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# IHRPT IMPROVEMENTS TO THE SOLID PERFORMANCE PROGRAM (SPP)<sup>\*</sup>

D.E. Coats, D.R. Berker, E.C. Hylin, S.S. Dunn, D.P. Babbitt, J.A. Tullos  
Software and Engineering Associates, Inc.  
Carson City, NV

## ABSTRACT

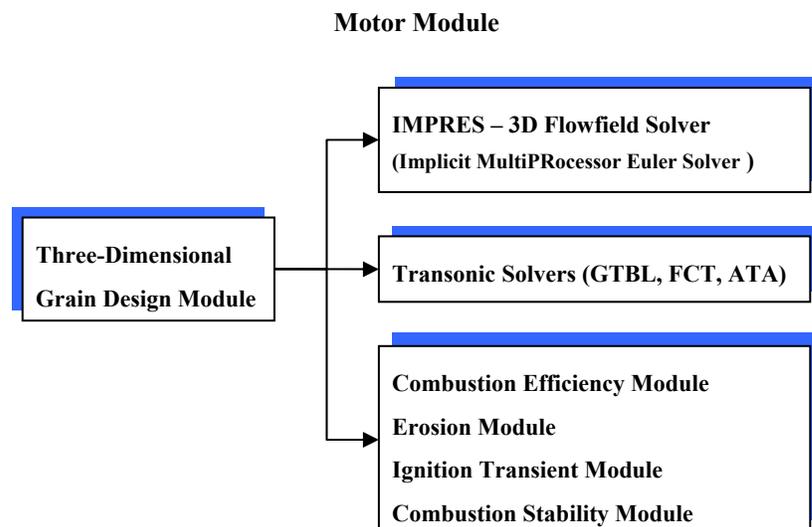
The JANNAF Solid Performance Program (SPP) is being upgraded as part of the Air Force Research Laboratory's IHRPT Modeling and Simulation effort. This paper describes the improvements to the nozzle performance modules within the SPP. Both full and parabolized Navier-Stokes solvers have been added to the code and are described in this paper along with a comparison of results.

## INTRODUCTION

SPP provides a framework that allows the nozzle and motor performance of most solid rockets to be analyzed to a reasonable degree of accuracy. The fundamental aspects of solid propellant rocket motor design, including propellant characterization, nozzle design, grain design and ballistics are integrated into a single code. As part of the Integrated High Payoff Rocket Propulsion Technology (IHRPT) modeling and simulation effort, the Air Force Research Laboratory has tasked Software and Engineering Associates, Inc. (SEA) to upgrade the nozzle performance capabilities within the SPP code.

This paper discusses the additional capabilities which have been added since the last open literature discussion of the code<sup>1</sup>, options which are currently being added and/or checked out, and a comparison of results using the new capabilities compared to prior versions of the code. In particular, both full and parabolized Navier-Stokes nozzle flow solvers have been added to the code and these results are compared to the Method of Characteristics/Boundary Layer Module solutions (MOC/BLM) of the existing code.

Figure 1 shows how the Motor module of the SPP interfaces with subsonic-transonic nozzle flow solvers and fits within the overall framework of the code.

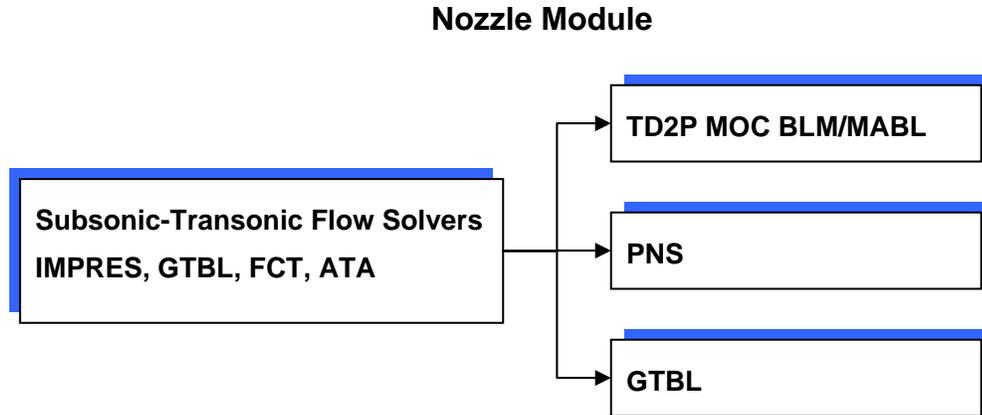


**Figure 1. Motor Module-Nozzle Module Interface**

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<sup>\*</sup> This work was performed under contract FA9300-05-C-0011 from the Air Force Research Laboratory.

The schematic of the Nozzle Module in shown is Figure 2 below. Not discussed in this paper are the IMPRES and FCT modules.



**Figure 2. Nozzle Module Schematic**

#### IMPROVEMENTS TO THE SPP NOZZLE FLOW SOLVERS

The new subsonic-transonic (STS) analysis module within the SPP code derives from the GTBL (Generalized Transonic and Boundary Layer) code<sup>2</sup> and has the following attributes:

- Finite rate chemical kinetics capability
- Equilibrium chemistry capability
- Resolution of the wall shear layer (boundary layer) for accurate heat transfer computation
- Robust geometry capability
- Accurate and stable numerical schemes
- Turbulence models applicable to both the boundary layer and other shear layers

In spite of all the impressive progress in the algorithmic developments, the challenge still remains with solving the coupled equations for multiphase/multispecies systems with stiff chemical reactions and inter-phase interaction. These types of systems are encountered in SRM combustion chambers. The challenge encountered in the numerical simulation of these flows arises from the fact that several phenomena (e.g., chemical reaction, collision/coalescence, convection, turbulence, droplet breakup etc.) all coexist in a motor cavity, each with its own time and length scale. Therefore, any assumption for simplification of stiff terms must be justified. That is, robustness should not be achieved at the expense of accuracy.

The GTBL code is a multispecies/multiphase Navier-Stokes/Euler flow solver. The discretization scheme is fully implicit. The left (L) and right (R) states of the inviscid fluxes for both phases are based on the Total Variation Diminishing (TVD) method. The Lax-Friedrichs (LF), Van-Leer (VL), and Roe methods are implemented for the gaseous phase to calculate the total inviscid fluxes by combining the left and right states. For Eulerian droplets the left and right states are combined according to the Steger-Warming formulation. Both schemes are second order accurate in space. The turbulence models used by GTBL are either Cebeci-Smith or  $k-\epsilon$ .

SEA has been modifying and extensively improving the GTBL code over the past five years and believes that it makes an attractive candidate for the improved subsonic-transonic module within SPP. While in theory, the GTBL could replace the entire SPP nozzle flowfield solver, in practice the

computational requirements for a full Navier-Stokes (N-S) code with finite rate chemistry and resolution of the boundary are still too high for regular engineering use. One of the major technical difficulties in adapting GTBL for use in SPP is finding ways to make it fast enough to use in parametric studies while maintaining sufficient accuracy to evaluate the effect of small changes in nozzle geometry.

Another consideration in using a N-S code for this task is the computer time required to generate heat transfer coefficients, Stanton numbers ( $C_h$  or  $\rho_e U_e C_h$ ), for use in nozzle wall erosion calculations. The Stanton number requires the wall enthalpy at both the adiabatic condition and the cold wall temperature. With an N-S solver employing a no slip wall boundary condition, a new N-S solution is required for each wall temperature. On the other hand, if the solution is run with a slip wall boundary condition, then a boundary layer solution could be used for each cold wall temperature desired. An efficient slip wall option is incorporated into the code that satisfies the above objectives.

Because the GTBL module is capable of computing the coupled core flow and boundary layer flowfield, the supersonic portion of the nozzle should also have a solver which is capable of the same fidelity along with short execution times. To this end, the VIPER PNS<sup>3</sup> flow solver is incorporated into the new SPP nozzle flowfield module. The PNS module is a full reacting gas, two phase flow solver with both slip and non-slip wall capability. The code is well documented and validated with over a decade of use. The merging of the various solutions procedures in the throat region of the nozzle is a non-trivial task which is in the final stages of check-out.

The turbulence models in the PNS module are extended to include the Spalart-Allmaras<sup>4</sup> one equation model in addition to the Cebeci-Smith<sup>5</sup> and  $k-\epsilon$ <sup>6</sup> models, which are currently in the code.

The current default option in SPP is to use the Approximate Transonic Analysis (ATA) to start the TD2P MOC calculation and to use the Boundary Layer Module (BLM) to compute the boundary layer loss. In the IHRPPT version of SPP the BLM module is being replaced with the Mass Addition Boundary Layer Module (MABL)<sup>7</sup>. The MABL module allows for both full finite rate or equilibrium chemistry within the boundary layer and includes mass injection at the wall capability.

The nozzle flow solvers and the user options for executing these solvers are shown in Table 1 below. The (E) in the table below indicates that the code is being run in the slip wall or Euler mode. Note that in all cases except one, if the slip wall is specified for any part of the core flow solver, then the boundary layer must be solved for by a boundary layer routine, either MABL or BLM.

