability for generic modeling.

Instantiations of the standard components available in the NPSS distribution and an associated, comprehensive, 0-D (fictitious) turbofan engine model supplied by NASA Glenn Research Center provide the next level of model fidelity for V&V of AGEM. The NPSS turbofan model gives us the ability to do a GEM-like V&V analysis for the low-bypass ratio turbofan configuration at multiple points in the flight envelope that include supersonic Mach numbers. The use of proprietary customer decks from multiple vendors to produce validation data represents the next stage in a validation process. For our preliminary work, we have focused on use of a single engine customer deck but would like to expand this to multiple vendors. Data from 3-D high-fidelity simulation studies that represents a level close to a full-scale engine test and finally the use of collected engine data increase the level of validation possible but are not considered in this study.

We are in the process of using data available from sources identified above at the component level to verify and validate individual engine components. To begin this process and to facilitate the construction of a reusable library of engine components, AGEM primary engine components have been decomposed into a hierarchy of basic component models and their dependent subsystems. From this decomposition process we have been able to identify subsystem components that have been reused throughout AGEM and distinguish the required underlying data structures that are used for subsystem component instantiation. As we build these subsystems back into a reusable library, we can take an object-oriented approach that more fully encapsulates data structures and enhances the ability to reuse the components in other applications. Identified library element subsystem configurations will be tested individually and a set of verification data

sets determined. Simultaneous to these activities, we will add to existing documentation at the library subsystem level. Each of these activities is required to make improvements for AGEM with respect to the V&V meters described above.

Given confidence in library subsystem components attained through the V&V activities above, we can assemble the library subsystem components back into engine components and then construct component level V&V tests to validate engine components. At this stage in the modeling and simulation process, we will have a set of simulation model elements that correspond closely to physical engine components. These AGEM components can be validated against component-level models and data collected from other data sources. Models for the inlet and nozzle system components are critical components to begin with in the validation process. The base installation of NPSS contains both inlet and nozzle components that can be configured and compared with AGEM model components. Validation test sets based on performance of each of the test engines can be constructed as a basic V&V test suite. Consider, for example, the component level V&V of the nozzle component. The verification test suite data which consists of model configuration data, model input data, and expected output data can be combined in a structured way within an HDF5 file. Testing scripts can be used to read these data elements from the file, set up and run the model (AGEM, NPSS model, or other cycle deck) and then quantify the difference between actual and expected model output. The HDF5 validation test set can begin with a single test case and be built up to include test cases from the entire flight envelope as the validation process matures.

It is impossible to construct a physical component test in isolation of inlet and nozzle elements. In the next level of the validation hierarchy we wish to construct a set of virtual component rig tests. Examples of engine components that can be tested in a rig test include fan and compressor components, combustors, and a combustor-turbine combination. In each of these cases we can set up the virtual rig test in a configuration that can be used to produce simulation data that can be compared with existing rig test data from a physical test if it is available. We will also construct virtual rig tests consisting of a similar set of NPSS components and compare results. A virtual rig test setup for the generic high-pressure compressor is shown in Figure 2.

Composability of individual components is a key question in the development of engine simulations. AGEM as well as GEM includes gas volume elements embedded within the individual components that contribute to the transient response of these components. The volume elements also provide coupling between downstream components and the upstream components that drive them. The coupling between components begs the question: Even though individual components have been verified and validated, when they are coupled together is the composed system valid? In order to address this question at a lower level than the full engine simulation, we have developed a virtual rig test of the engine core, as shown in Figure 3. This has also been done for the NPSS engine model. We can now construct validation data sets in the same manner used for individual component virtual rig tests and compare the results. These results can also be analyzed using physical test data and data available from customer decks in order to establish their validity.

The AGEM, NPSS turbofan model, and transient customer decks are capable of completing transient analyses of engine model performance. Typical transient analyses are performed under conditions where engine operating environment and/or engine control inputs are changing. Inline with our goal for credible

