COST/EFFORT DRIVERS AND DECISION ANALYSIS

Jon Seidel
NASA Glenn Research Center
September 16, 2010

Abstract

Engineering trade study analyses demand consideration of performance, cost and schedule impacts across the spectrum of alternative concepts and in direct reference to product requirements. Prior to detailed design, requirements are too often ill-defined (only "goals") and prone to creep, extending well beyond the Systems Requirements Review. Though lack of engineering design and definitive requirements inhibit the ability to perform detailed cost analyses, affordability trades still comprise the foundation of these future product decisions and must evolve in concert. This presentation excerpts results of the recent NASA subsonic Engine Concept Study for an Advanced Single Aisle Transport to demonstrate an affordability evaluation of performance characteristics and the subsequent impacts on engine architecture decisions. Applying the Process Based Economic Analysis Tool (PBEAT), development cost, production cost, as well as operation and support costs were considered in a traditional weighted ranking of the following system-level figures of merit: mission fuel burn, take-off noise, NOx emissions, and cruise speed. Weighting factors were varied to ascertain the architecture ranking sensitivities to these performance figures of merit with companion cost considerations. A more detailed examination of supersonic variable cycle engine cost is also briefly presented, with observations and recommendations for further refinements.

Cost/Effort Drivers & Decision Analysis
(Applications of the Process Based Economic Analysis Tool)

Jon Seidel

NASA Glenn Research Center
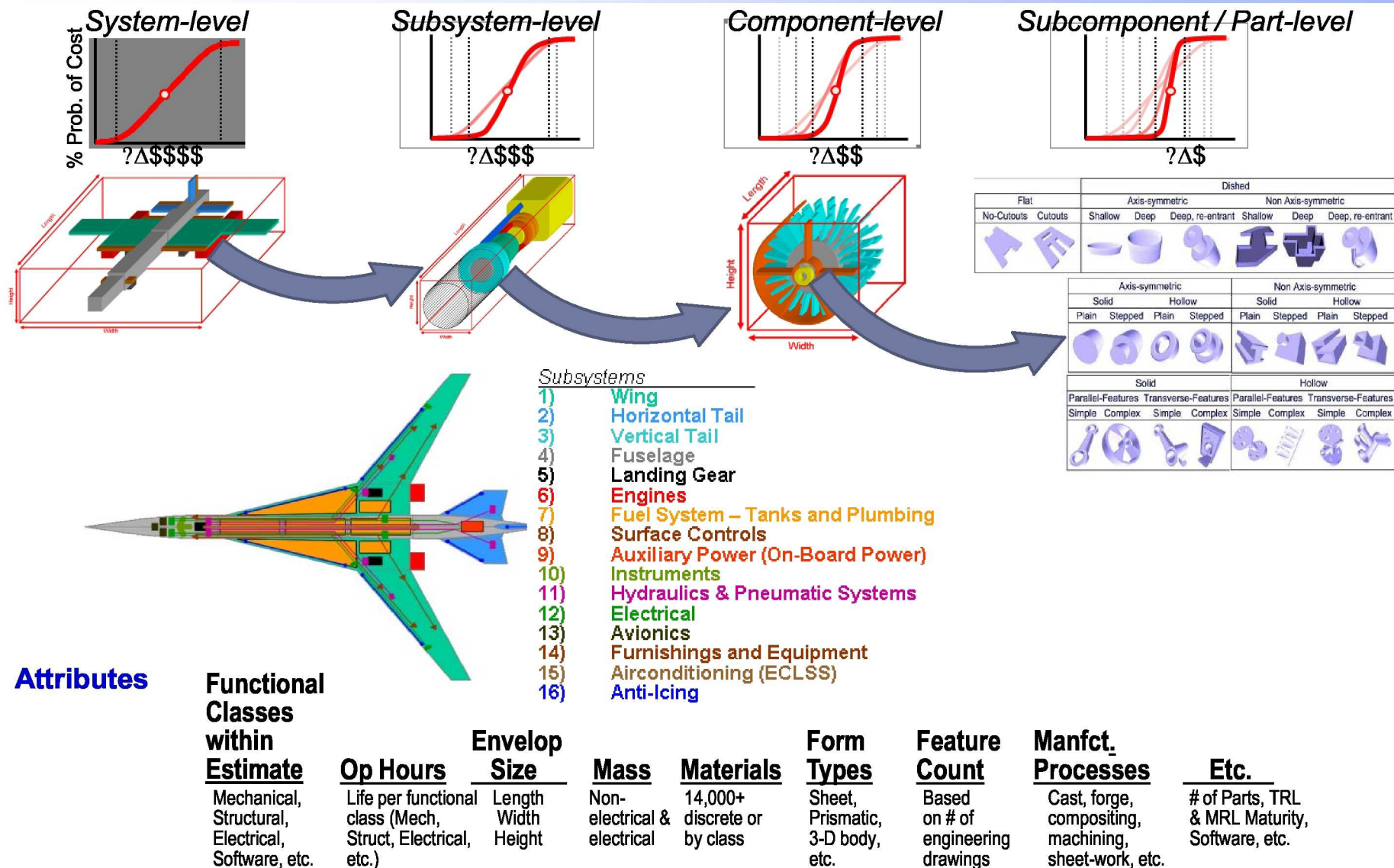
September 16, 2010

