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INTEGRATION

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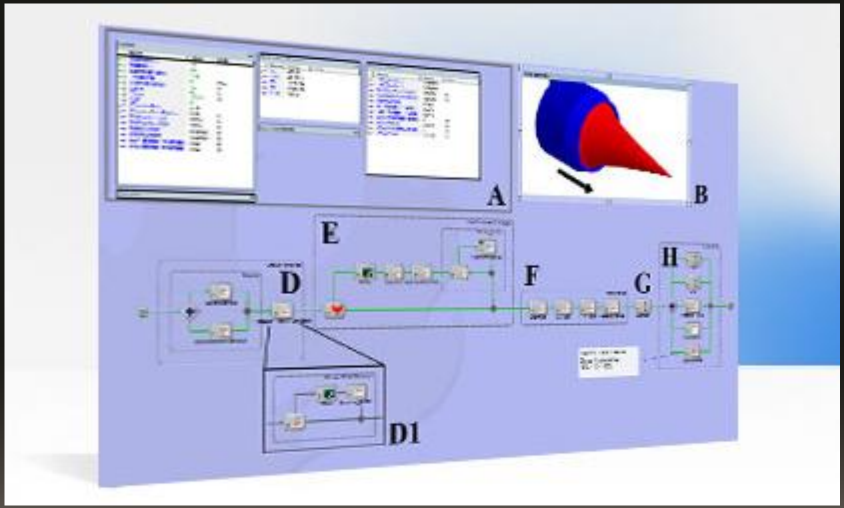
Rocket Science in the Fast Lane

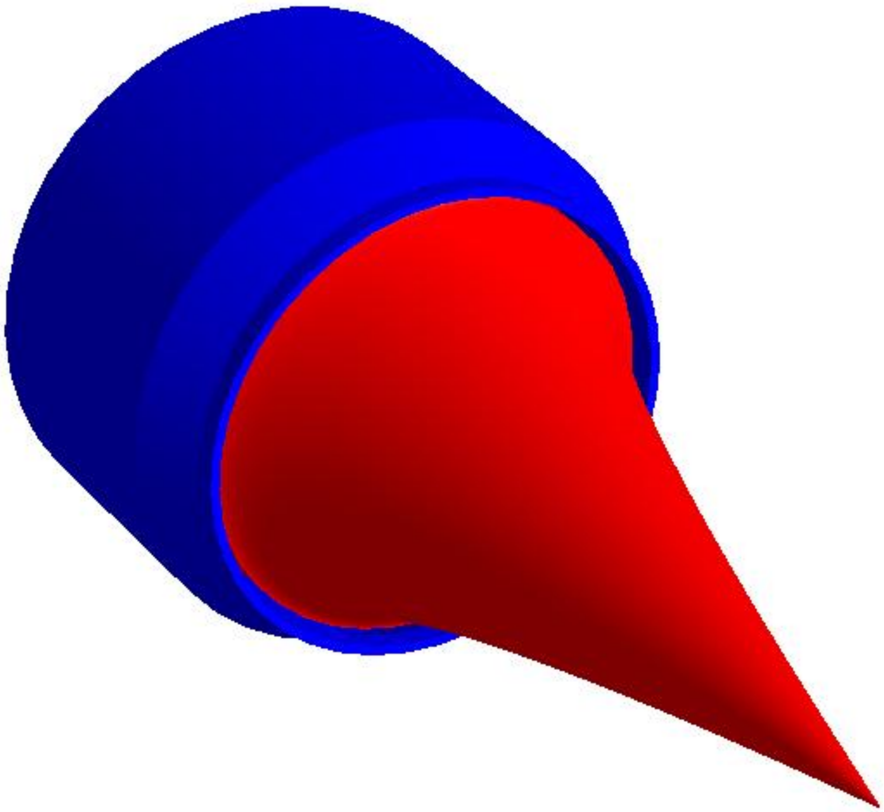
Optimizing a New Upper Stage Rocket Engine in 6 weeks



J. Simmons, PhD

Apr 15, 2015

The Dual-Expander Aerospike Nozzle Upper Stage Engine



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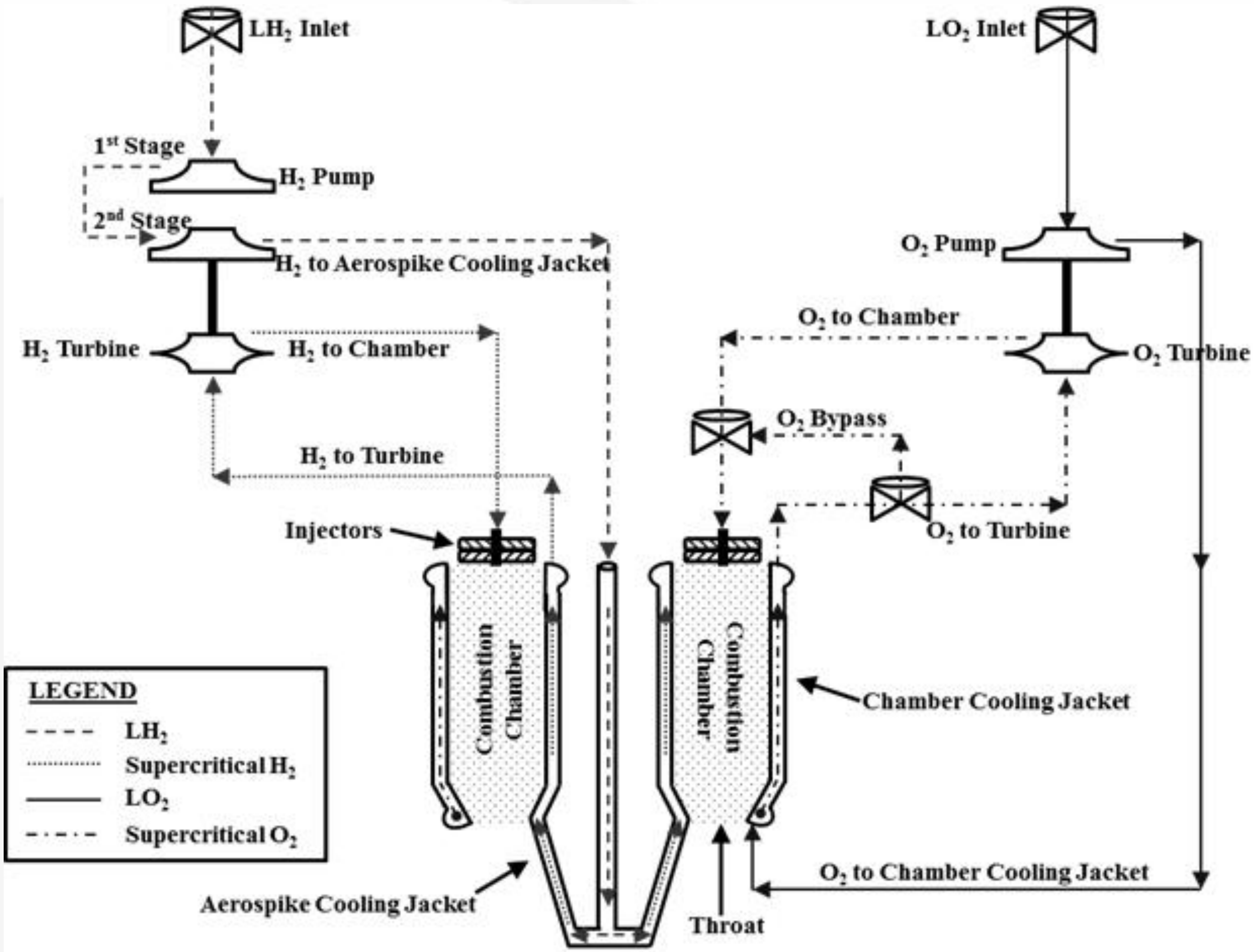
NIPPON STEEL & SUMITOMO METAL
SEOUL SEOUL SEMICONDUCTOR