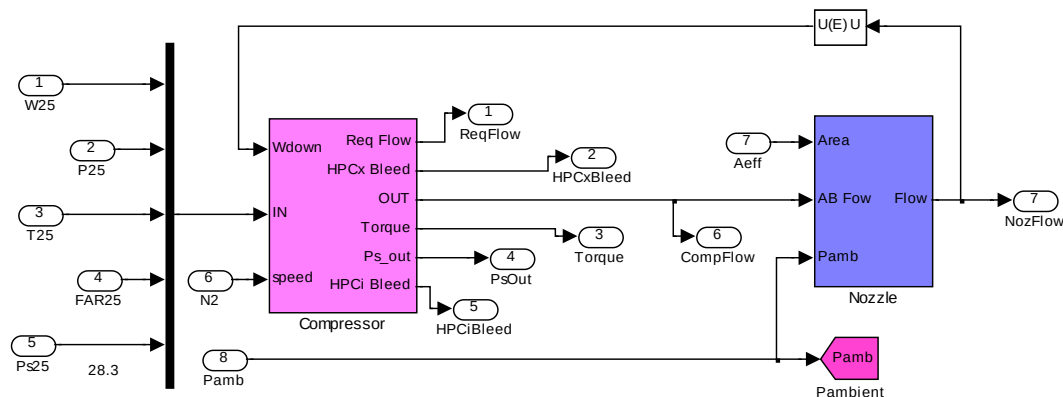


Figure 2: Virtual Compressor Rig Test

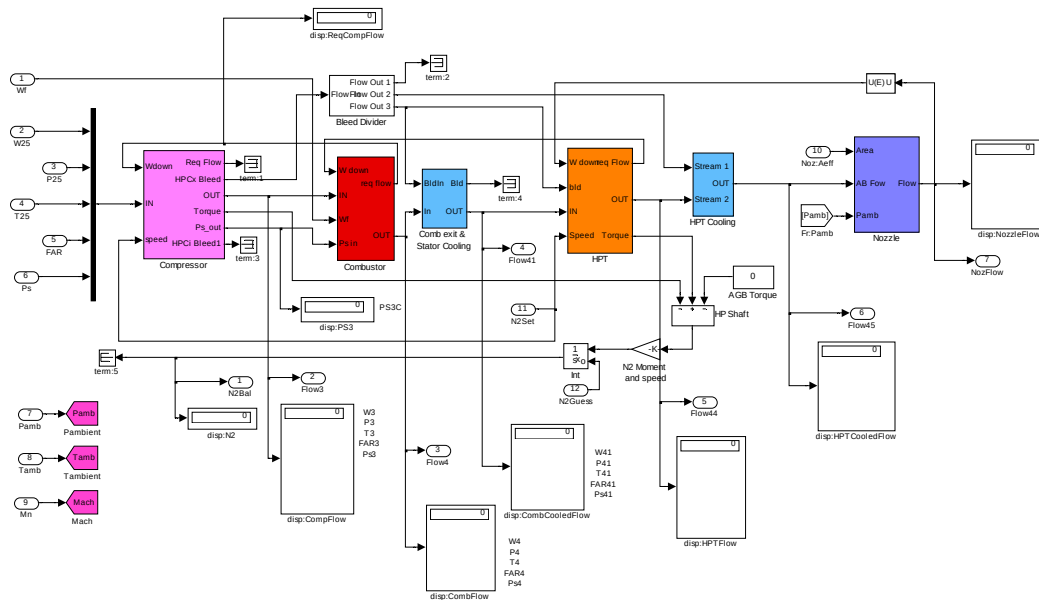


Figure 3: Core Virtual Rig Test

transient behavior we have chosen a set of transient test conditions that can be used to validate AGEM. These include the following transient state validation test-mission segment profiles 1) From idle to full power during take-off roll to rotation, 2) The transition from constant speed climb to straight and level cruise, and 3) Cruise condition acceleration to super cruise with full afterburner. Many other transient conditions can be identified. However, these constitute a reasonable sample to test against our goal for credible transient operation. Completion of the transient state tests is required for satisfying requirements for the Levels 2 and 3 on the VAL meter.

A sensitivity analysis can be used to discover relationships between model input variables, configuration parameters and changes in important calculated variables within the model. The AGEM Simulink model exposes intermediate calculation results and is particularly useful for performing sensitivity analyses. The validation process under development will use a sensitivity analysis to show that output variables change in the proper direction with respect to changes in model inputs and parameters. Satisfying these conditions is required for achieving Level 2 on the VAL meter. Level 4 of the validation meter requires a more detailed uncertainty analysis that quantifies the slope of changes in output variables and includes an analysis of the propagation of uncertainty from model input to important model outputs.

It is important to recognize that during each of the steps in the proposed validation process described above we advocate the development of data sets representing the four different test engine configurations that have been described: 1) The AAF model (simulated), 2) The NPSS turbofan model (simulated), 3) Customer deck for at least 2 different engines (simulated), and 4) Rig test and flight test data from an actual engine to the extent that it is available (physical test). The full engine test must consider flight conditions taken at a reasonable density within the flight envelope as shown in Figure 4. By establishing a generic flight envelope that is normalized with respect to maximum altitude and Mach number as shown, a reusable set of envelope points can be scaled to different engine applications and be used in a quantitative test. The flight envelope validation test set will be constructed and model exercised to address relevant aspects of the VAL meter for measuring validation status of AGEM. For lowest levels, 0.0-3.0, on the VAL meter, we require that AGEM runs to completion at steady-state for each point in the flight envelope. Parameters of AGEM must be adjusted so that steady-state results of AGEM can be compared with steady-state NPSS simulations and steady-state customer decks. A sensitivity analysis that examines sensitivity of internal model calculations with respect to changes in parameters and inputs is required for testing compliance at the 3.0-5.5 level (Level 2) on the VAL meter. Transient model analysis is also required for Level 2. The flight envelope test, virtual component and subsystem tests, and V&V test cases establish the basis for a

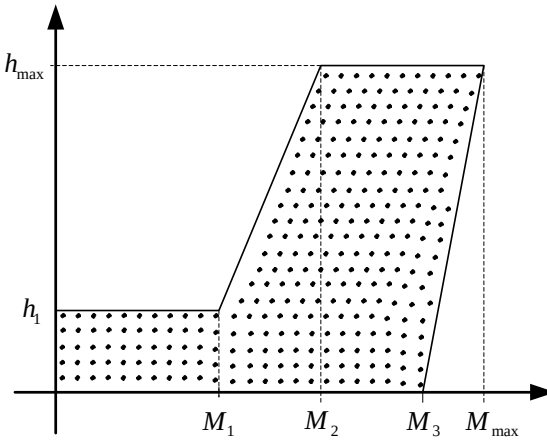


Figure 4: Normalized Flight Envelope

quantitative assessment of AGEM with respect to data from more than one test engine, and these establish a case for VAL meter readings in the 5.5-7.5 range of the scale. Fully qualified uncertainty analysis and knowledge of the propagation of uncertainty through the model as well as a measure of sensitivity slopes qualifies the model for readings in the 7.5-9.9 range.

IV. Current Status

The conversion, verification, and validation of the AGEM model is currently in progress. The basic elements of this process have been described above. This section contains a brief summary of the efforts that are currently underway to produce both the AGEM model validated against several test cases and a maintained library of components that can be used as a Simulink block set for propulsion system modeling.

A. Augmented Generic Engine Model Conversion Status

In this subsection, we discuss the current conversion status of the AGEM model. The components that are available from the original GEM model have been assembled into the configuration shown in Figure 1 above. The key difference between the AGEM shown and the original GEM is the addition of a second burner element for the afterburner. The afterburner element shown is modified from the original GEM model burner. Subsystem elements of the original burner that perform calculations related to heat transfer associated with the dome and liner elements present in the main burner are removed in the afterburner instantiation of the burner element. Operation of the afterburner also requires that the nozzle contain a variable exit area element that is not necessary in the non-augmented GEM model. The variable nozzle area control must ultimately be provided by the control system that is used to control the engine's operation. For the purposes of this effort, we have assumed that the area schedule is supplied to the model as test data along with other control inputs and model parameter values.

B. V&V Status

GEM has been operational and in use both for stand-alone simulations on PC workstations and for real-time code execution on TEDS for over a year and a half. V&V of GEM is documented to some extent in Ref. 4 and more completely in a user guide in Ref. 12. In the extension of GEM for uses in AGEM, we adopt additional V&V activities necessary to accredit the model for intended uses described in Section II. This section contains a description of the current status of that activity with respect to the VER and VAL meter factors described above.