Briefing Contents

▪

▸ Discussion of decomposition strategies and the limits of conceptual design detail

▸ PBEAT application to a Subsonic Engine Study showing the breadth of decision analysis

▸ PBEAT application to a Supersonic Engine Study with expanded subcomponent depth
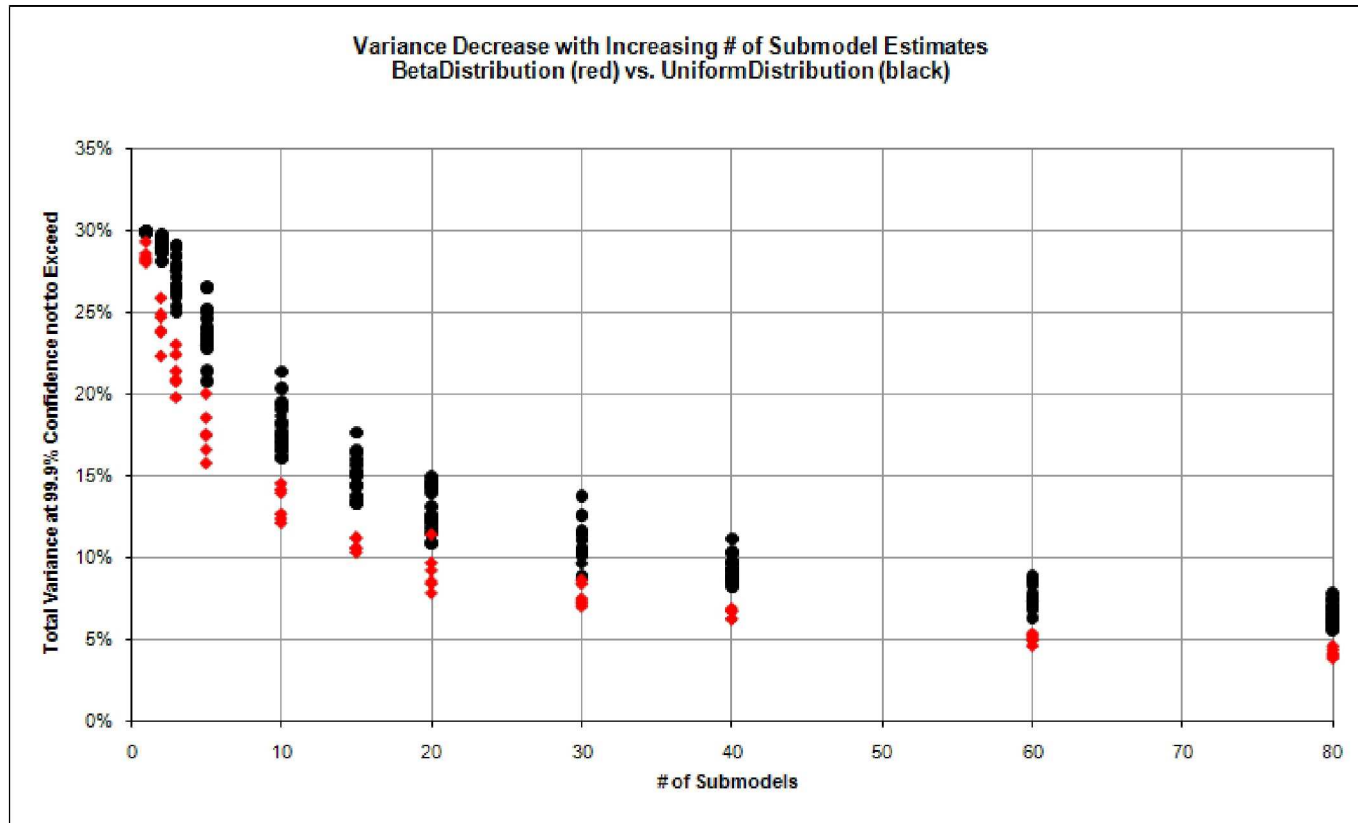
▸ Summary Observations