The DEAN uses 2 novel design choices



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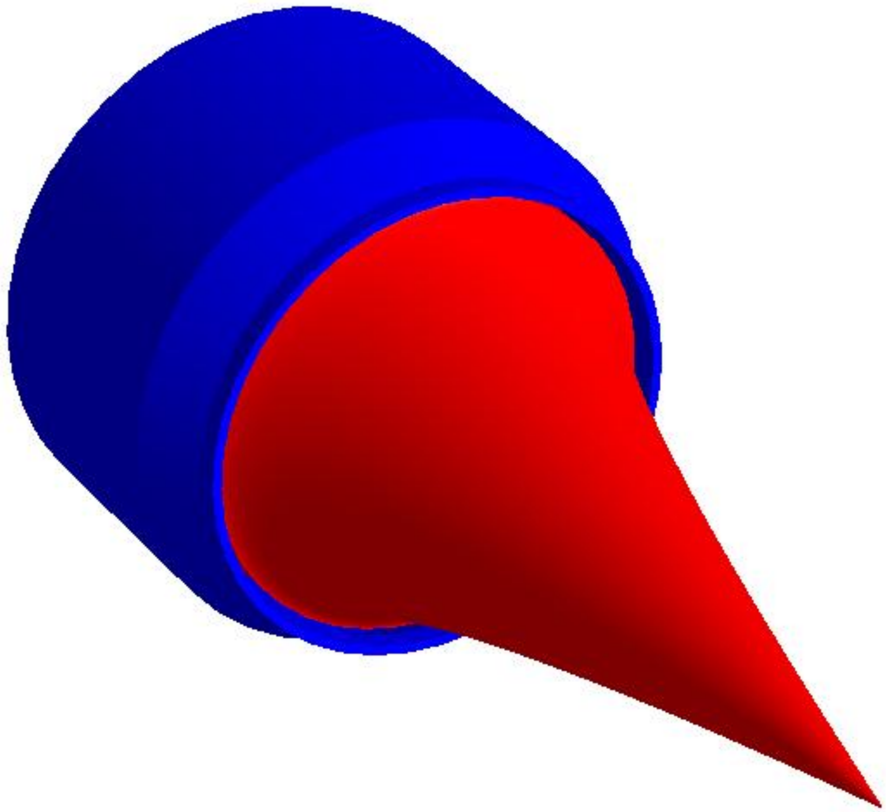
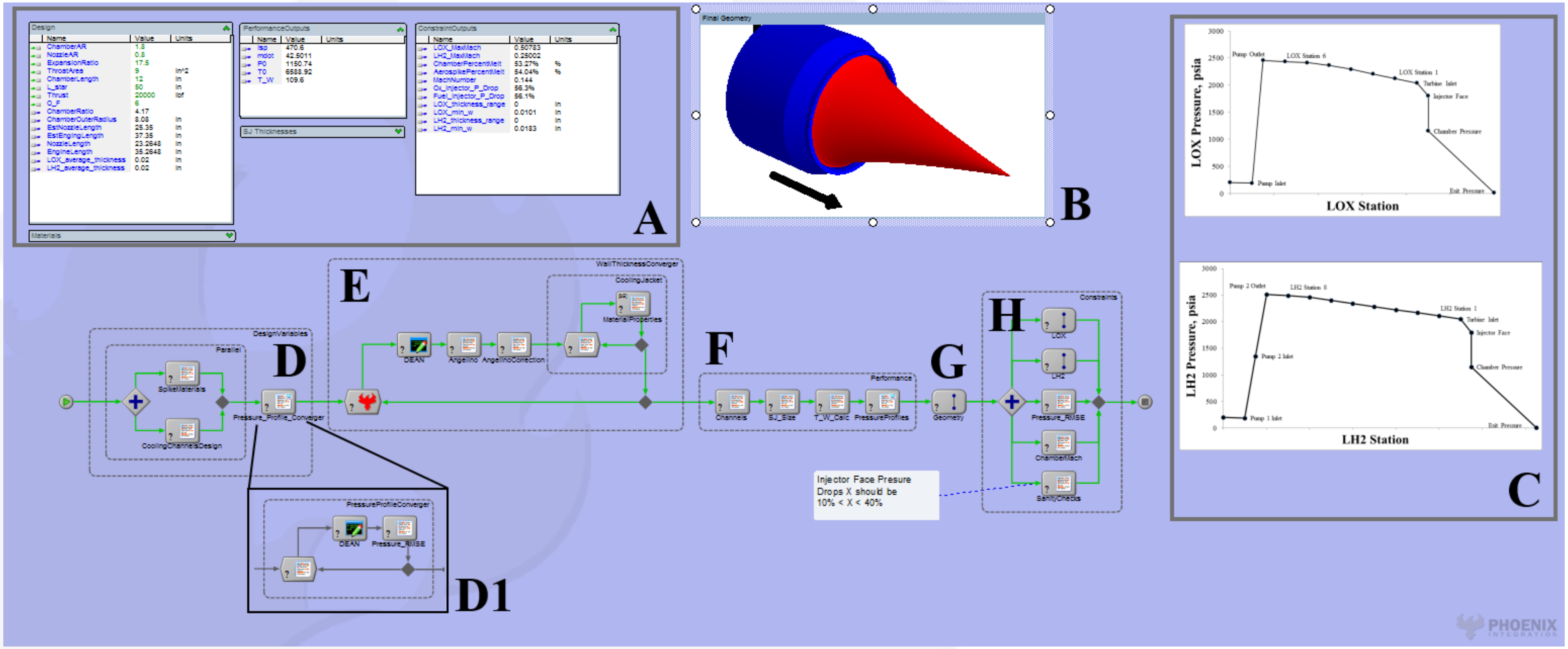