**Table 1. Nozzle Flow Solvers**

<u>SubSonic-TransSonic</u>	<u>Super Sonic</u>	<u>Boundary Layer</u>
GTBL	GTBL	GTBL
GTBL	PNS	PNS
GTBL(E)	GTBL(E)	MABL
GTBL(E)	PNS(E)	MABL
FCT	PNS(E)	MABL
FCT	MOC	MABL
ATA	MOC	MABL/BLM (current default)
ATA/MABL	PNS	MABL/PNS
ATA	PNS(E)	MABL

## PROGRAM VERIFICATION AND VALIDATION

Computer program verification and validation is perhaps the most important part of improving an established code. In the case of adding existing code to an existing program, the verification step is essentially making sure that neither the code being added or the existing code is broken in the process and that the linkages between the modules are working properly. In the case of complex codes like SPP, GTBL, and Viper, verification is a non-trivial task and requires adherence to good software engineering practices. Validation is much more difficult because of the complex physics involved and interaction between the various models used to represent the physics. The validation process is comprised of testing individual modules/models against known data sets and, then testing the entire computer program against measured motor data. The SPP code predictions have been compared against an existing motor database for some time. Twelve of these motors and their characteristics are shown in Table 2.

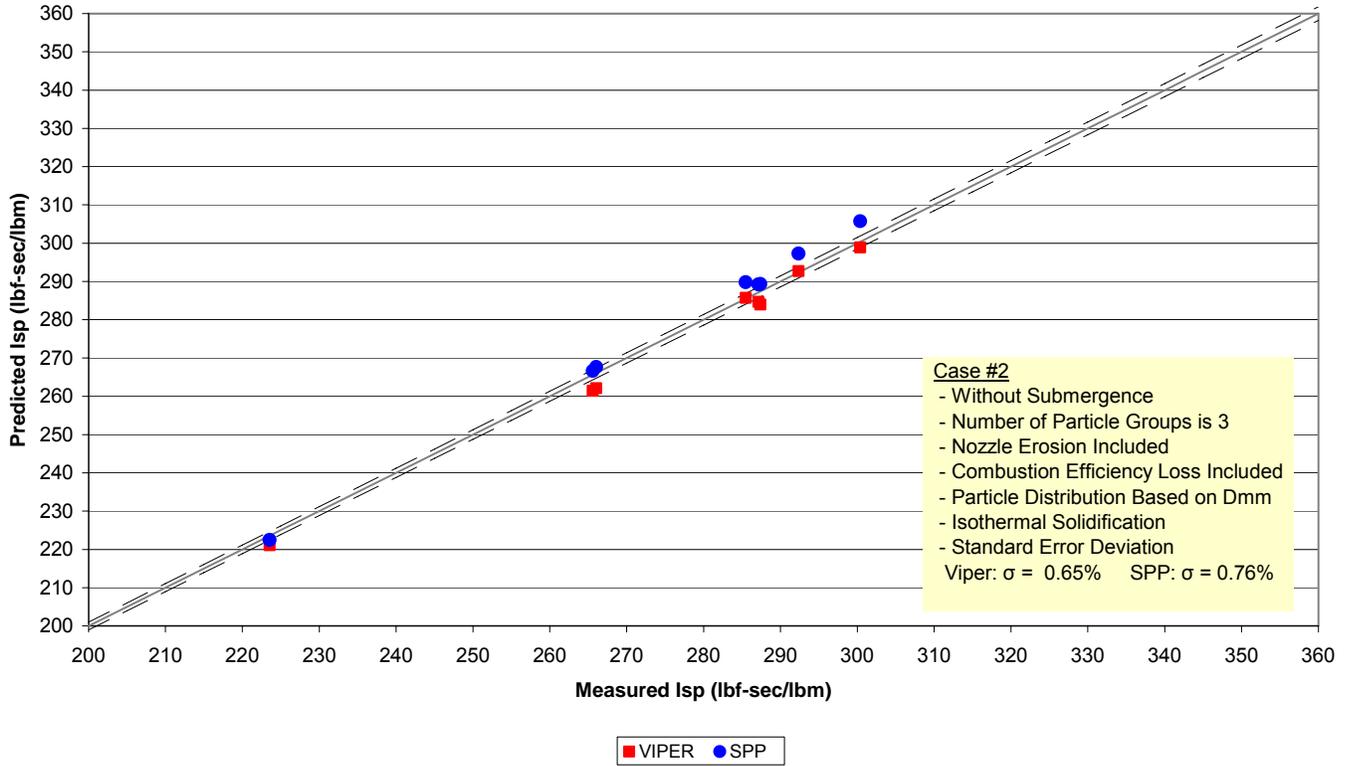
Because of the complex physics involved in predicting motor nozzle performance, there are many options which may be selected in computing motor performance losses. In the following comparisons, we used three particle groups to represent the log-normal distribution of alumina droplets in the flow. The mean droplet size was computed using the Hermesen correlation within the SPP code and converted the  $D_{43}$  particle size to the mass median size,  $D_{mm}$ . The submergence correlation within the SPP was not used. Both nozzle erosion losses and combustion efficiency were considered using the standard SPP models. Results are shown with and without isothermal particle solidification. The results without solidification are currently considered to be more physically correct. However, the non solidification results using the TD2P/MOC module are questionable due to a problem in the non-solidification logic. This problem is currently being investigated. It should be noted that the results shown here are a work in progress and that the boundary layer, throat erosion, and combustion efficiency losses are all being revised as part of the IHRPT work effort.

Figure 3 shows the results when comparing the standard SPP methodology (i.e., TD2P/MOC-BLM) to the newer PNS module (i.e., PNS module computes both the coupled divergence-two phase flow loss and boundary layer loss). In Figure 3, the isothermal particle solidification option is used in both calculations. These results further indicate that the standard SPP method uniformly predicts higher performance than the PNS method. The computations were repeated in Figure 4 with particle solidification turned off. The results from these runs indicate that when the heat of fusion is not being liberated during solidification, the performance loss for both methods is below the measured values for most cases.