System-level

% Prob. of Cost

$?\Delta\$\$\$\$$

Subsystem-level

$?\Delta\$\$\$$

Component-level

$?\Delta\$\$$

Subcomponent / Part-level

$?\Delta\$$

Subsystems

1) Wing
2) Horizontal Tail
3) Vertical Tail
4) Fuselage
5) Landing Gear
6) Engines
7) Fuel System – Tanks and Plumbing
8) Surface Controls
9) Auxiliary Power (On-Board Power)
10) Instruments
11) Hydraulics & Pneumatic Systems
12) Electrical
13) Avionics
14) Furnishings and Equipment
15) Airconditioning (ECLSS)
16) Anti-Icing

Attributes

Functional Classes within Estimate	Op Hours	Envelop Size	Mass	Materials	Form Types	Feature Count	Manfct. Processes	Etc.
Mechanical, Structural, Electrical, Software, etc.	Life per functional class (Mech, Struct, Electrical, etc.)	Length Width Height	Non-electrical & electrical	14,000+ discrete or by class	Sheet, Prismatic, 3-D body, etc.	Based on # of engineering drawings	Cast, forge, compositing, machining, sheet-work, etc.	# of Parts, TRL & MRL Maturity, Software, etc.

4

Sample of Co-Variance Effect on Estimate Uncertainty & the Impact on Conceptual Design Studies

▸ This numerical experiment using Latin Hypercube depicts the offsetting effect of uncertainty for an increasing number of equally contributing submodels.