The DEAN Simulation Workflow in ModelCenter




easy
STAPLES

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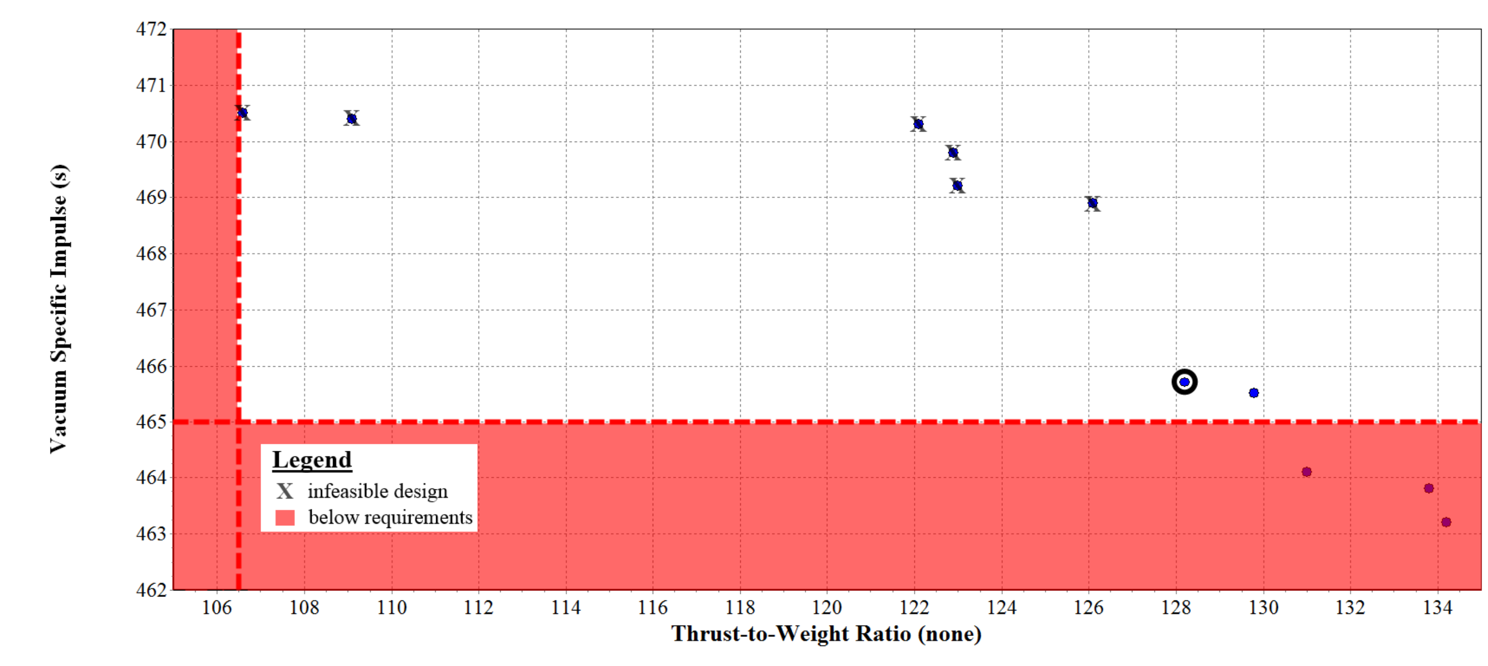
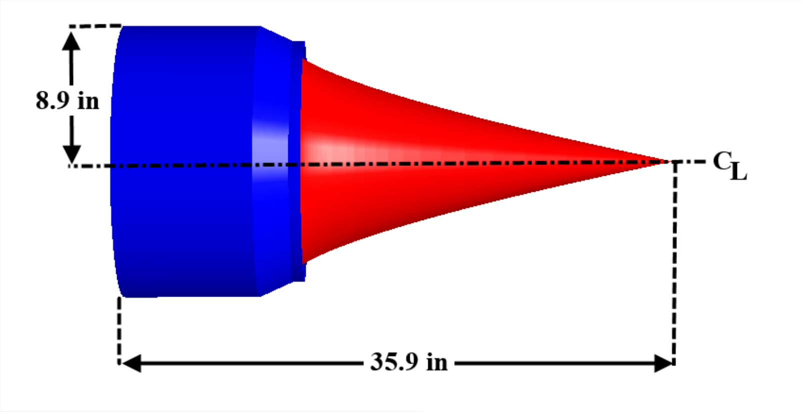
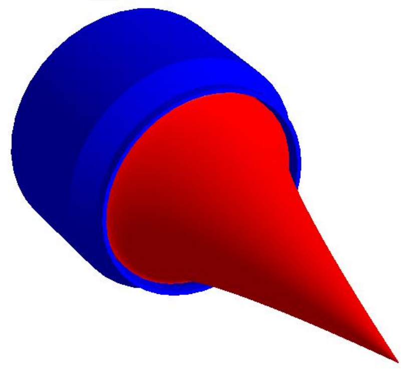
The three DEAN missions

IHPRPT/NGE	X-37	SLS
		
25 klbf < F < 35 klbf 465.0 s < I_{sp} 106.5 < T/W	F = 6,600 lbf 450.5 s < I_{sp} 106.5 < T/W	F = 100 klbf or 294 klbf 448.0 s < I_{sp} 106.5 < T/W