In preparation for version control at the component and subsystem level and to facilitate the construction of a library of engine subsystem models, each of the engine components have been decomposed into a hierarchy of subsystem models. Using this process we have established a tree of Simulink subsystems that are composed to yield higher level components and ultimately the entire AGEM

in a top-level Simulink model file. In conjunction with many of these Simulink subsystem models, a verification model has been developed that drives the subsystem with a single set of required inputs and displays results of the subsystem calculation. These constitute the beginning of a verification suite. A similar set of NPSS models based on NPSS engine library components have been assembled and can be used to address the verification question. The verification suite is still incomplete, and we have not yet documented results of verification efforts with respect to the verification suite. We have begun the process of establishing multiple element models that consider, for example, combinations of the combustor and high-pressure turbine or HPC-combustor-HPT (engine core); however, verification of the calculations of these combinations of elements have not yet been done. All component models, subsystems, and MATLAB code that sets up the MATLAB workspace is ready for entry into software revision control, and basic software quality engineering principles are being put into place for code maintenance and further development. In comparing our progress in these activities with the factors delineated in Table 1, we assess our progress on the VER meter for AGEM at 3.0/10.0.

Validation of AGEM against several test engine model formulations is currently in progress. One of the main goals for validation of the model is to assess its ability to be calibrated to produce off-design, steady-state and transient performance analyses close to model formulations at different levels of fidelity. The models that have been selected for validation (based on their availability) are 1) The AAF engine model developed as a case study in Ref. 10, 2) An NPSS model of a fictitious engine, and 3) Steady-state and transient customer decks for a production turbofan engine. Each of these produce output data that is in different formats. However, tools exist for using the HDF5 standard as a common data file format for storing validation case data and ultimately performing a comprehensive analysis that leads to quantitative validation statements. At present time, virtual rig tests have been constructed for the fan, high-pressure compressor (HPC), combustor, high-pressure turbine (HPT), low-pressure turbine (LPT) and engine core (HPC-Combustor-HPT). We are in the process of developing validation data sets at a single operating point to validate virtual rig tests using each of the three test engine models. We are also developing test data sets to support the full engine virtual test validation for each test model. If flight test data becomes available, this data can be placed in the proper format to complete validation tests against real engine data. The assembly of data for validation throughout the flight envelope and the collection of validation data for transient analysis tests is in the planning stages.

The completed AGEM in one configuration runs to completion and obtains an answer for output variables. This model has not yet been fully calibrated for operation against one of the three simulated test engine models. The calibration depends on characteristic lengths, volumes, and other key parameter data that is yet to be determined for the test engines. Transient analyses have not yet been conducted for any of the test engines. Code has been developed to automate the sensitivity analyses for AGEM. However, we do not yet have sensitivity data to compare AGEM results with. Likewise, a mechanism for assessing the propagation of uncertainty through AGEM has been put into place but is still not mature. Based on these observations, we estimate the VAL meter reading for our AGEM work to be approximately 2.8/9.9. However, much of the required background work has been done to bring this rating up to a Level 4 reading on the VAL meter.

V. Conclusions

Although both the VER and VAL meter readings for AGEM are relatively low, the prerequisites for moving AGEM to higher levels on the V&V scales are in place. We stress that the process of model V&V efforts represent an iterative process that must be done in conjunction with the development of the model. These efforts must be carefully documented to show supporting evidence that the model is both correct and usable for the intended applications. This documentation can also be used to establish confidence in the reuse of model subsystem components for other generic engine configurations. The development of documentation and conducting V&V efforts after a simulation model has been completed is difficult and some what expensive. The effort expended in conducting V&V efforts should be weighed against the risk of using results of simulation experiments from models that have not been sufficiently validated. The V&V scales provided in the literature represent a useful, though qualitative way to assess V&V maturity for a simulation model.

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The Advanced Virtual Engine Test Cell (AVETeC)

An Integrated Approach to Conversion, Verification, Validation, and Integrity of AFRL Generic Engine Model and Simulation

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Al Behbahani
AFRL Propulsion Directorate

**42nd AIAA/ASME/SAE/ASEE
Joint Propulsion Conference
July 9-12, 2006, Sacramento, CA**



Outline

- **Motivation for Modeling and Simulation Work**
- **The Augmented Generic Engine Model (AGEM)**
- **Model Verification and Validation (V&V)**
- **Assessment of AGEM V&V Status**
- **Summary and Future Work**



Modeling and Simulation Goals

- **Develop an advanced engineering design, test, and analysis environment** that enables high-fidelity, multi-disciplinary, full propulsion system simulations to be performed early in the design process.
- Virtual “test cell” will augment physical testing through the integration of physics-based modeling, advanced visualization, and high-end computing technologies to **drastically reduce the time-to-solution**.
- **Facilitate collaborative applied research** by assisting *industry, academia, and government* in developing new technologies and products through **advanced modeling and simulation**.
- Focus on developing high-quality solutions and products that **reduce time-to-market**.



The Generic Engine Model

➤ Characteristics of the Generic Engine Model (GEM) Include:

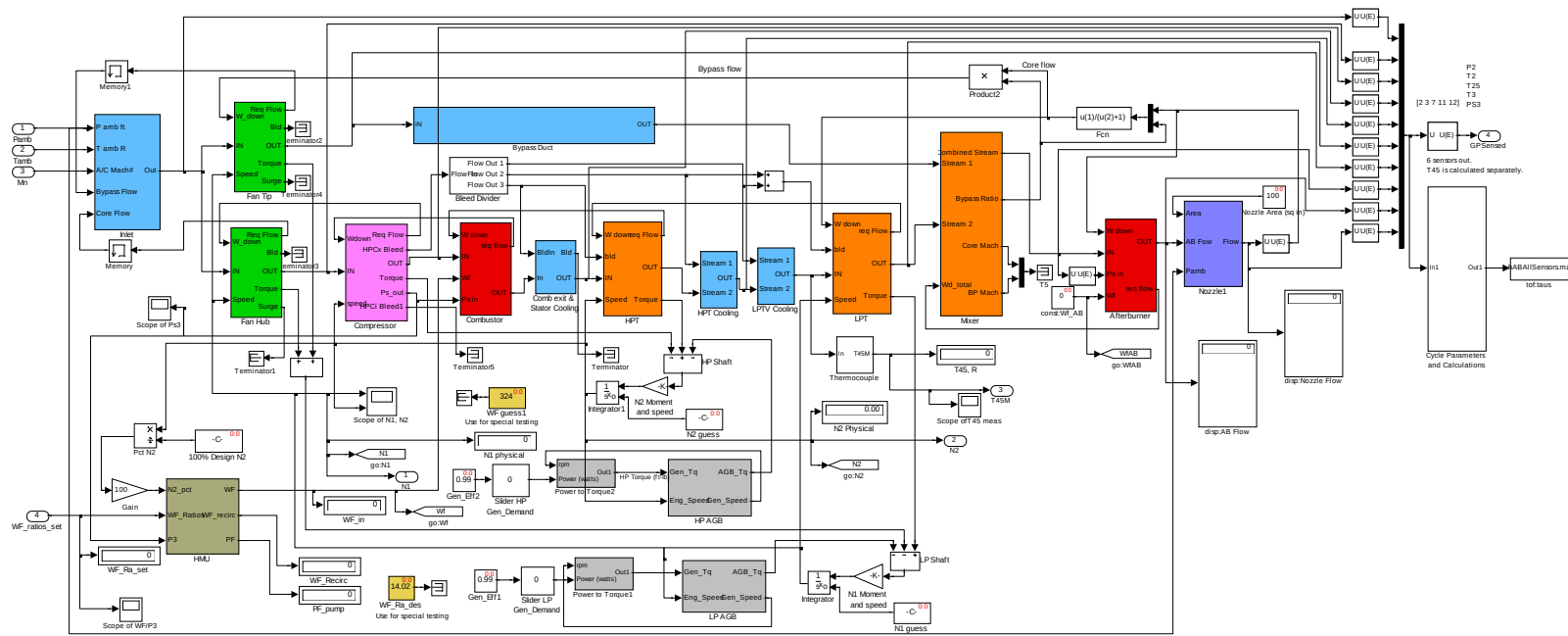
- 2 Spool, non-augmented, high bypass ratio, subsonic
- Off-design performance modeling
- Thermodynamic cycle calculations
- Combined transient and steady state analysis
- Nonlinear, physics-based, hierarchical model structure
- Real-time execution of both engine and engine control

➤ The Augmented Generic Engine Model (AGEM):

- 2 spool, augmented, low bypass ratio, supersonic, turbofan
- Instantiate afterburner from burner component
- Modify inlet, nozzle for supersonic operation
- Modify component maps
- Inlet guide vanes, variable stator vanes, variable nozzle area
- More complex control architecture