**Table 2. Motor Database Used for SPP Validation**

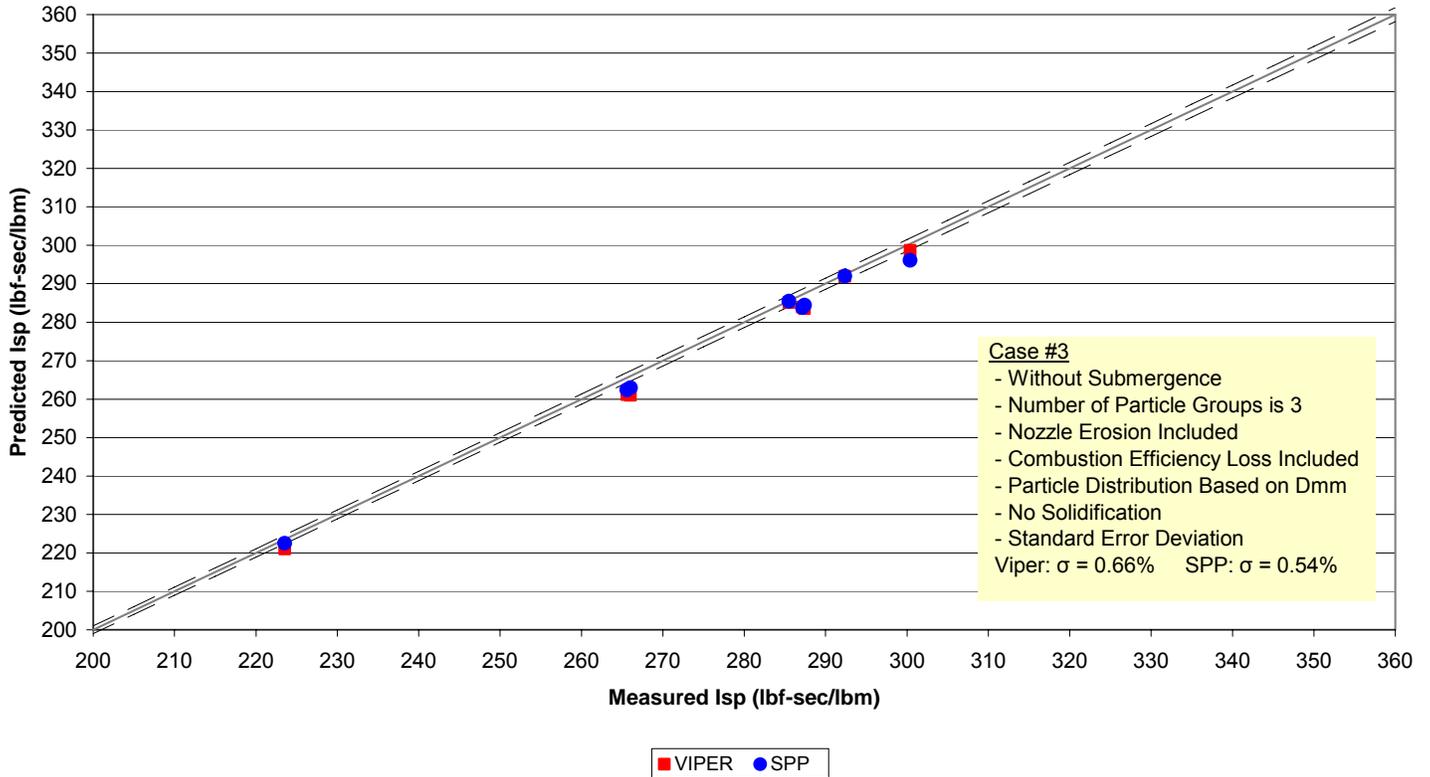
Test Case	SPP Vol. I, Section	Propellant Type	Grain Geometry	$\bar{P}_c$	$D_T$	Submergence %	$\frac{R_c/k}{U_p/D_n}$	Expansion Section	$\epsilon$	Classification	Motor Description
<b>AIM</b>	9.1	PBAN 84.5% Solids 16.4% Al	Conocyl	730	2.03	8.0	2/2	Cone	103.2	Space	AIM is a small space motor with a relatively high expansion ratio, 103.2. The nozzle inlet is a circular arc-cone-circular arc throat. The exhaust nozzle is a 19.7° cone.
<b>C4 Stage 3 (ADP)</b>	9.2	HTPB/HMX 90.0% Solids 18.0% Al	Conocyl	900	4.04	10.0	2/3.9	Contour	50.3	Strategic	An Advanced Design Prototype (ADP) strategic missile upper stage motor from United Technologies Corp.
<b>IUS Large Motor</b>	9.3	HTPB 86.0% Solids 18.0% Al	Cylinder	550	6.85	37.4	2/1	Contour	35.7	Space	Inertial Upper Stage Solid Rocket Motor, Stage 1 (IUS-SRM). Developed for the Air Force Space Division by CSD. It has a submerged nozzle with a circular arc contour.
<b>Reduced Smoke Maverick (RSM) Motor (TX633)</b>	9.4	HTPB 87.0% Solids 0.0% Al	Modified Cylinder	1520/370	1.2	0.0	1.5/1.5	Cone	2.0	Tactical	Reduced Smoke Maverick (RSM) is a boost sustain tactical motor with very low metal content in the propellant. The nozzle is separated from the chamber by a blast tube. The RSM is unique in the sense that it is near the limit of the assumptions used in developing the SPP.
<b>Minuteman II (MMII) Stage 2 Wing VI</b>	9.5	CTPB 86.0% Solids 15.0% Al	Modified Cylinder	445	9.63	13.4	0.93/2.0	Contour	24.8	Strategic	Minute Mann II, Stage 2, Wing 6 motor (MM226) is a strategic ballistic missile built by Aerojet Solid Rocket Company.
<b>Titan IIIC Stage 0</b>	9.6	PBAN 86.0% Solids 16.0% Al	Segmented Cylinder	550	37.5	0.0	.39/.39	Cone	8.0	Booster	Titan IIIC booster is a large solid rocket motor built by CSD. The nozzle has a steep inlet and small radius of curvature ratio throat.
<b>IUS-SRM2</b>	9.7	HTPB 86.0% Solids 18.0% Al	Modified Cylinder	609	4.28	18.7	2/2	Contour EEC	48.0 174.3	Space	Inertial Upper Stage Solid Rocket Motor, Stage 2, (IUS-SRM2) was developed for the Air Force Space Division by CSD. The IUS-SRM2 is an apogee kick motor (AKM) to circularize a GEO orbit.
<b>Titan 34D Stage 0 (T34-D)</b>	9.8	PBAN 84.0% Solids 16.0% Al	Segmented Cylinder	600	37.7	0.0	0.4/0.4	Cone	8.0	Booster	Titan 34D (T34D) is a large solid booster, that is an advanced replacement for the Titan IIIC Stage 0 motor. An axisymmetric motor with a star grain used in the forward closure. This motor is used to demonstrate the axisymmetric grain design module.
<b>Trident C4 Stage 2</b>	9.9	Double Base	Cylinder Aft Finocyl	7.68	7.68	26.0	1.3/1.8	Contour	20.4	Strategic	Typical ballistic missile stage with a finocyl grain and low length-to-diameter ratio. Used to test the 3-D grain design.
<b>SEP</b>	9.10	HTPB/BMX 90.0% Solids 20.0% Al	Conocyl	473	2.25	15.6	1.7/0.5	Contour	137.0	Space (Apogee Kick)	A space motor built by CSD and nozzle built by SEP of France. The motor uses a high performance propellant containing 12% HMX and 20% aluminum.
<b>Sidewinder</b>	9.11	CTPB 82.0% Solids 16.0% Al	Star/Tube	1.67	1.67	3.0	0.4	18° Cone	5.5	Tactical (Air to Air)	Sidewinder MK-36 is a tactical motor. Used in SPP to verify 2-D grain design module and standardized stability program (SSP)
<b>Extended Delta Star</b>	9.12	CTPB 86.0% Solids 16.0% Al	8 Point Star	560	4.28	25.0	1/1	Contour	30.8		Extended Delta Star 37E TE-M-364-4 is an elongated version of the Delta rocket motor by Thiokol. Used as the third stage on the Improved Delta Vehicle. This motor has been used as a test case for SPP since the code's first release.

**Measured Isp vs Predicted Isp  
Comparison Between  
SPP and VIPER Codes  
(Case #2)**



**Figure 3. Comparison of Standard SPP and PNS (VIPER) Nozzle Performance Prediction with Isothermal Solidification**

**Measured Isp vs Predicted Isp  
Comparison Between  
SPP and VIPER Codes  
(Case #3)**



**Figure 4. Comparison of Standard SPP and PNS(VIPER) Nozzle Performance Prediction without Solidification**

The purpose of these comparisons is not to show which method is more accurate, but to indicate that the choices in loss models have a significant impact on the computed results. Without a compelling reason, the authors feel that the most physically complete models should be used in the performance prediction methodology.

Because a new turbulence model has been added to the PNS module and is being added to the GTBL module, a series of test cases were run to compare the results with the current default turbulence model in the PNS, i.e., the Cebeci-Smith (CS) model. The Spalart-Allmaras (SA) model is added in part because the Cebeci-Smith model uses the boundary layer velocity thickness as a length scale. The computation of the velocity thickness requires that the edge of the boundary layer be known. For Euler calculations, the boundary layer edge is approached asymptotically at infinity and hence the velocity thickness also asymptotes. In a PNS or N-S solution, the edge of the boundary layer is not as easily determined, especially in highly rotational flow of the type found in solid rocket motors. The Spalart-Allmaras model uses the distance from the wall to establish a length scale which is well defined. The test cases we selected were the Extended Delta motor, the SEP motor, and the IUS Large motor (see Table 2 for details). The SA model required a much finer grid spacing than did the CS model to achieve a grid independent solution. The results from this study are shown in Table 3. Also shown in the table for comparison are the MOC/BLM boundary layer losses.

**Table 3. Boundary Layer Loss Comparisons**

<b>Boundary Layer Loss Model</b>	<b>PNS Cebeci-Smith</b>	<b>PNS Spalart-Allmaras</b>	<b>MOC/BLM</b>
<b>Motor</b>	<b><math>\Delta I_{sp}(\text{sec})</math></b>	<b><math>\Delta I_{sp}(\text{sec})</math></b>	<b><math>\Delta I_{sp}(\text{sec})</math></b>
<b>Extended Delta</b>	-3.200	-2.550	-1.599
<b>SEP</b>	-5.727	-4.316	-2.869
<b>IUS Large Motor</b>	-2.779	-1.939	-1.433

As seen in the above table, the PNS/CS solution predicts the highest boundary layer losses, followed by the PNS/SA method, and then the MOC/BLM procedure. The BLM model also uses the Cebeci-Smith turbulence model; however, it uses perfect gas properties and calculates the boundary layer loss by the JANNAF standard method, involving the use of the boundary layer momentum and displacement thicknesses (see CPIA 246 for details) along with some questionable assumptions.

### **SUMMARY AND CONCLUSIONS**

The IHPRPT version of the SPP™ code represents, from a physics based modeling standard, a much improved version of the Solid Performance Program over the version released in 2004. Improvements to the SPP code include full and parabolized Navier-Stokes solvers, an improved boundary layer solver, and improvements to the turbulence models. These improvements have been added to the code and are currently being checked out. The results of the modified code are compared to motor firing data and indicate that further review of all of the SPP loss mechanisms is required.

### **ACKNOWLEDGEMENTS**

The authors would like to thank the customers who have supported the development of the SPP, GTBL, and VIPER codes. In particular, we would like to thank the Air Force Research Laboratory and Mr. Hieu Nguyen for their support and guidance. This work was conducted under contract FA9300-05-C-0011 from the Air Force Research Laboratory.