IHPRPT/NGE 30klbf Results



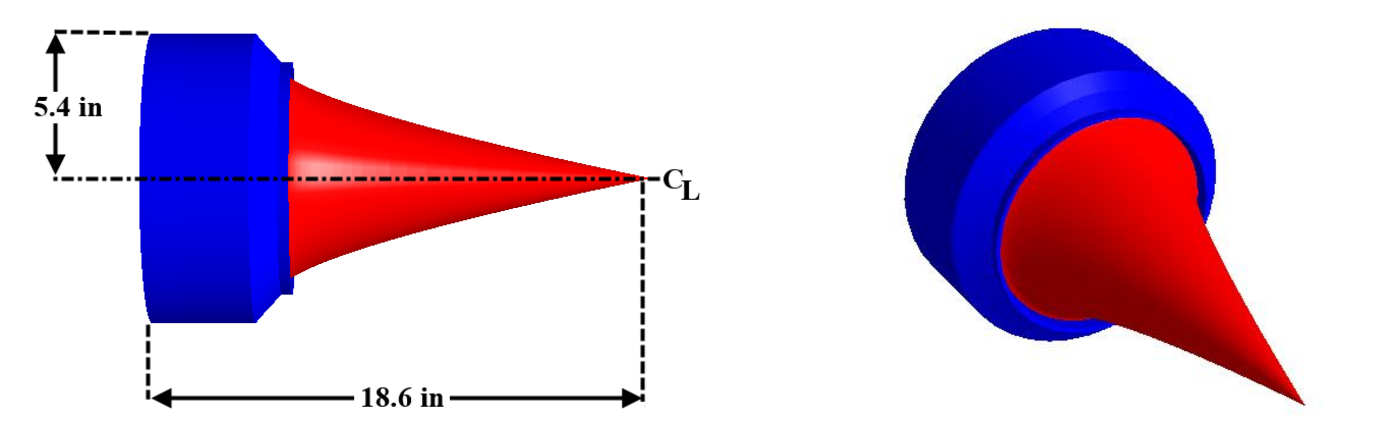




DEAN exceeds requirements & outperforms traditional engines

Case	Engine	I_{sp_vac} (s)	T/W	Length (L/L_{NGE})	Outer Radius (r/r_{NGE})
Case 1: 25,000 lbf					
	DEAN	466.0	128.1	0.48	0.23
	RL10	464.1	42.9	1.98	1.16
Case 2: 30,000 lbf					
	DEAN	465.7	128.2	0.53	0.24
	RL10	464.1	43.5	2.15	1.28
Case 3: 35,000 lbf					
	DEAN	469.4	127.0	0.58	0.28
	RL10	464.1	43.9	2.31	1.38

The DEAN's performance and compact size make it an excellent candidate for space planes

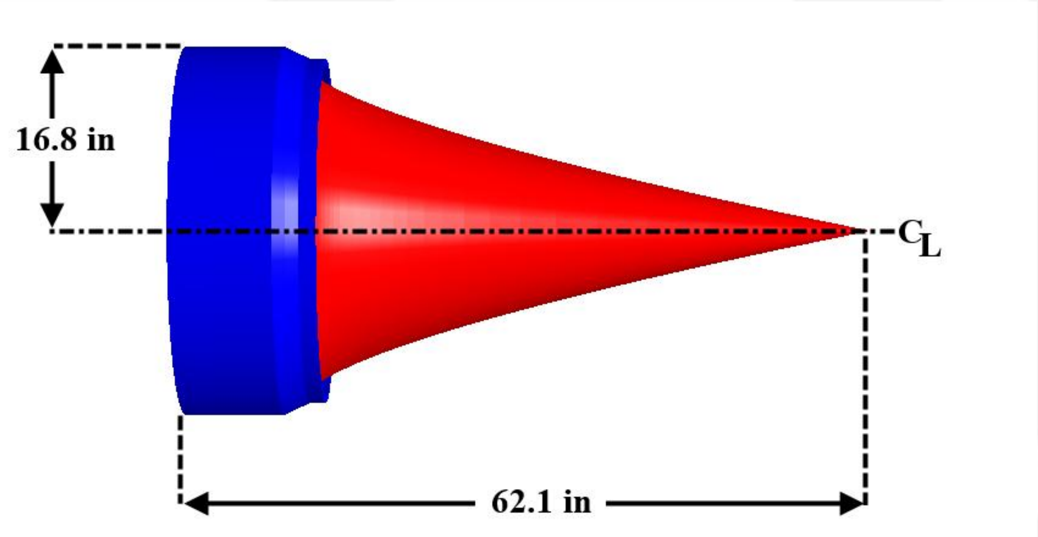


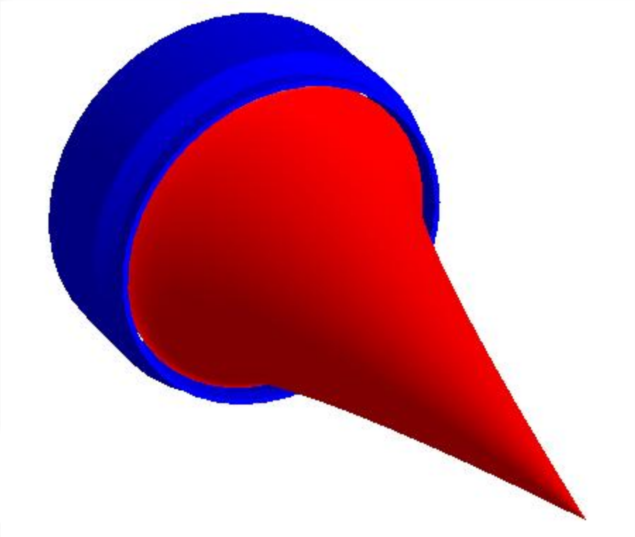
Engine	I_{sp_vac} (s)	T/W	Length (L/L_{AR2-3})	Outer Radius (r/r_{AR2-3})
DEAN	457.2	107.5	0.78	0.54
RL10A-4	449.7	48.0	1.91	1.24

The DEAN is also an excellent candidate for super-heavy lift, outperforming the RL10 & J-2X

Case	Engine	F (lbf)	I_{sp_vac} (s)	T/W	Length (in)	Outer Radius (in)
Case 1: 4 RL10s						
	DEAN	100,000	465.9	110.2	62.1	16.8
	SLS Design	99,000	462.5	37.3	86.5	108.0
Case 2: J-2X						
	3 DEANs	300,000	465.9	110.2	62.1	36.2
	SLS Design	294,000	448.0	55.0	180.0	60.0