▸ These somewhat idealized results (statistically small sample, no bias in variance) demonstrate the large benefit modest decomposition and decreasing benefit afforded by the effort to create ever-increasing detailed submodels.
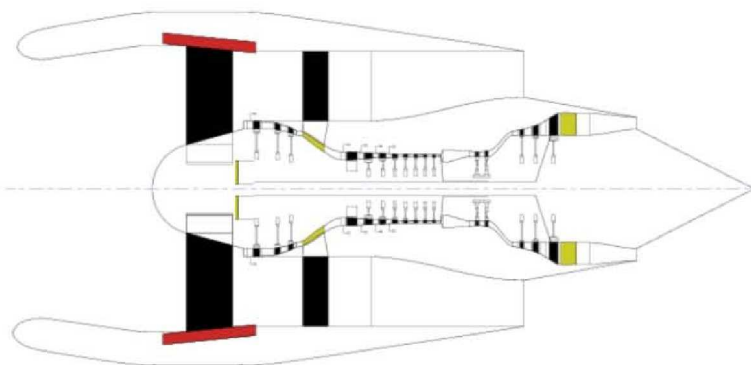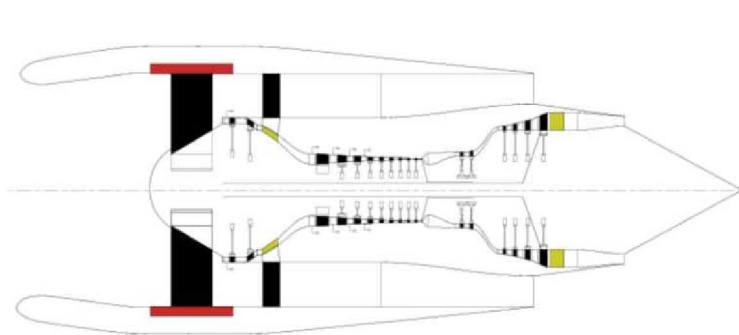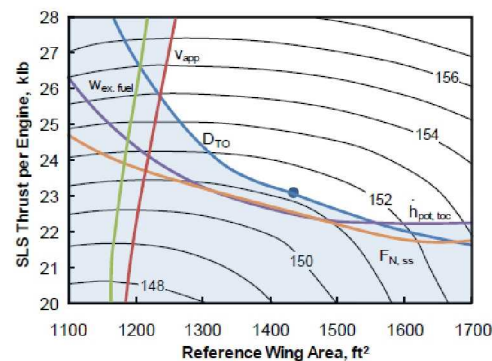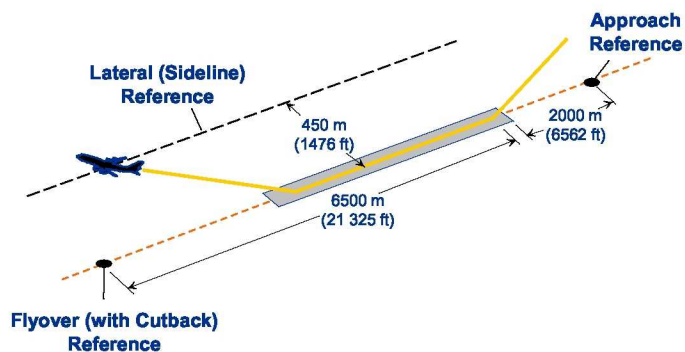

Variance Decrease with Increasing # of Submodel Estimates
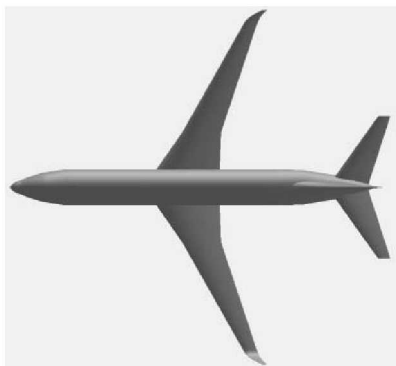BetaDistribution (red) vs. UniformDistribution (black)

www.nasa.gov

PBEAT Application & Decision Analysis using NASA's Subsonic Engine Concept Study for an Advanced Single-Aisle Transport

- Engine configurations for a narrow body aircraft, similar to the Boeing B737 and Airbus A320, were parametrically studied by NASA. The following nomenclature identifies the engine configuration trade-space:
  - Hi = High work LPC
  - Lo = Lo work LPC
  - DD = Direct-Drive front Fan
  - G = Geared front Fan
  - FPR13 thru FPR17 = Fan Pressure Ratio 1.3 thru 1.7
  - FIXED = Fixed area fan nozzle
  - VAN = Variable Area fan Nozzle
  - Spiral-1 = OPR 32, Cruise Mach 0.80
  - Spiral-2 = OPR 42, Cruise Mach 0.80
  - Spiral-3 = OPR 42, Cruise Mach 0.72

- The resulting 48 mission-sized engine/aircraft configurations were used to explore the cost-benefit of increased efficiency, reduced noise, and reduced emissions.

- PBEAT Benchmark systems (Boeing 747, 777, 737, 787) calibrated using publically available data facilitated analogy estimating at the subsystem-level. Like the Benchmarks, more than 40 PBEAT attribute parameters were used in characterizing the trade space for each of the 17 subsystems.

▸ Outputs from the conceptual design/analysis codes (NPSS/WATE++, FLOPS, PDCYL) augmented by formulas for complexity drivers (detailed part count, design replication, etc.) were used to perform cost estimates using the PBEAT code.

www.nasa.gov

PBEAT Application & Decision Analysis using NASA's Subsonic Engine Concept Study for an Advanced Single-Aisle Transport

▸ The abbreviated table below shows aircraft performance characteristics (noise, emissions, and flight time) and subsystem results of PBEAT cost analysis aggregated to the system level.