Augmented Generic Engine Model

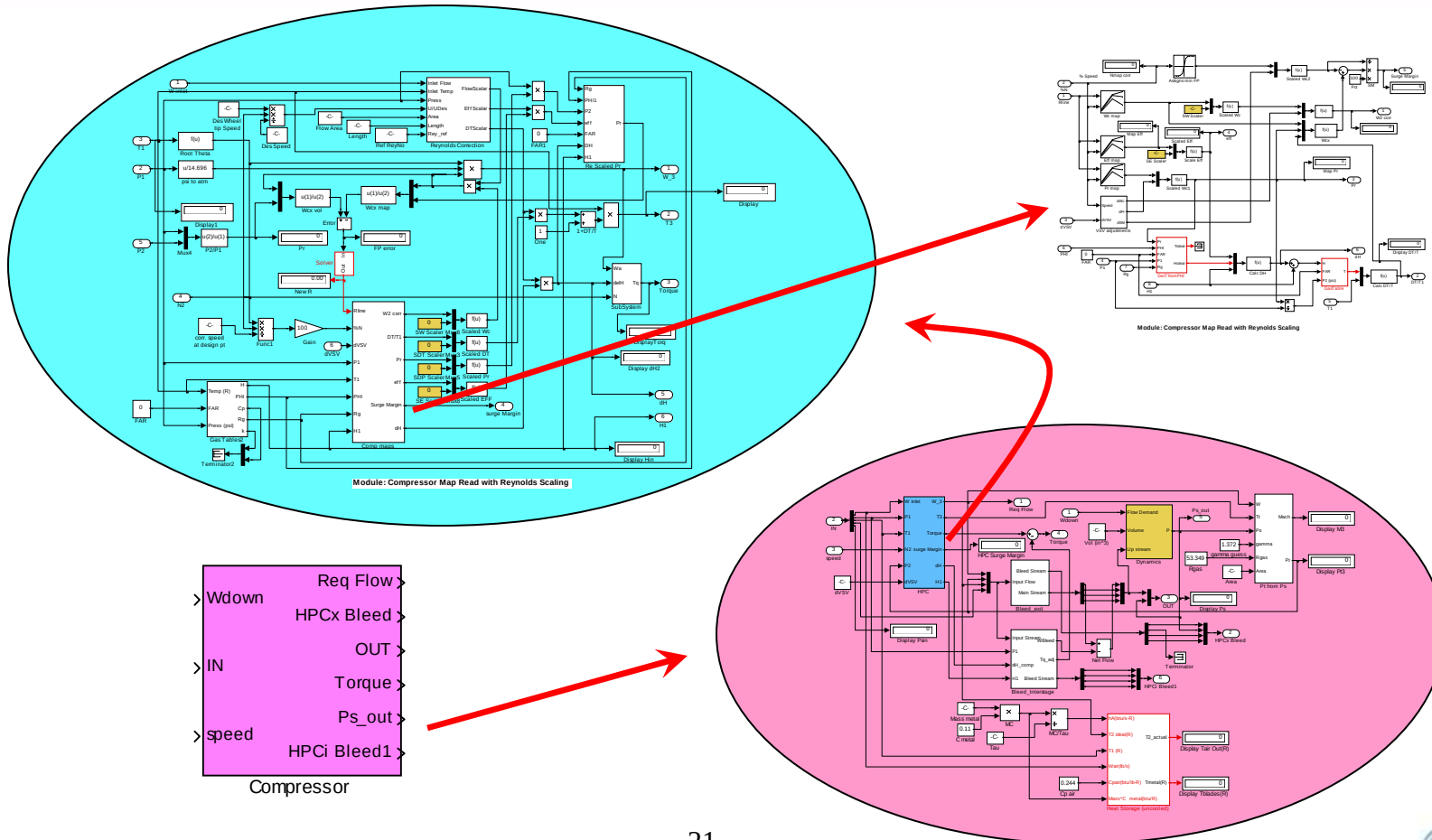


AGEM Advantages

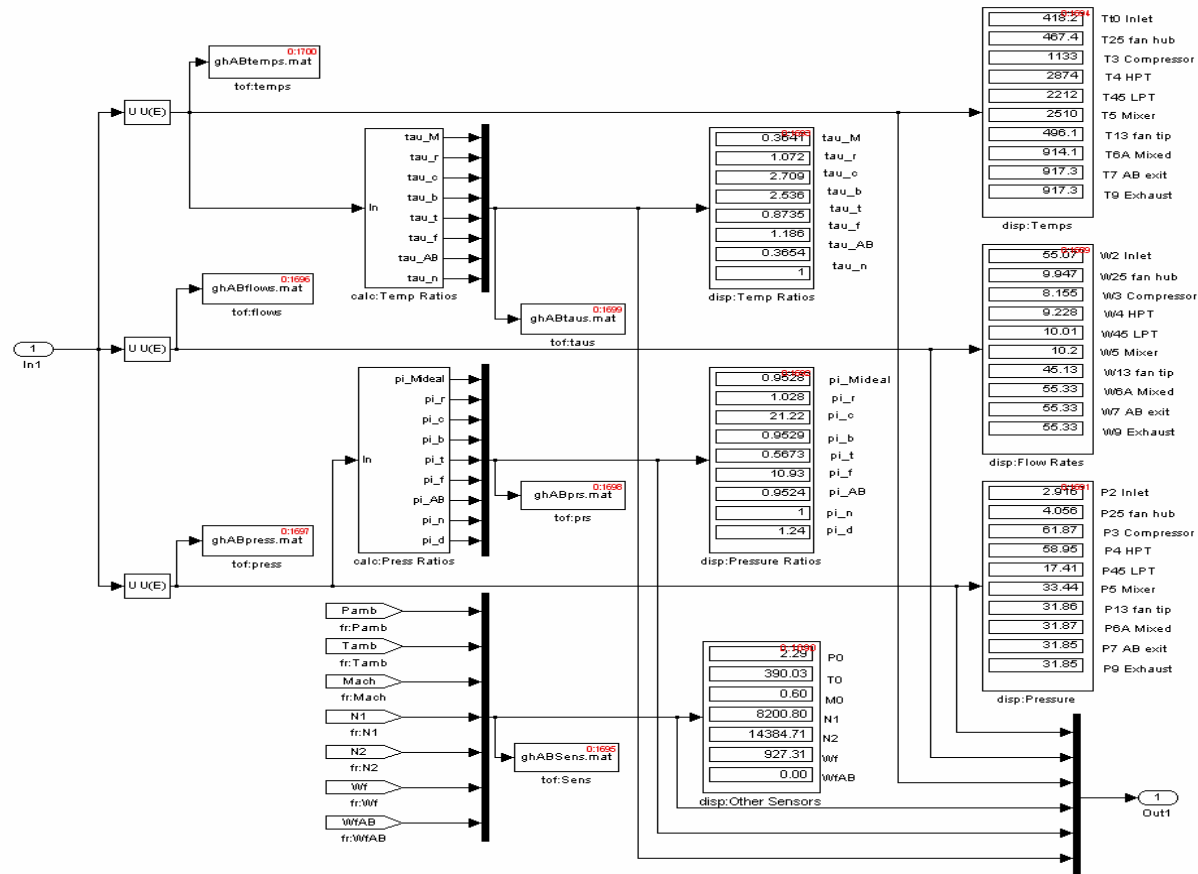
- **Graphical Coding, Modeling Environment Supports both Top Down and Bottom Up Development**
- **Relationships between Components are Easily Understood**
- **There are No Black Boxes and No Proprietary Blocks**
- **Simple Blocks are Used to Minimize Costs Associated with Advanced Block Sets**
- **Model Parameters are Separated from Model Structure to Enhance Reusability**
- **Model Signals are Easily Accessed for Flexibility in Formulating Simulation Experiments**
- **Relatively Easy Transition to Real-Time Model Execution**



Hierarchical Modeling Structure



AGEM Signal Accessibility



GEM Intended Uses

- **Demonstrate a Capability of Independent Testing and Hardware Verification and Validation of Propulsion System Components**
- **Provide a Non-Proprietary Turbine Engine Performance Simulation for Study and Research**
- **Demonstrate a Capability for Control System Development and Testing**



Turbine Engine Dynamic Simulator (TEDS)



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Modeling, Verification, and Validation

- **Verification of a Model Means that Modeling Equations have been Coded According to Design**
- **Validation of a Model Means that the Model has been Designed Correctly and Can Be Used**
- **Ideally, Modeling, Verification and Validation:**
 - **Begins with a Clear Modeling Purpose and Intended Uses**
 - **Modeling Assumptions are Documented**
 - **Required Model Accuracy is Stated Prior to Development**
 - **Verification and Validation (V & V) are Integrated into the Design Process**



Modeling, Verification, and Validation

- **The Ideal Case Described is Often not Practiced**
- **The Push Toward Reusability Confounds the Ideal Approach for V & V**
- **By Definition, a Model is an Approximation of the Physical Reality that it Represents**
- **Complete V & V is not Possible**
- **V&V is Expensive and V&V Effort Must be Balanced Against the Risk Associated with Model Use for Intended Purposes**
- **Logan and Nitta (Lawrence Livermore National Lab) Describe an Evolutionary Approach to V&V, Discuss Qualitative and Quantitative Measures of V&V Levels**



Potential Intended Uses for the AGEM

- **V&V of Actuators, Engine Controllers, and Advanced Control Algorithms**
- **Integration of the AGEM with Other Propulsion System Components for System-of-Systems, Multidisciplinary Design Trade Studies**
- **Evaluation of On-Board Engine Health Management and Prognostics Algorithms**
- **Engine Model Tuning and Performance Trending**
- **Parameter Fitting for Specific Fighter Engine Types**
- **Extract Components and Subsystems into a Reusable Library for Future (Currently Undefined) Uses**