SLS Geometry

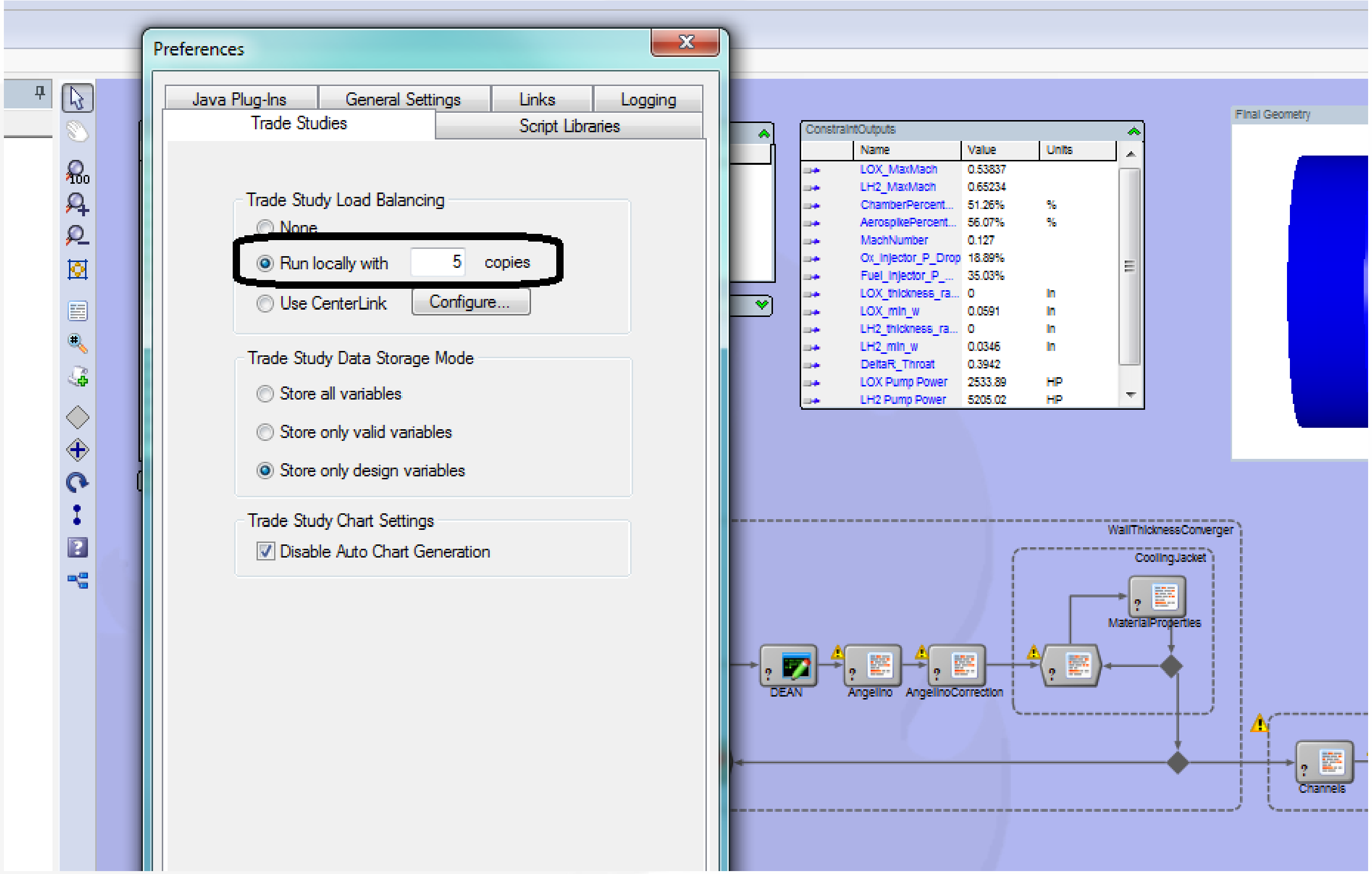




The DEAN optimization process

Step	Description
1	Set vacuum thrust per mission requirements
2	Find the smallest throat area with wall temperatures below 60% melt pt
3	Run a DOE over expansion ratio & chamber length to bound trade space
4	Create formal definition of the multi-objective optimization problem
5	Configure the Darwin Optimizer to implement the optimization problem
6	Seed the Darwin Optimizer with Pareto designs from Step 3
7	Run the Darwin Optimizer to generate Pareto front for the design problem

Using "Local Load Balancing" delivered greater than 4x speedup



Guidelines for Optimization

- It is a good idea to restart from a calculated optimum when you suspect convergence problems
- If a calculated optimum is nonsensical (not uncommon at during initial design studies), you may need to update the problem formulation (e.g., modify design variable bounds)
- Scaling of variables and constraints
  - Poorly scaled optimization problem may cause convergence problem
  - Constraints and design variables are automatically scaled to be of the same order of magnitude by the ModelCenter optimization trade study
- Optimizer tends to exploit any weakness of analysis programs
  - Be careful not to allow the optimizer to move into variable ranges where analysis programs are not accurate

Using DOE data, conducted ANOVA in the Variable Influence Profiler

	Specific Impulse	Thrust-to-Weight Ratio	Engine Length	Outer Chamber Radius	LOX Maximum Mach Number	LH2 Maximum Mach Number	Chamber Wall Temperature	Aerospike Wall Temperature	Inj Face Pressure Drop LOX	Inj Face Pressure Drop LH2	Required Power for LOX Pump	Required Power for LH2 Pump	Δr at Throat
Expansion Ratio	+	-	+	+	+				+	+			-
Throat Area		X	+	+	+	+	-	-	+	+	-	-	+
Chamber Length	+	X	+		+	+			+	+			
Characteristic Length		X			-								
Vacuum Thrust							+	+	-	-	+	+	
Oxidizer-to-Fuel Ratio	X					-				+	+	-	

X = significant influence | + = direct relationship | - = inverse relationship

Using DOE data, conducted ANOVA in the Variable Influence Profiler

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Expansion Ratio	+	-	+	+	+				+	+			-
Throat Area		X	+	+	+	+	-	-	+	+	-	-	+
Chamber Length	+	X	+		+	+			+	+			
Characteristic Length		X			-								
Vacuum Thrust							+	+	-	-	+	+	
Oxidizer-to-Fuel Ratio	X					-				+	+	-	