▸ The cost results were later simplified by incorporating fuel usage and O&S cost into a single metric and subsequently expressing development cost, average unit production cost and O&S cost as a cost per flight hour.
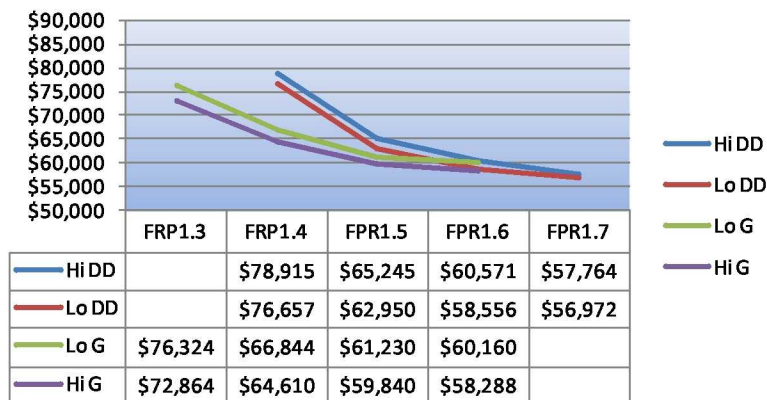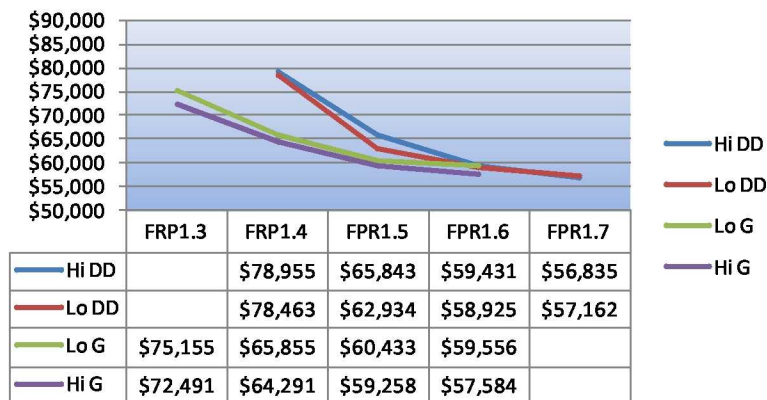
Spiral	Configuration Name	AUPC	Mass	DEV	O&S	FUEL	NITROGEN OXIDES EMISSIONS	Emissions LTO	Noise	Block Time
S1	HI DD FPR14 VAN	$79,139,988	99,820	$3,329,688,170	$20,192	37,698	198.9	10.3	254.3	7.65
S1	HI DD FPR15 FIXED	$52,985,977	82,688	$2,765,360,074	$13,379	33,612	167.3	9.6	259.4	7.64
S1	HI DD FPR16 FIXED	$44,787,136	77,690	$2,571,631,395	$11,245	33,162	158.2	10.0	266.3	7.63
S1	HI DD FPR17 FIXED	$40,408,688	74,715	$2,454,768,426	$10,110	33,336	150.0	10.7	270.2	7.62
S1	HI G FPR13 VAN	$69,951,437	95,537	$3,077,493,312	$17,908	35,711	203.1	9.2	247.8	7.68
S1	HI G FPR14 VAN	$54,326,144	83,236	$2,736,556,304	$13,803	33,897	176.4	9.7	254.2	7.63
S1	HI G FPR15 FIXED	$44,611,238	77,415	$2,540,250,822	$11,230	32,449	160.8	9.3	259.0	7.64
S1	HI G FPR16 FIXED	$41,694,784	75,561	$2,476,114,434	$10,462	32,880	156.9	9.9	266.0	7.63
S1	LO DD FPR14 VAN	$72,767,228	96,859	$3,238,537,708	$18,546	36,352	200.4	10.7	254.2	7.65
S1	LO DD FPR15 FIXED	$48,941,848	80,492	$2,670,278,851	$12,333	32,590	176.0	9.7	259.3	7.64
S1	LO DD FPR16 FIXED	$42,074,616	75,927	$2,487,306,567	$10,542	32,247	168.7	10.1	266.1	7.63
S1	LO DD FPR17 FIXED	$39,140,849	73,964	$2,421,813,920	$9,777	32,606	163.7	10.8	270.0	7.63
S1	LO G FPR13 VAN	$74,755,924	99,773	$3,222,159,921	$19,168	36,378	219.0	9.7	248.2	7.68
S1	LO G FPR14 VAN	$57,082,817	85,386	$2,830,344,270	$14,524	34,116	186.0	10.4	254.3	7.63
S1	LO G FPR15 FIXED	$46,698,738	78,986	$2,598,211,661	$11,774	32,516	175.3	9.8	259.2	7.64
S1	LO G FPR16 FIXED	$44,073,241	77,379	$2,554,601,379	$11,075	32,931	172.4	10.3	266.2	7.63
S2	HI DD FPR14 VAN	$83,604,650	101,475	$3,326,955,926	$21,366	36,351	262.9	11.3	254.5	7.65