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# IHPRPT Improvements to the Solid Performance Program (SPP)

**54<sup>th</sup> JANNAF PROPULSION MEETING  
DENVER, COLORADO  
MAY 14 - 17, 2007**

**Douglas Coats, Daniel Berker, E. Carl Hylin, Stuart Dunn,  
Deborah Babbitt, and James Tullos  
Software and Engineering Associates, Inc  
Carson City, NV  
775-882-1966**



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# SPP NOZZLE PERFORMANCE IMPROVEMENT



- **Extensions to the SPP Nozzle Performance Module**
  - Include PNS Nozzle Flow Field Solver
  - Include Upgraded Subsonic-Transonic Flow Solver





# Extensions to the SPP Nozzle Performance Module

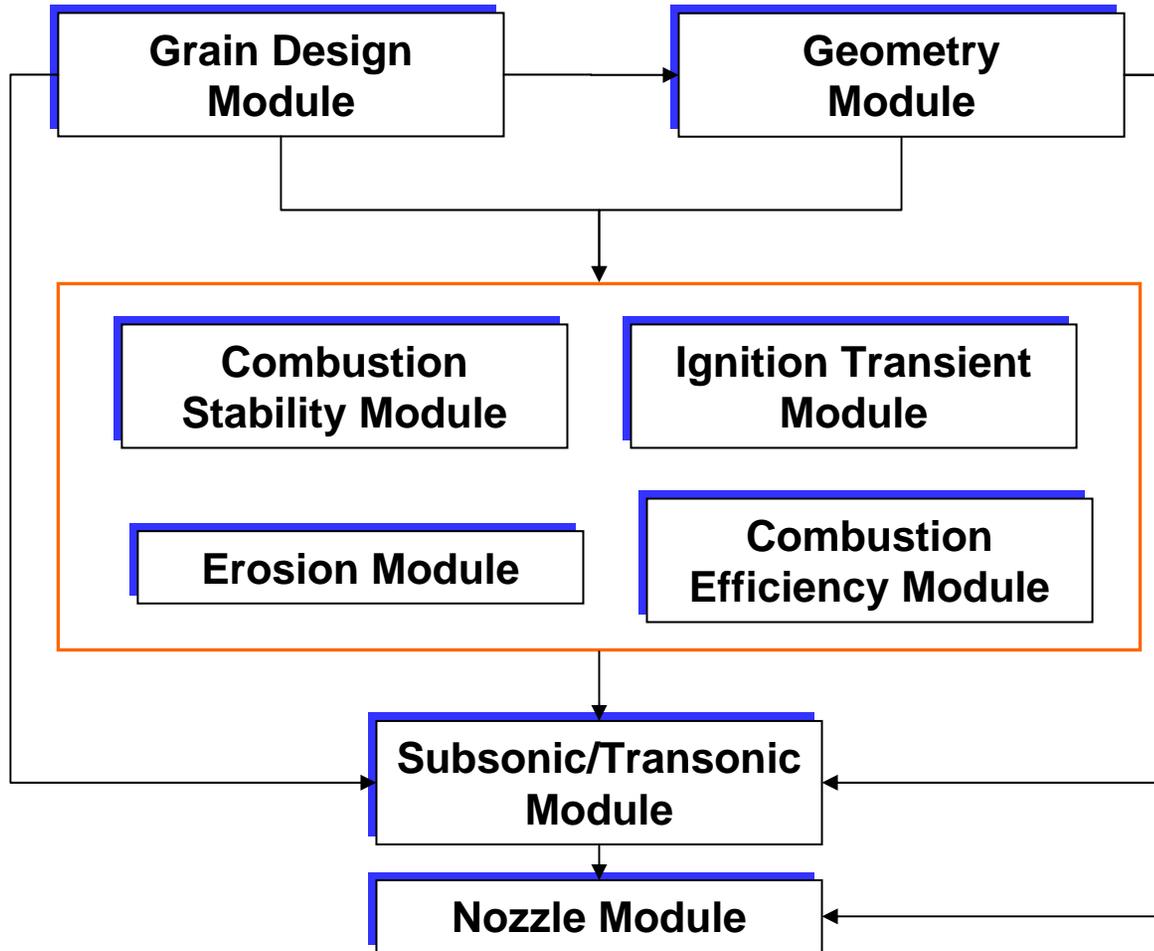


- **Include PNS Nozzle Flow Field Solver**
  - Extract from SEA's VIPER 3.6 code
- **Include Upgraded Subsonic-Transonic Flow Solver**
  - Extract Fully Coupled Transonic (FCT) solver from SPP for initial guess generation
  - Extract solver from SEA's GTBL code





# SPP Flow Diagram





# SPP Control Script



- **All modules coordinated by centralized PERL script**
- **PERL chosen for portability and text manipulation capabilities**
- **Duties of control script:**
  - **Determines modules to run based on user input**
  - **Coordinates order to run modules**
  - **Coordinates input/output between modules**
  - **Notifies user of certain input errors before execution**
    - **Inconsistent modules**
    - **Multiple modules performing the same task**
    - **Required inputs not specified**