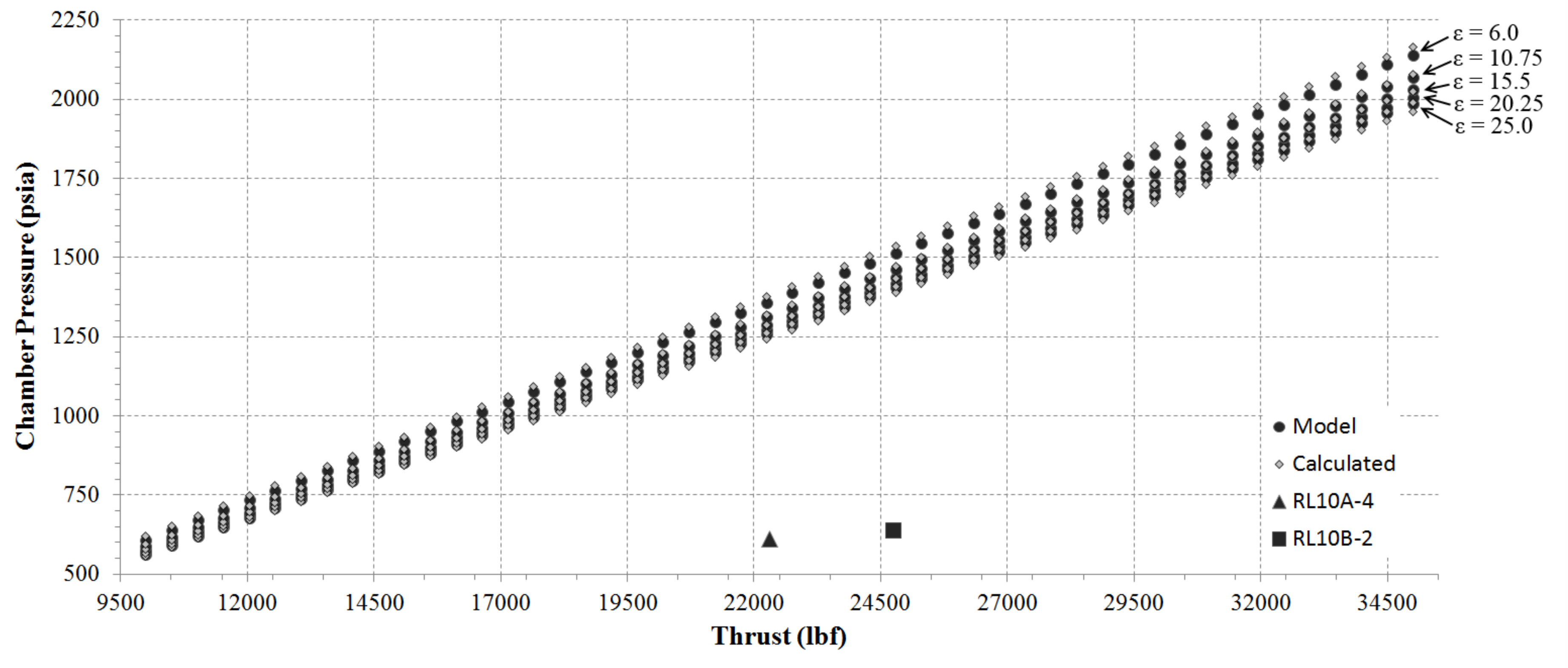
X = significant influence | + = direct relationship | - = inverse relationship

Used 6 trade studies to verify the DEAN conforms to rocket theory

Verification Tests	
Mass Flow variation with Vac Thrust	I_{sp} variation with O/F
Chamber Pres variation with Vac Thrust	Engine Wt variation with Throat Area
Chamber Pres variation with Throat Area	Engine Wt variation with Expansion Ratio
I_{sp} variation with Expansion Ratio	Engine Wt variation with Chamber Length
I_{sp} variation with Molecular Weight	Engine Wt variation with Char Length

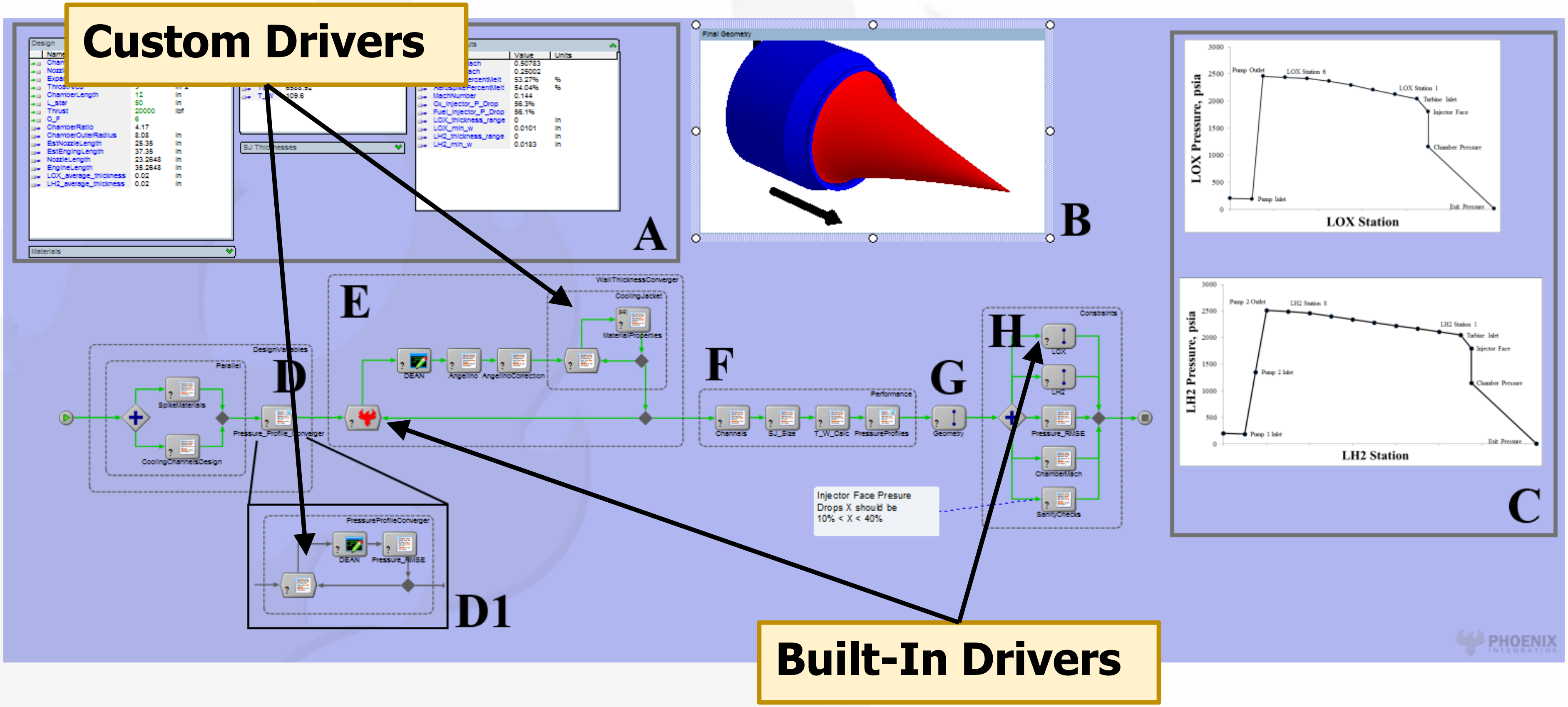
These studies also demonstrated the DEAN was scalable and reliable (98.7%).