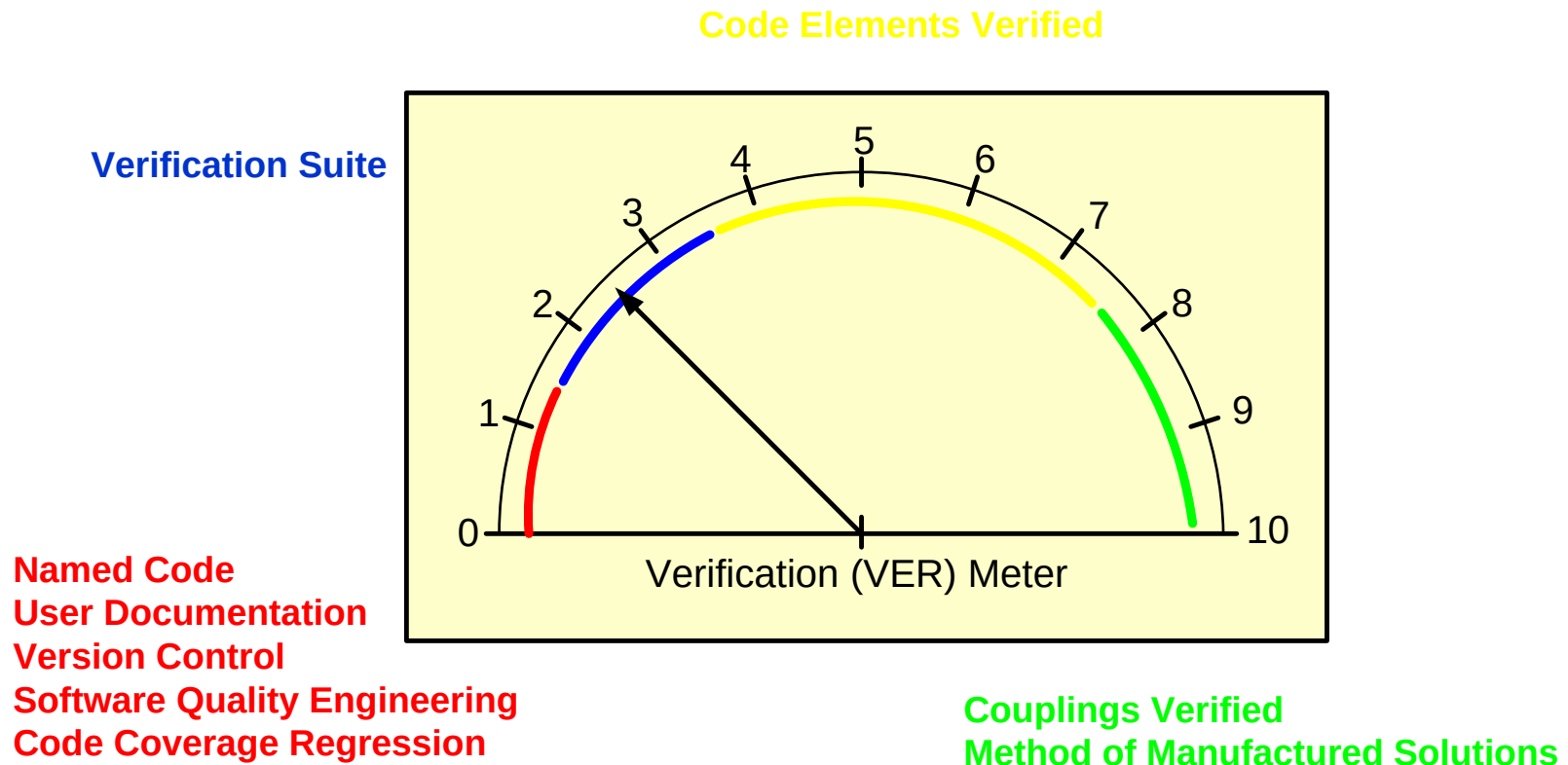


Potential Intended Uses for the AGEM

- **These Intended Uses Constitute a Departure from Original Modeling Intent**
- **The Risk Associated with Using the Results of Simulations for Newly Stated Objectives is Higher**
- **Original V&V Efforts May No Longer be Adequate**
- **We Need to Reconsider Modeling Assumptions, Reformulate, V&V Strategy and Re-Assess the Required Level of V & V that Balances Risk and Cost**
- **Logan and Nitta (Lawrence Livermore National Lab) Describe an Evolutionary Approach to V&V, Discuss Qualitative and Quantitative Measures of V&V Levels**



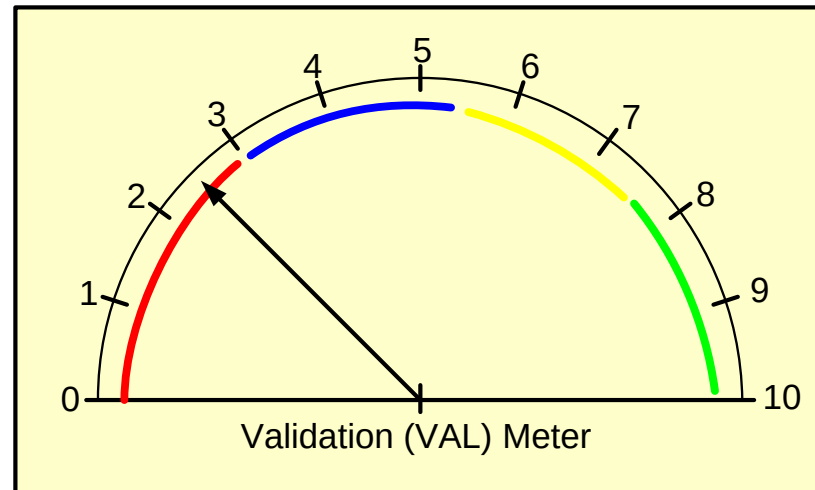
Verification Meter Scale



Validation Meter Scale

Validation for Time, Space, Iteration
Qualitatively Correct Sensitivities

Integral Validation for > 1 System Level Test
Hierarchical Validation for > 1 Subsystem Tests
Integral or Hierarchical Validation Across Systems
Quantitative Validation over Range of Data