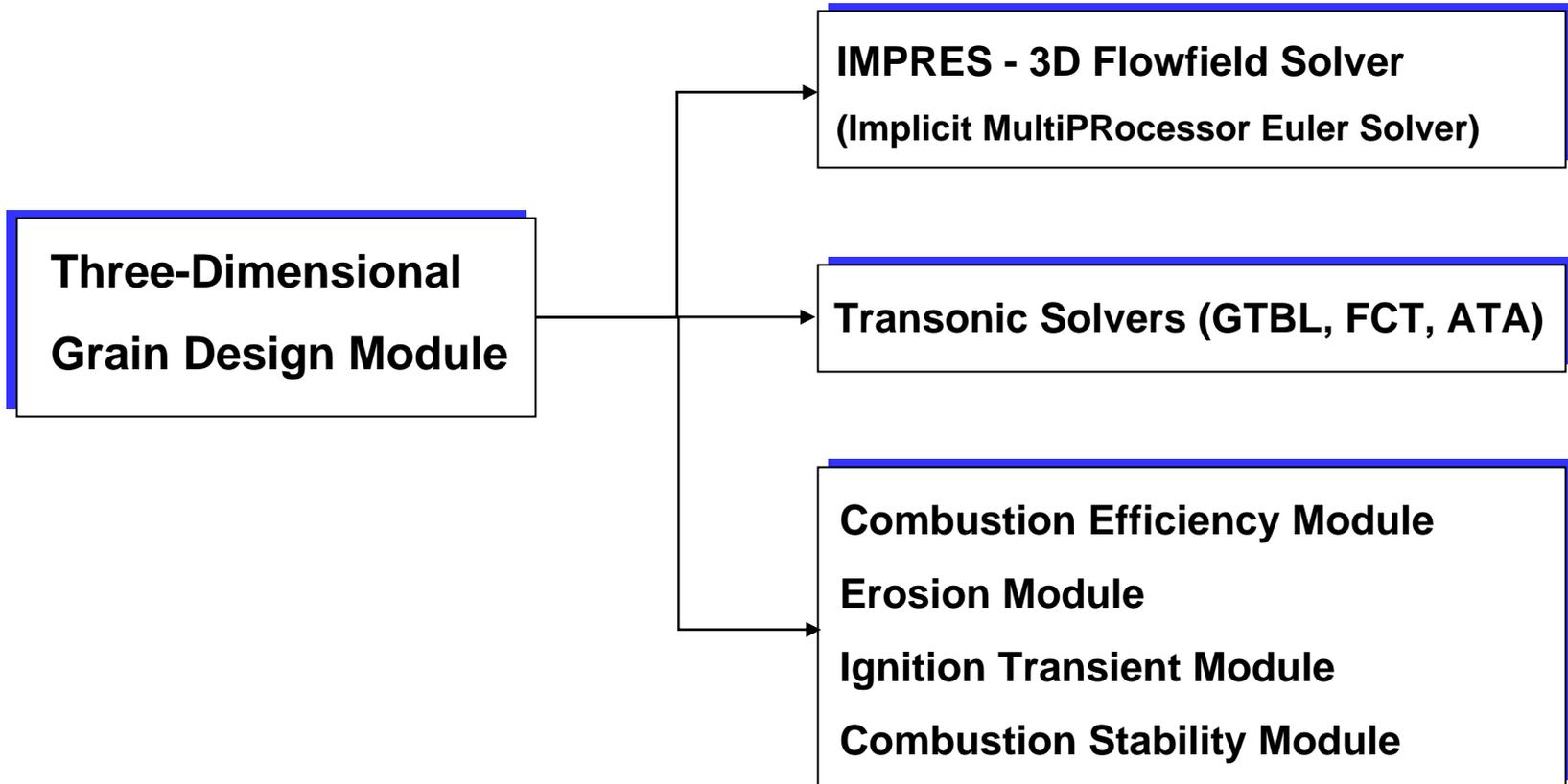




# SPP Flow Diagram



## Motor Module

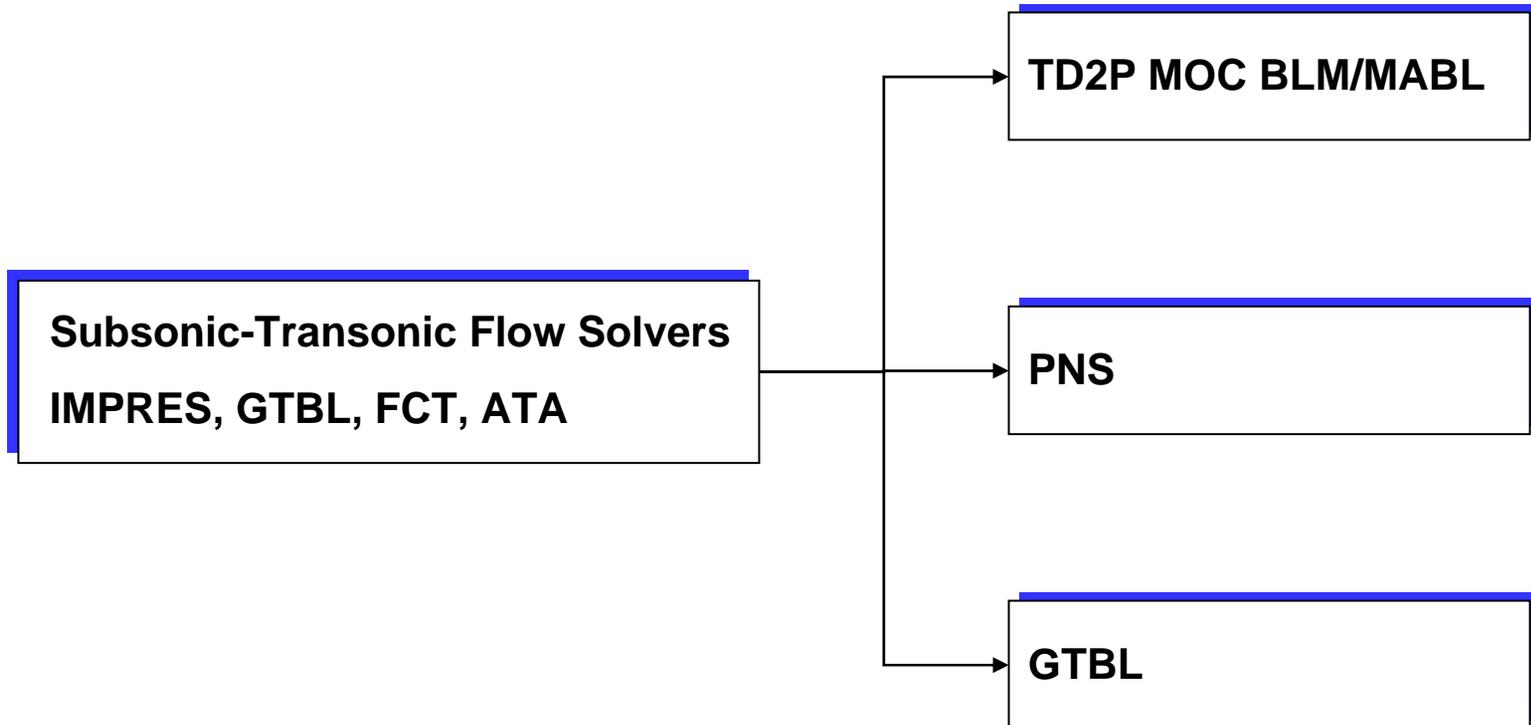




# SPP Flow Diagram

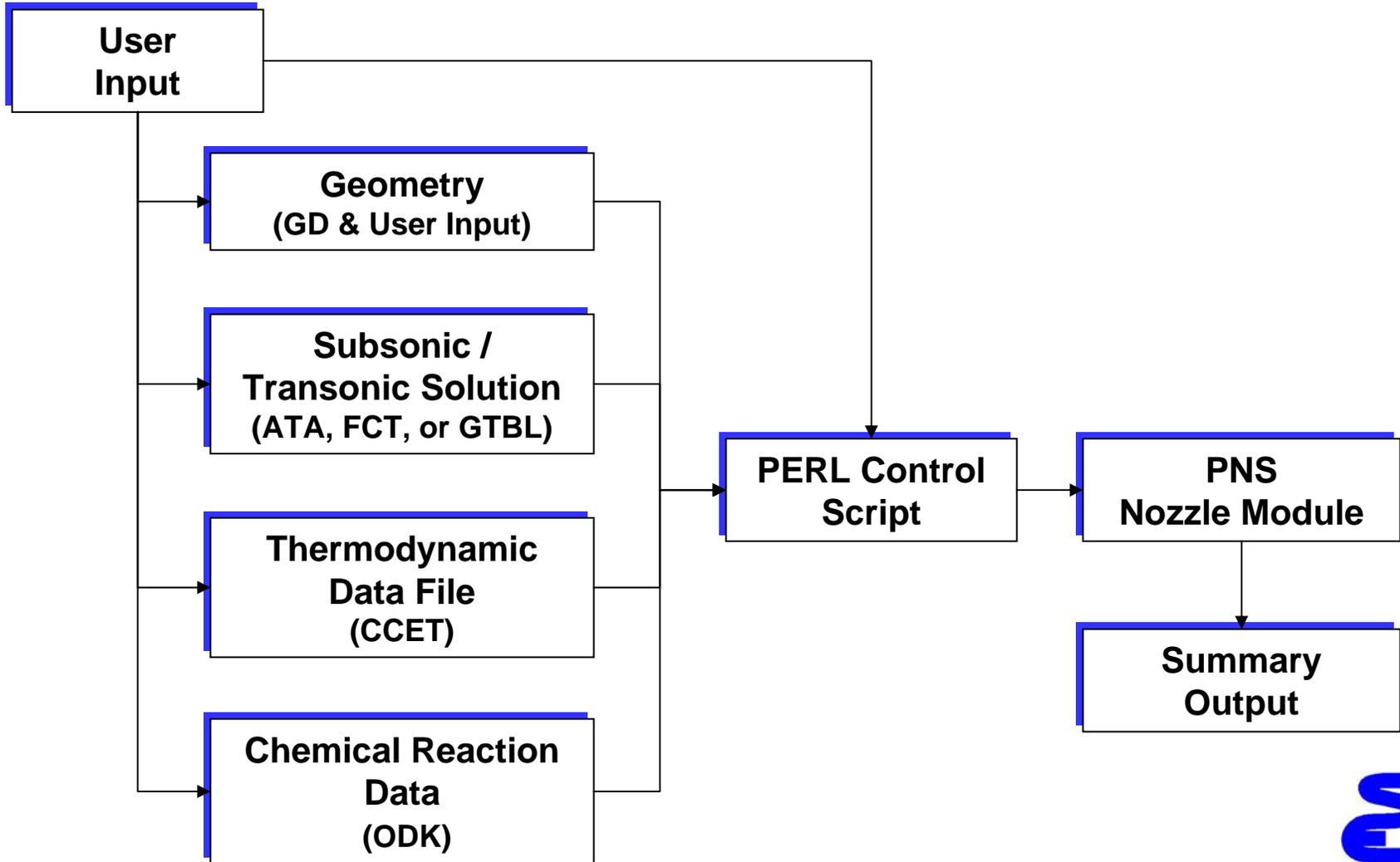


## Nozzle Module





# SPP Module Flow Example





# GTBL

## Generalized Transonic and Boundary Layer



- **GTBL Code**
  - **New, state-of-the-art technology**
  - **Interior ballistics:**
    - **Full, axisymmetric Navier-Stokes (RANS) solution**
    - **Generalized moving coordinate system**
    - **Distributed gas production term**
  - **Chemistry:**
    - **Kinetic or equilibrium chemistry**
    - **Local compressibility effects**
  - **Heat transfer & thermal environment:**
    - **Accurately calculates extreme transient cases**





# Particle Capabilities in GTBL



- **Capabilities/Options**
  - Up to two droplet types (e.g. “fuel” , “oxidizer”, or two metal oxides)
  - Droplet evaporation
  - Group combustion models (neighbor effects)
  - Effects of turbulent diffusion
  - Coupling to finite-rate chemistry
  - Droplet Breakup
  - Droplet Collision/Coalescence





# PNS Module Attributes



- **PNS: Parabolized Navier-Stokes Solver**
- **SEA VIPER 3.6 Code**
  - PNS Module Extracted
  - VIPER 10+ years proven
- **Full finite rate chemistry**
- **Multiple particle groups with collision/coalescence and breakup**
- **Isothermal and kinetic droplet solidification models**
- **Three turbulence models**
  - Cebeci-Smith
  - $k-\varepsilon$
  - Spalart-Allmaras one equation model





# Nozzle Flow Solver Options



## SubSonic - TransSonic

GTBL

GTBL

GTBL(E)

GTBL(E)

FCT

FCT

ATA

ATA/MABL

ATA

## Supersonic

GTBL

PNS

GTBL(E)

PNS(E)

PNS(E)

MOC

MOC

PNS

PNS(E)

## Boundary Layer

GTBL

PNS

MABL

MABL

MABL

MABL

MABL/BLM  
(current default)

MABL/PNS

MABL





# SPP Verification & Validation



- **Verification**
  - Existing codes
  - Make sure it still works, both target and updates
  - Check integration and linkages
- **Validation**
  - Test individual models against existing data sets
  - Compare entire model against motor firing data





# SPP Validation



- **Comparison to motor firing data**
  - Twelve motors from the existing SPP database
  - Bates motors
  - New motors
  - **Common IHRPT Modeling & Simulation Motor Comparison Database**
    - Minuteman 3, third stage
    - 125# Bates Motor
    - TBD