Example verification study results

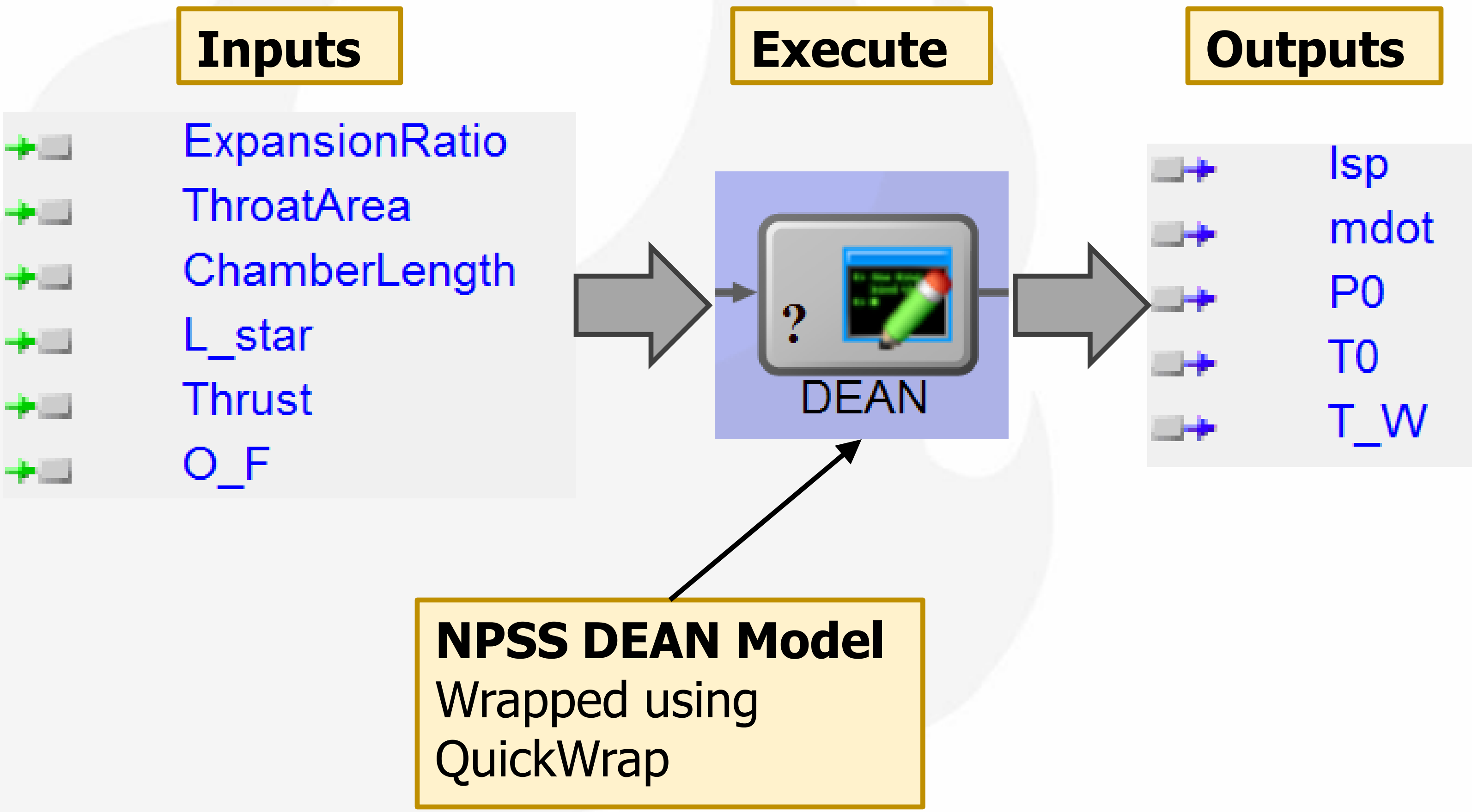


Credit Wikipedia

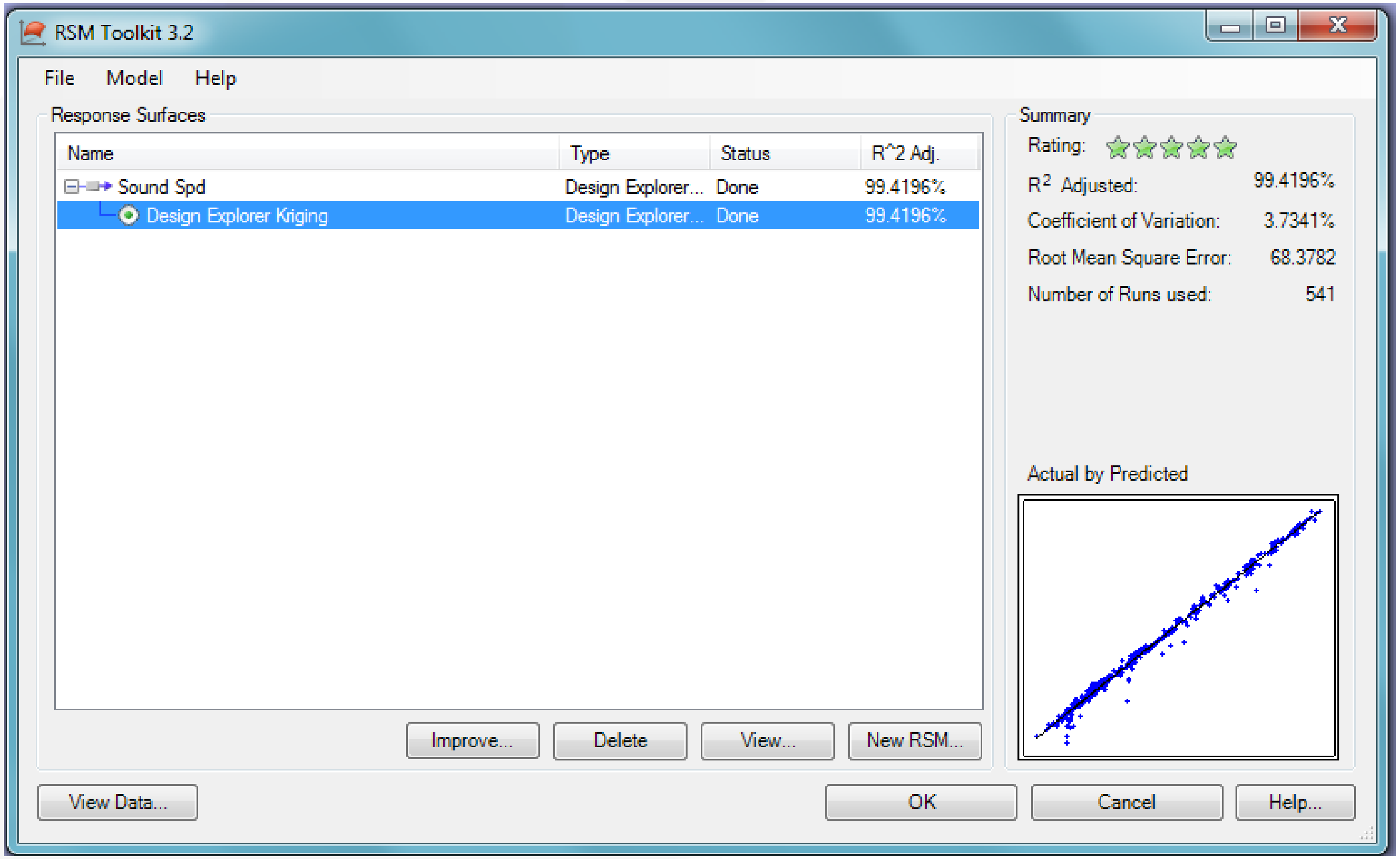
The DEAN simulation workflow uses custom & built-in drivers