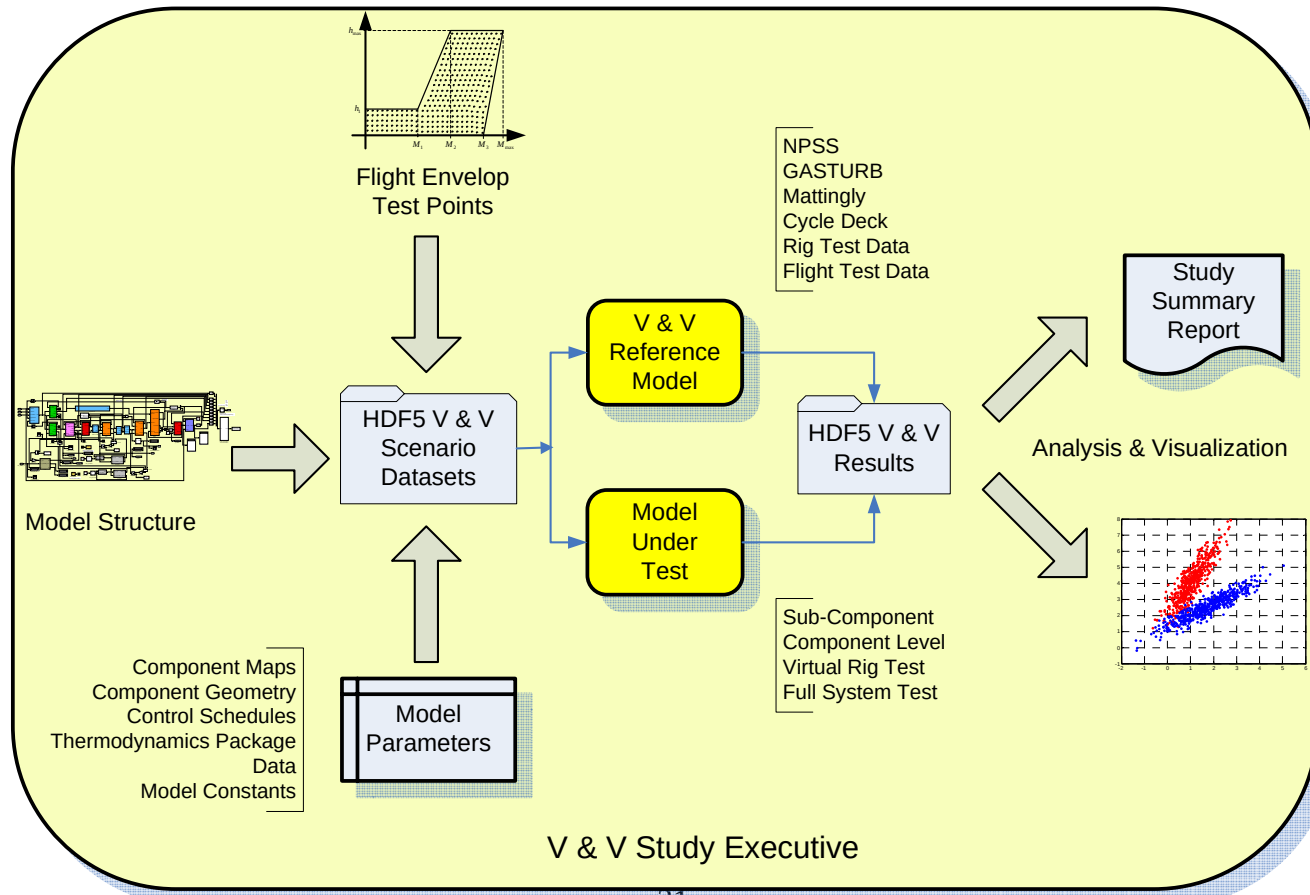


Run First Step
Run to Completion
Obtains Answer
Calibrated Solution

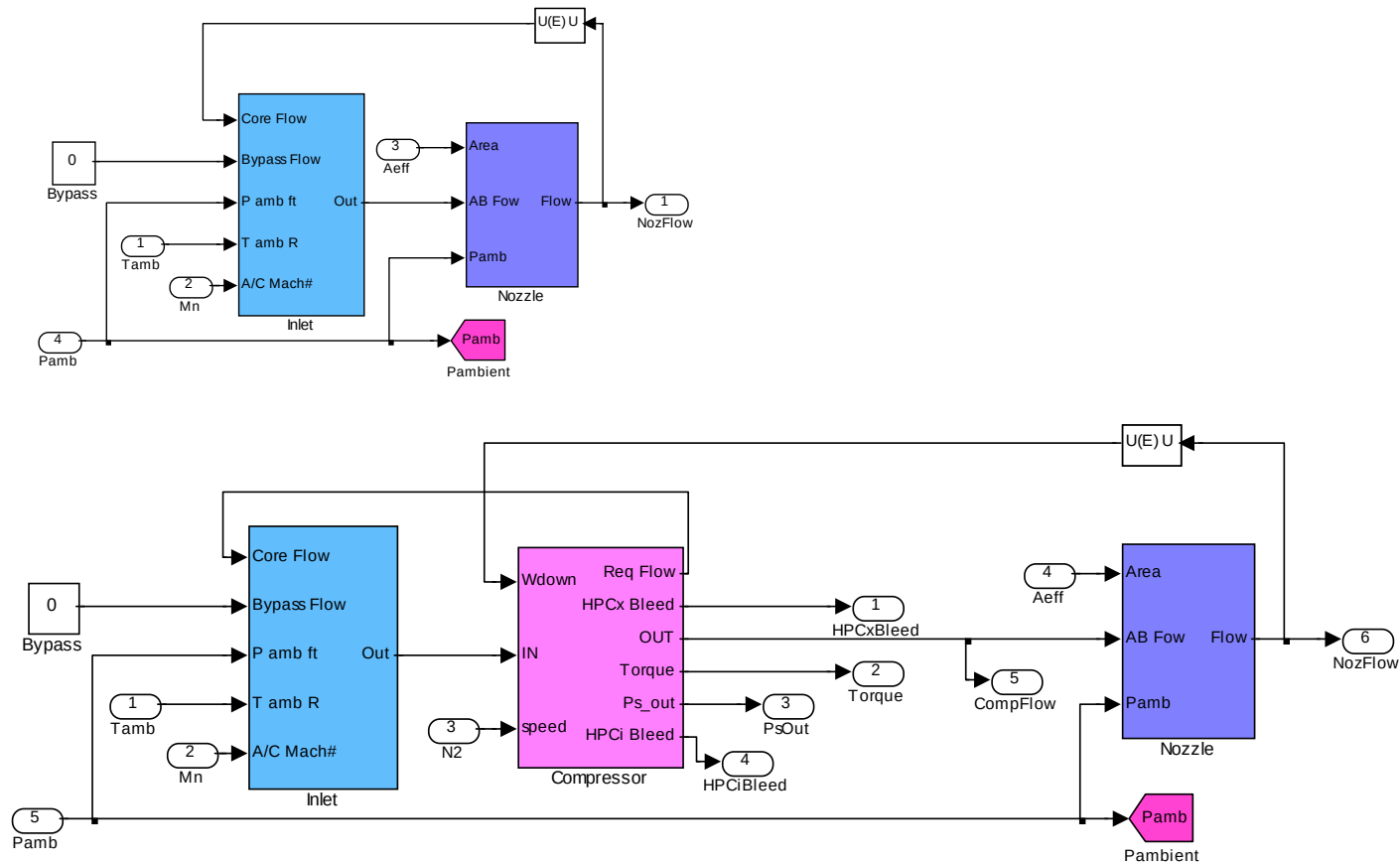
Predictive Validation Bound Assessed
All Uncertainty Terms Quantified
Sensitivity Slopes Validated