# Twelve SPP Database Motors



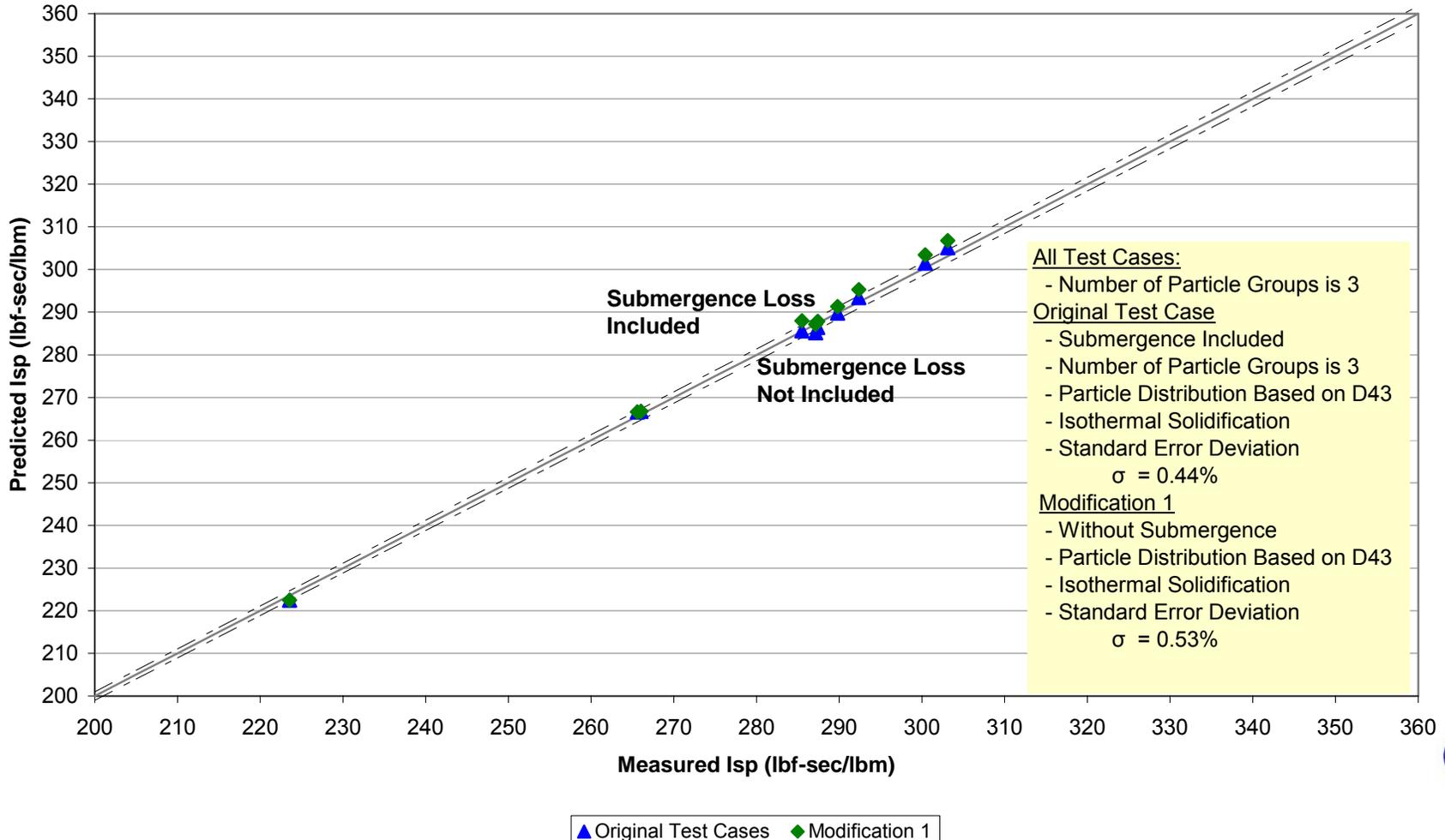
Test Case	SPP Vol. I, Section	Propellant Type	Grain Geometry	$\bar{P}_c$	$D_T$	Submergence %	$\frac{R_c/R_r}{U_p/D_n}$	Expansion Section	$\epsilon$	Classification	Motor Description
AIM	9.1	PBAN 84.5% Solids 16.4% Al	Conocyl	730	2.03	8.0	2/2	Cone	103.2	Space	AIM is a small space motor with a relatively high expansion ratio, 103.2. The nozzle inlet is a circular arc-cone-circular arc throat. The exhaust nozzle is a 19.7° cone.
C4 Stage 3 (ADP)	9.2	HTPB/HMX 90.0% Solids 18.0% Al	Conocyl	900	4.04	10.0	2/3.9	Contour	50.3	Strategic	An Advanced Design Prototype (ADP) strategic missile upper stage motor from United Technologies Corp.
IUS Large Motor	9.3	HTPB 86.0% Solids 18.0% Al	Cylinder	550	6.85	37.4	2/1	Contour	35.7	Space	Inertial Upper Stage Solid Rocket Motor, Stage 1 (IUS-SRM). Developed for the Air Force Space Division by CSD. It has a submerged nozzle with a circular arc contour.
Reduced Smoke Maverick (RSM) Motor (TX633)	9.4	HTPB 87.0% Solids 0.0% Al	Modified Cylinder	1520/370	1.2	0.0	1.5/1.5	Cone	2.0	Tactical	Reduced Smoke Maverick (RSM) is a boost sustain tactical motor with very low metal content in the propellant. The nozzle is separated from the chamber by a blast tube. The RSM is unique in the sense that it is near the limit of the assumptions used in developing the SPP.
Minuteman II (MMII) Stage 2 Wing VI	9.5	CTPB 86.0% Solids 15.0% Al	Modified Cylinder	445	9.63	13.4	0.93/2.0	Contour	24.8	Strategic	Minute Mann II, Stage 2, Wing 6 motor (MM226) is a strategic ballistic missile built by Aerojet Solid Rocket Company.
Titan IIIC Stage 0	9.6	PBAN 86.0% Solids 16.0% Al	Segmented Cylinder	550	37.5	0.0	.39/.39	Cone	8.0	Booster	Titan IIIC booster is a large solid rocket motor built by CSD. The nozzle has a steep inlet and small radius of curvature ratio throat.
IUS-SRM2	9.7	HTPB 86.0% Solids 18.0% Al	Modified Cylinder	609	4.28	18.7	2/2	Contour EEC	48.0 174.3	Space	Inertial Upper Stage Solid Rocket Motor, Stage 2, (IUS-SRM2) was developed for the Air Force Space Division by CSD. The IUS-SRM2 is an apogee kick motor (AKM) to circularize a GEO orbit.
Titan 34D Stage 0 (T34-D)	9.8	PBAN 84.0% Solids 16.0% Al	Segmented Cylinder	600	37.7	0.0	0.4/0.4	Cone	8.0	Booster	Titan 34D (T34D) is a large solid booster, that is an advanced replacement for the Titan IIIC Stage 0 motor. An axisymmetric motor with a star grain used in the forward closure. This motor is used to demonstrate the axisymmetric grain design module.
Trident C4 Stage 2	9.9	Double Base	Cylinder Aft Finocyl		7.68	26.0	1.3/1.8	Contour	20.4	Strategic	Typical ballistic missile stage with a finocyl grain and low length-to-diameter ratio. Used to test the 3-D grain design.
SEP	9.10	HTPB/BMX 90.0% Solids 20.0% Al	Conocyl	473	2.25	15.6	1.7/0.5	Contour	137.0	Space (Apogee Kick)	A space motor built by CSD and nozzle built by SEP of France. The motor uses a high performance propellant containing 12% HMX and 20% aluminum.
Sidewinder	9.11	CTPB 82.0% Solids 16.0% Al	Star/Tube		1.67	3.0	0.4	18° Cone	5.5	Tactical (Air to Air)	Sidewinder MK-36 is a tactical motor. Used in SPP to verify 2-D grain design module and standardized stability program (SSP)
Extended Delta Star	9.12	CTPB 86.0% Solids 16.0% Al	8 Point Star	560	4.28	25.0	1/1	Contour	30.8		Extended Delta Star 37E TE-M-364-4 is an elongated version of the Delta rocket motor by Thiokol. Used as the third stage on the Improved Delta Vehicle. This motor has been used as a test case for SPP since the code's first release.



# SPP Performance Model Comparison



Measured Isp vs Predicted Isp  
ATA Test Cases  
Original & Modification #1 Test Cases