Analysis models in ModelCenter provide a common interface



ModelCenter can model data as well as executable analyses



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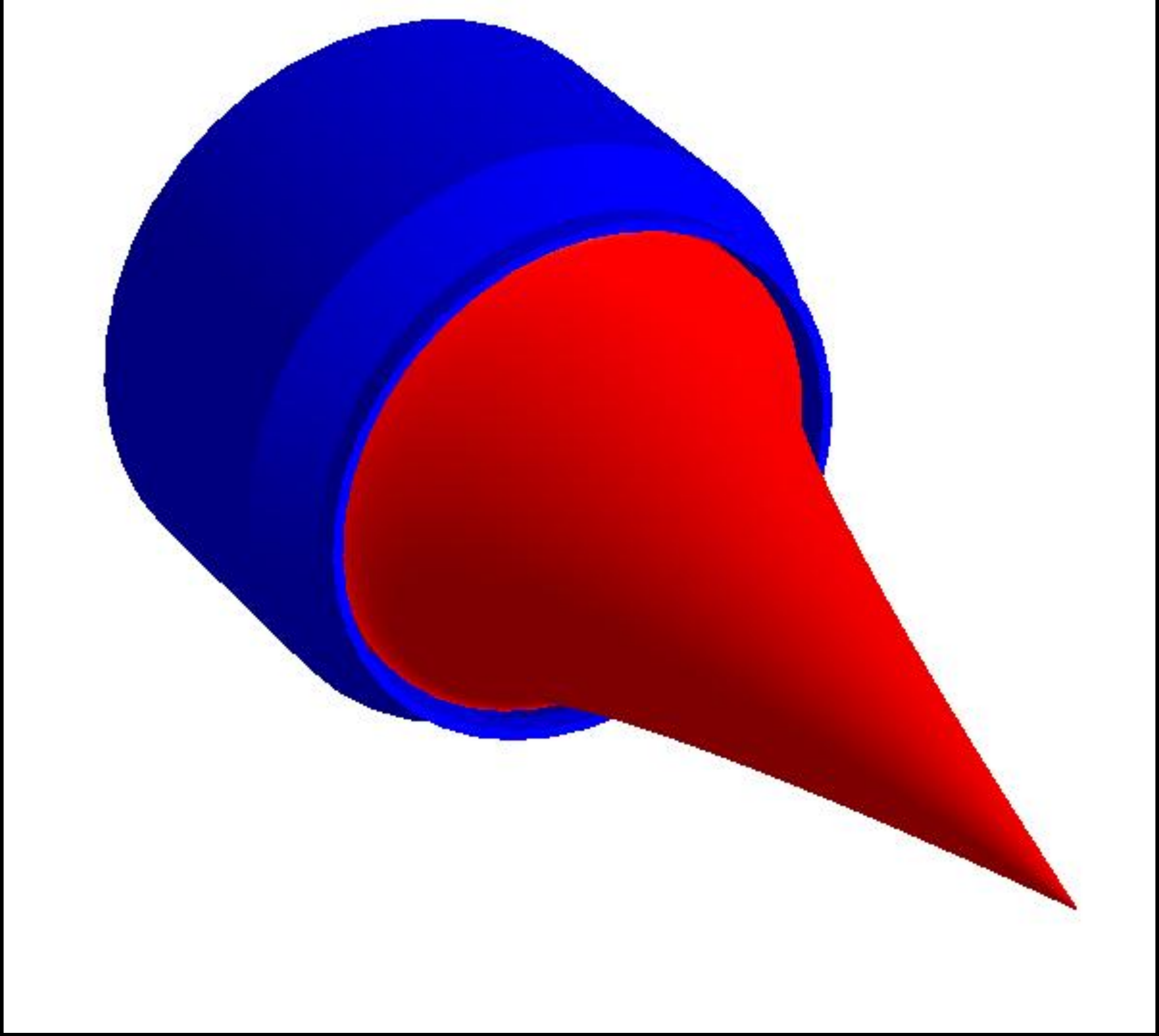
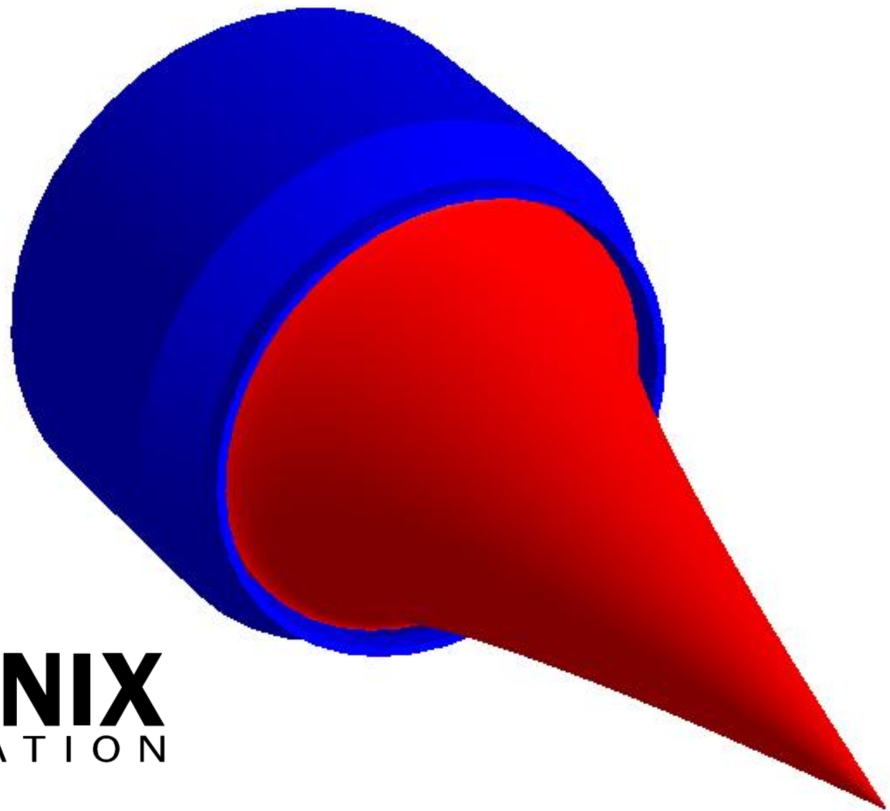


Q&A



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