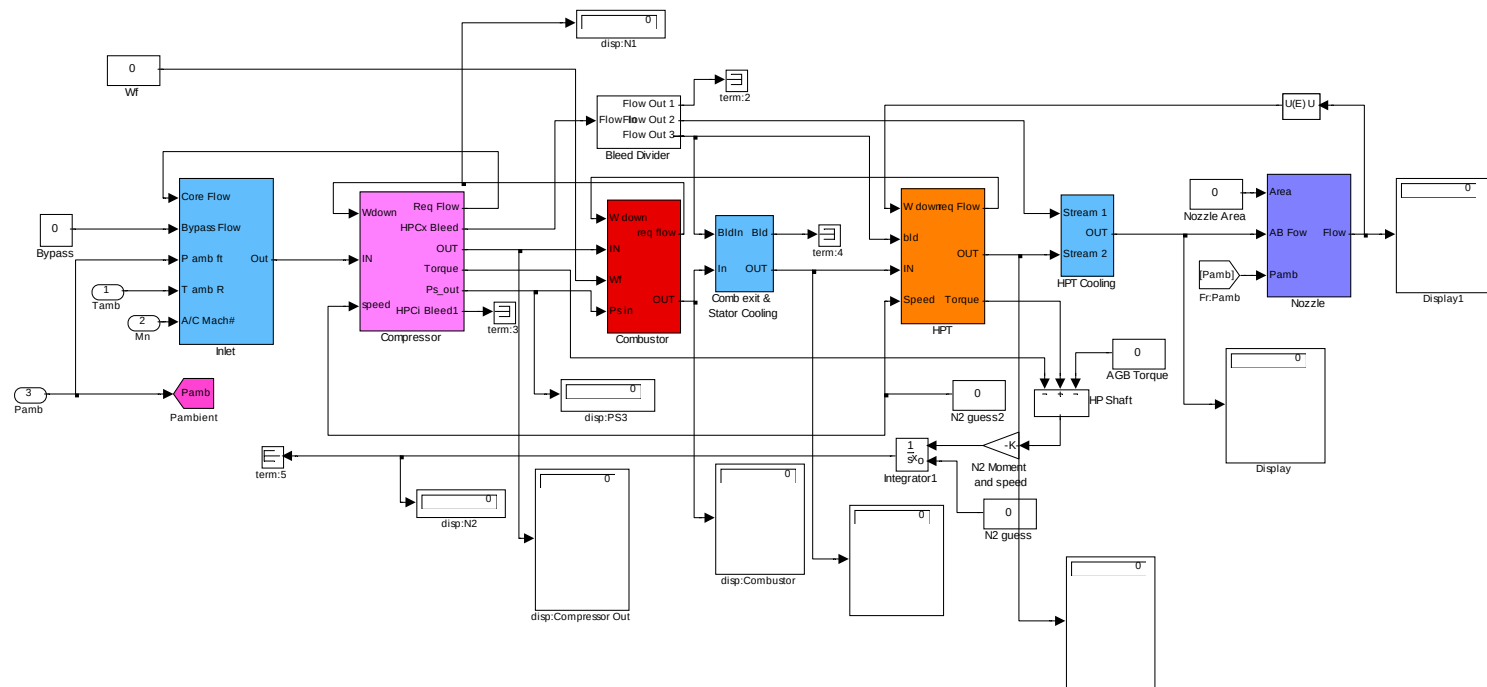
Vision for Verification and Validation



Component Level V & V Configurations



Core Rig Test



Future Work

- **More Carefully Assess Required V&V Levels Associated with Intended Uses**
- **Develop a Plan for Increasing V&V Levels**
- **Extend our Assessment to Quantitative Measures of V&V Level**
- **Pursue the Intended Uses and Decide if V&V Efforts are Sufficient.**
- **Model Refinements and Improvements**
- **Automate V&V Study Executive, Analysis and Visualization Components**



Backup Slides



TEDS Real Time Controls

➤ What we have:

- Real-time simulation environment capable of (propulsion) system simulation/emulation
- Development platform for rapid prototyping in engine modeling, control and health management
- Hardware interfacing capabilities for HIL demonstration
- Base library of propulsion system components
- A well structured, easily understood model of system interactions

➤ What we can do:

- Predict engine operation and performance for generic and specific engines
- Study system interactions under normal and faulted conditions
- Study the sensitivity of internal model variables to changes in the operating environment and subsystems during normal and faulted operation
- Use the model as a basis for identifying degradations in subsystem performance as components age