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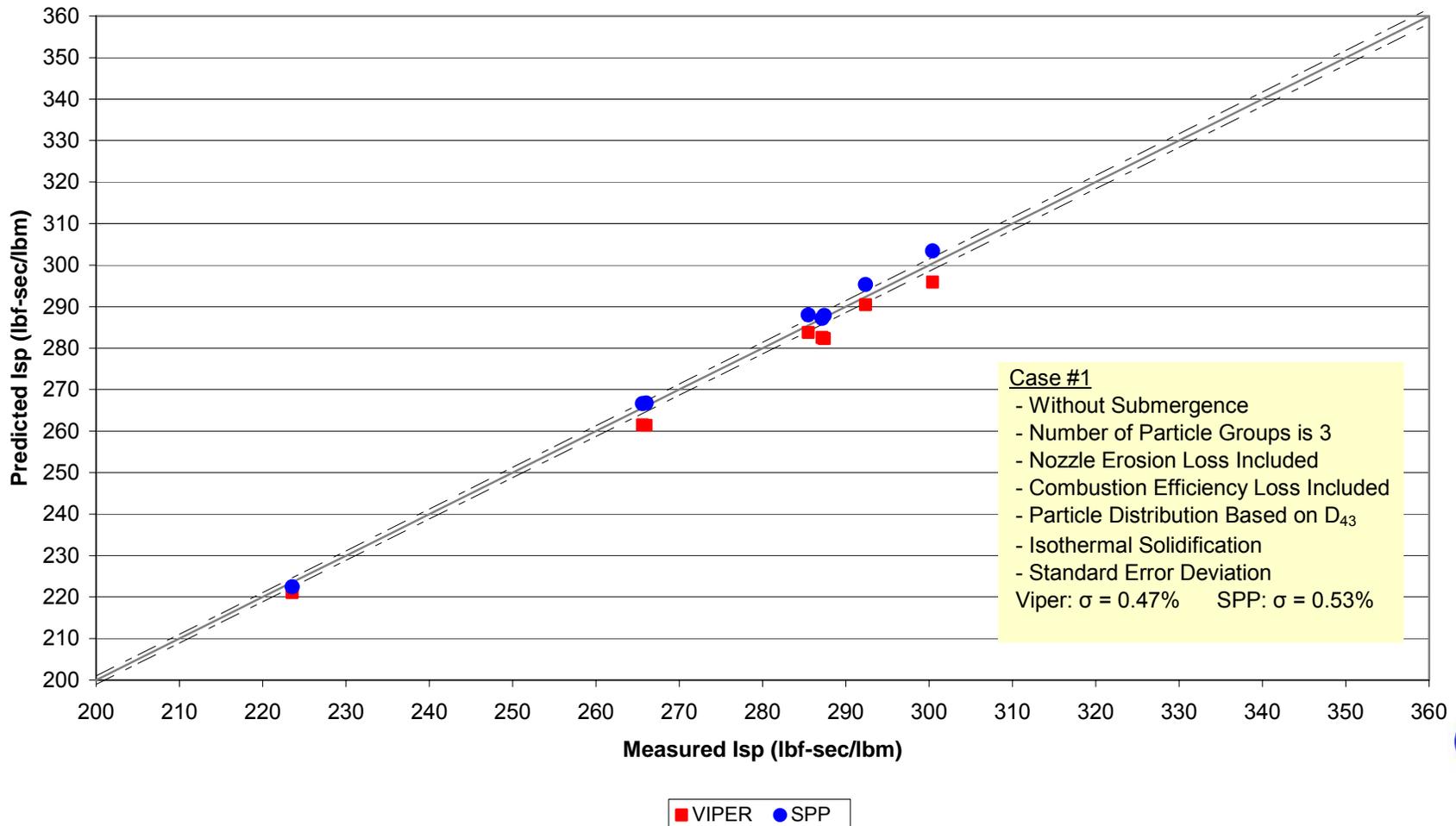




# SPP Performance Model Comparison



Measured Isp vs Predicted Isp  
Comparison Between  
SPP and VIPER Codes  
(Case #1)

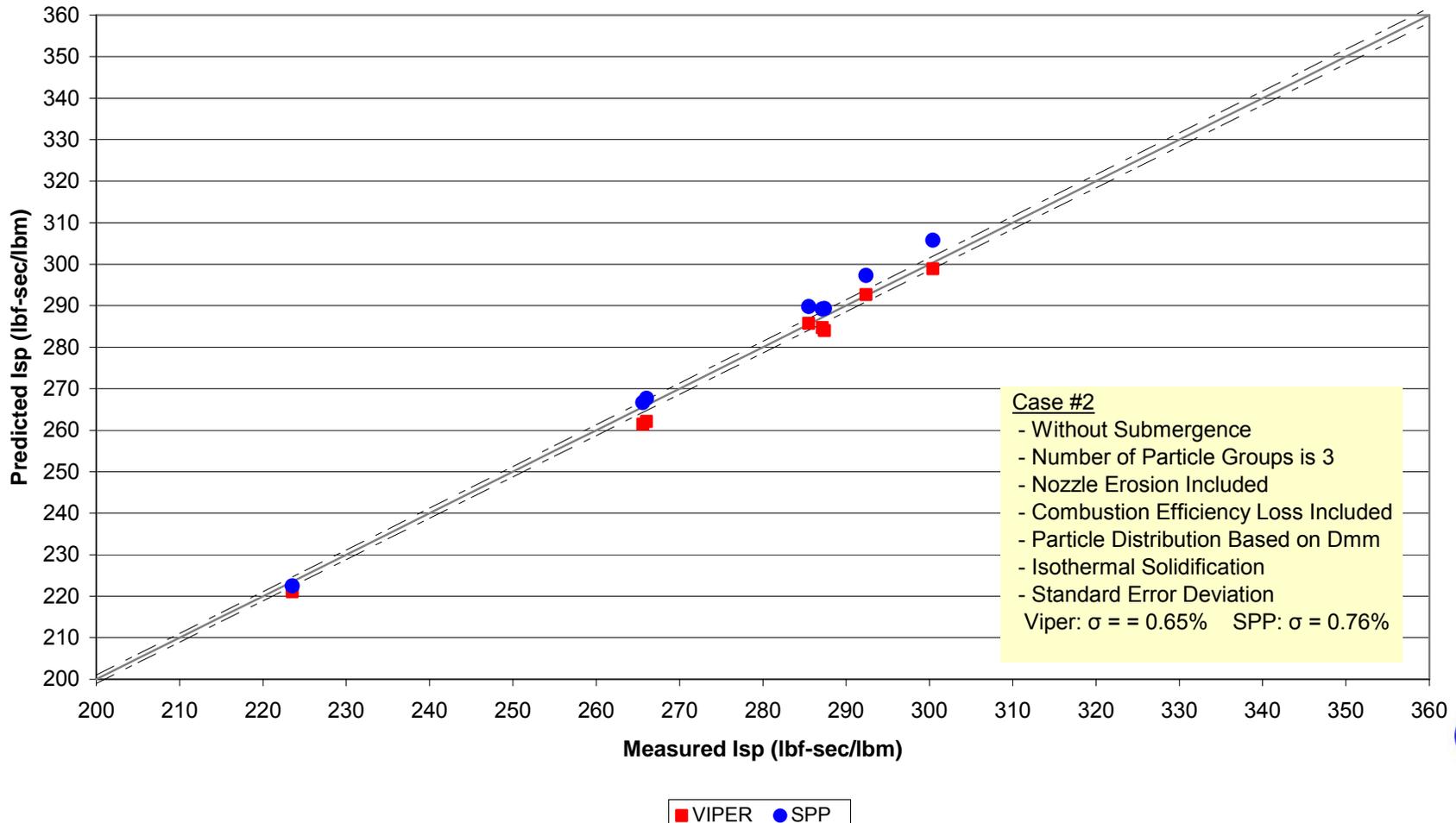




# SPP Performance Model Comparison



## Measured Isp vs Predicted Isp Comparison Between SPP and VIPER Codes (Case #2)

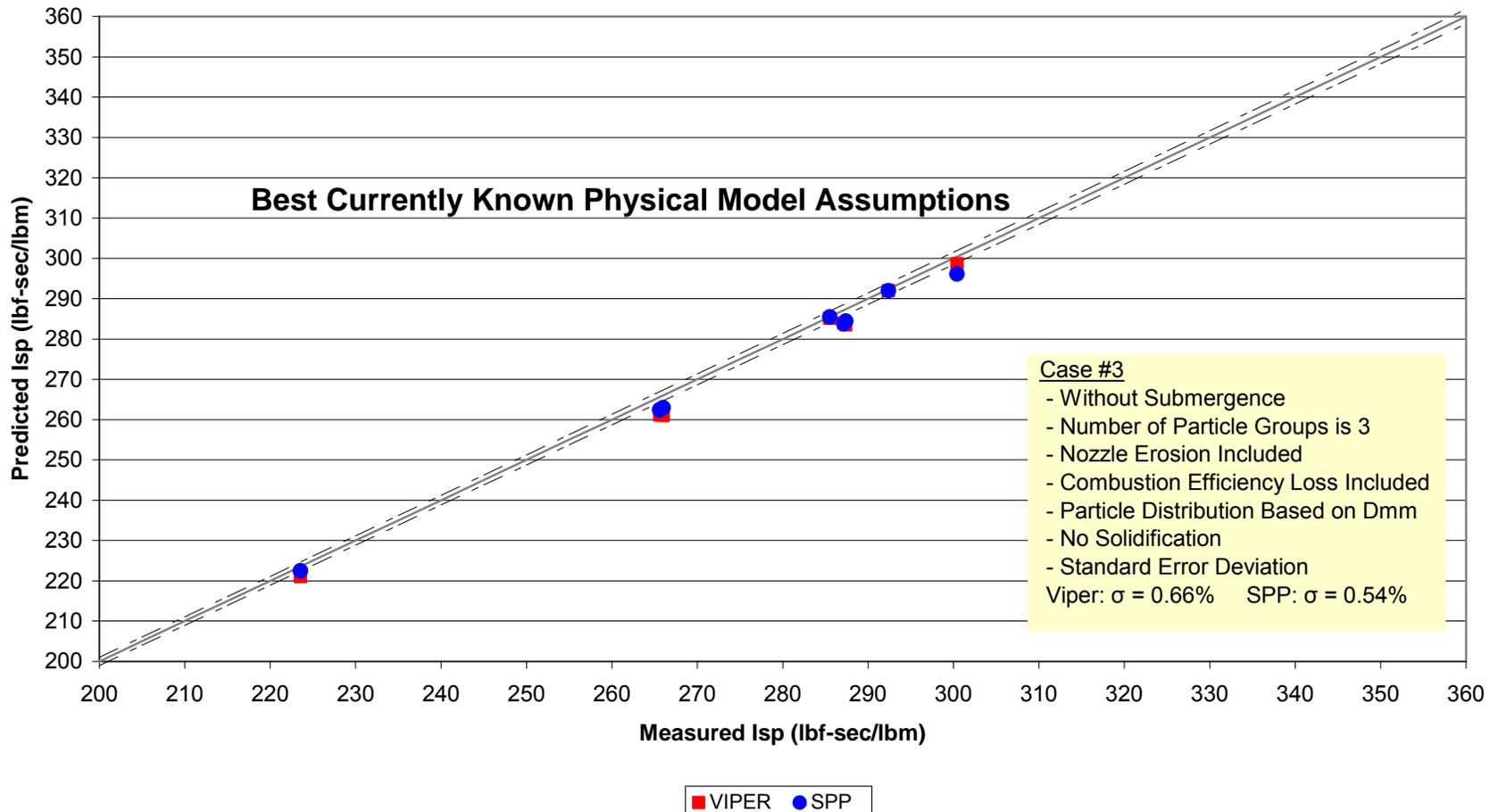




# SPP Performance Model Comparison



## Measured Isp vs Predicted Isp Comparison Between SPP and VIPER Codes (Case #3)





# Turbulence Model Comparison Boundary Layer Loss

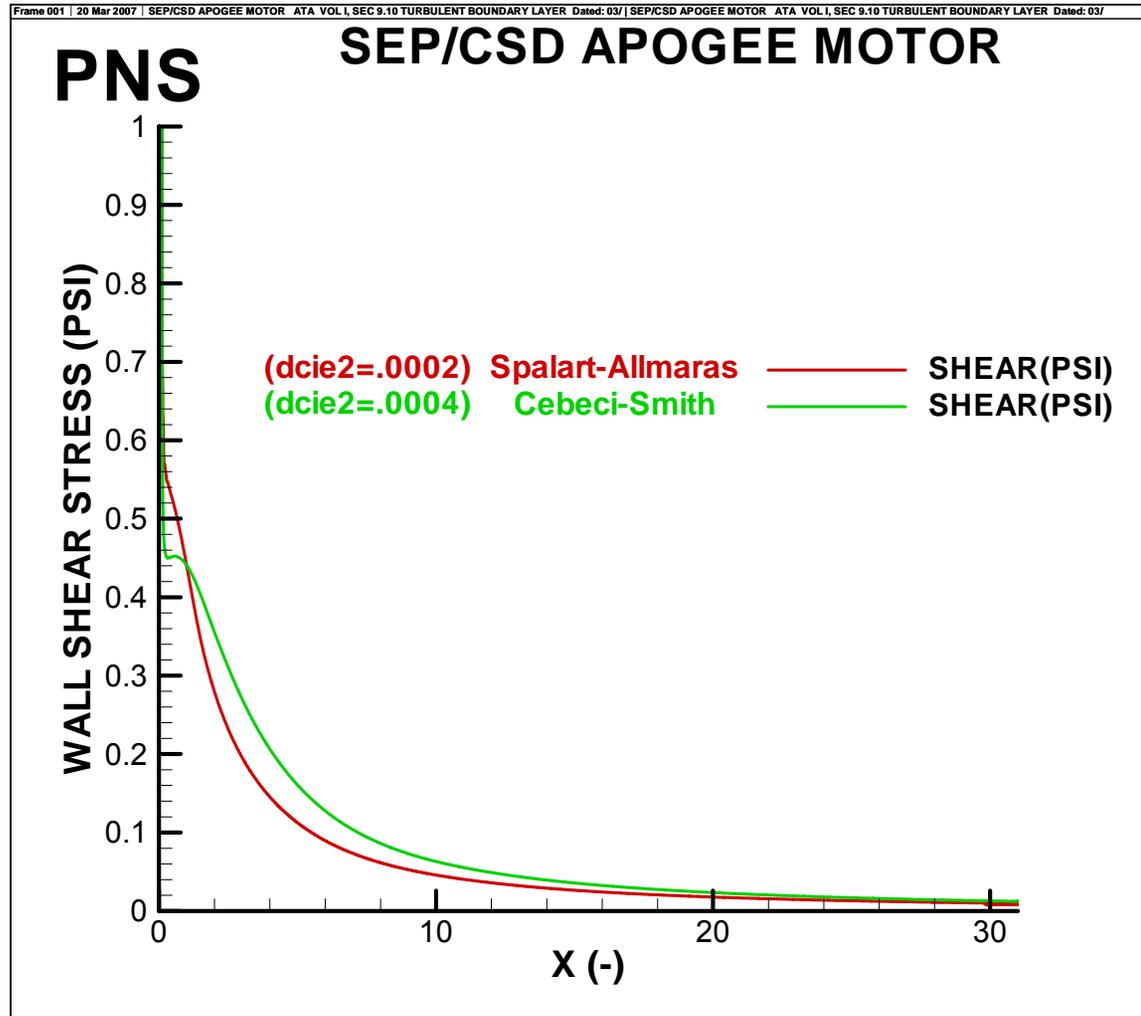


<b>Boundary Layer Loss Model</b>	<b>PNS Cebeci-Smith</b>	<b>PNS Spalart-Allmaras</b>	<b>MOC/BLM</b>
<b>Motor</b>	$\Delta I_{sp}$ (sec)	$\Delta I_{sp}$ (sec)	$\Delta I_{sp}$ (sec)
<b>Extended Delta</b>	-3.200	-2.550	-1.599
<b>SEP</b>	-5.727	-4.316	-2.869
<b>IUS Large Motor</b>	-2.779	-1.939	-1.433



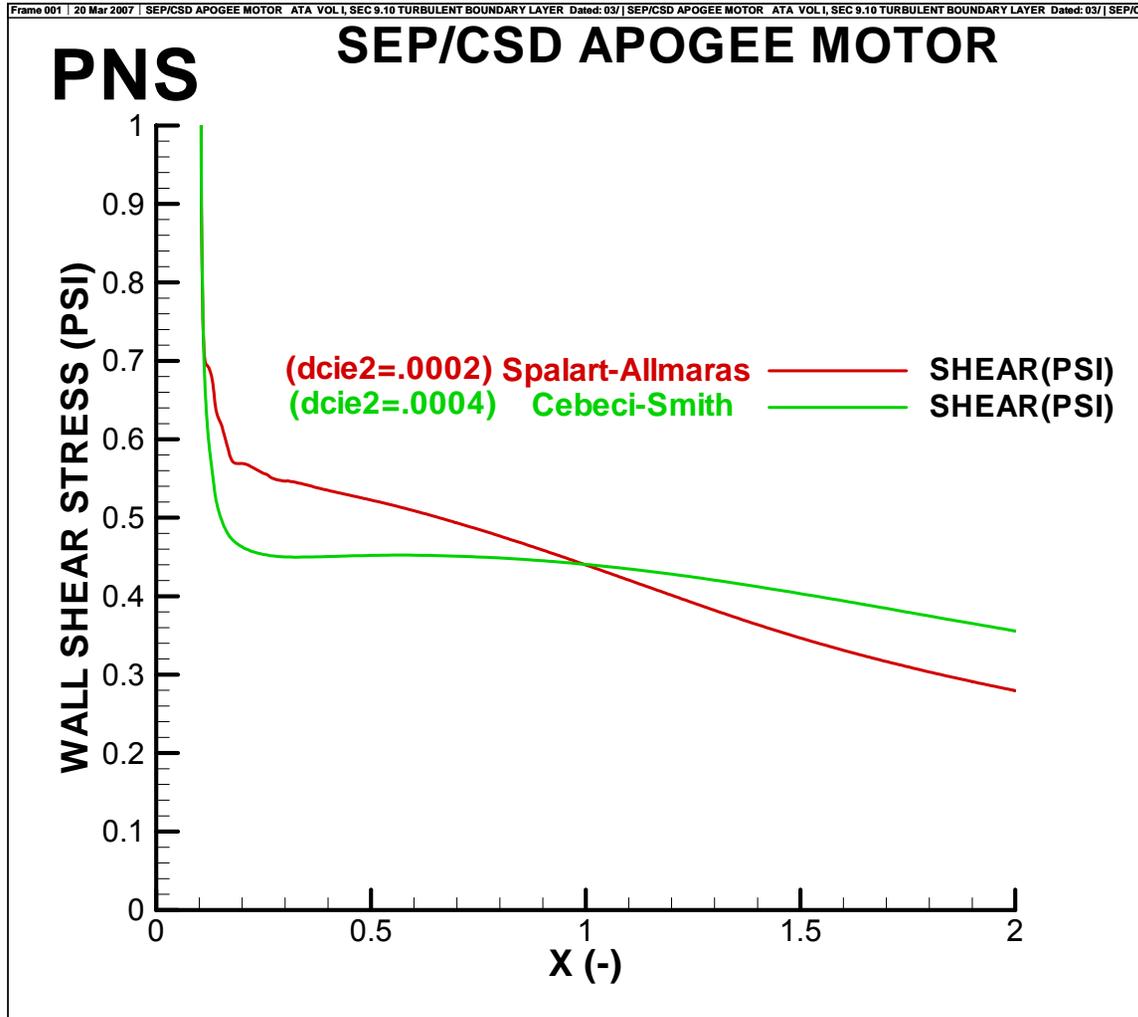


# Turbulence Model Comparison





# Turbulence Model Comparison





# Conclusions



- **SPP: Improved Models**
  - Addition of PNS
  - Addition of Full Navier-Stokes Solver
    - Chemistry
    - Particle flow and size change models
- **PNS: Turbulence Model**
  - Addition of Spalart-Allmaras
- **Other Loss Mechanisms: Implementation of**
  - Remains Important
  - Accurately predict nozzle performance in SRM's





# Acknowledgements



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