8

www.nasa.gov

▸ The aircraft cost per flight hour provided a concise method for evaluating the varied engine design configurations in this direct Cost/FoM decision approach.
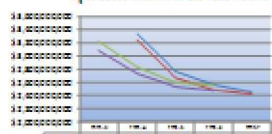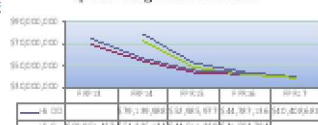
Spiral 1 COST/FLT-HR

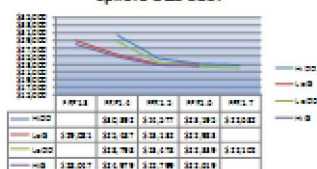|	FRP1.3	FRP1.4	FPR1.5	FPR1.6	FPR1.7
Hi DD		$78,915	$65,245	$60,571	$57,764
Lo DD		$76,657	$62,950	$58,556	$56,972
Lo G	$76,324	$66,844	$61,230	$60,160	
Hi G	$72,864	$64,610	$59,840	$58,288	

Spiral 2 COST/FLT-HR

	FRP1.3	FRP1.4	FPR1.5	FPR1.6	FPR1.7
Hi DD		$78,955	$65,843	$59,431	$56,835
Lo DD		$78,463	$62,934	$58,925	$57,162
Lo G	$75,155	$65,855	$60,433	$59,556	
Hi G	$72,491	$64,291	$59,258	$57,584	

Spiral 3 COST/FLT-HR

	FRP1.3	FRP1.4	FPR1.5	FPR1.6	FPR1.7
Hi DD		$82,797	$68,858	$61,627	$59,151
Lo DD		$75,725	$63,756	$59,274	$56,674
Lo G	$71,889	$65,456	$60,641	$60,421	
Hi G	$67,127	$62,186	$58,754	$57,314	

Spiral 1 DEVELOPMENT COST

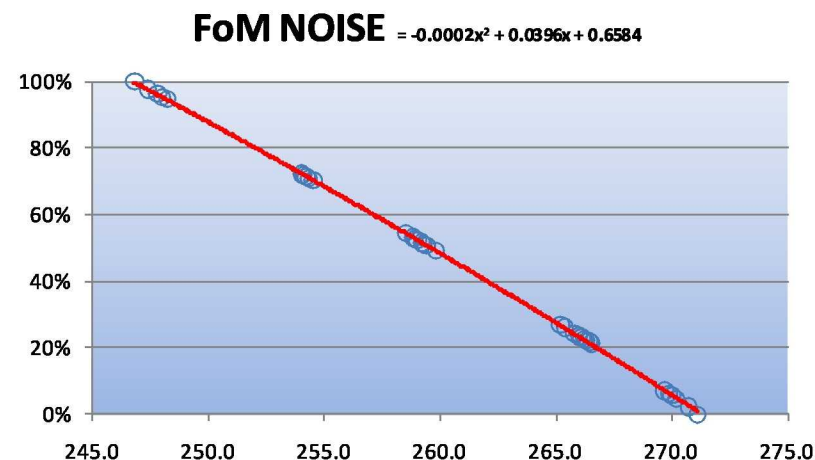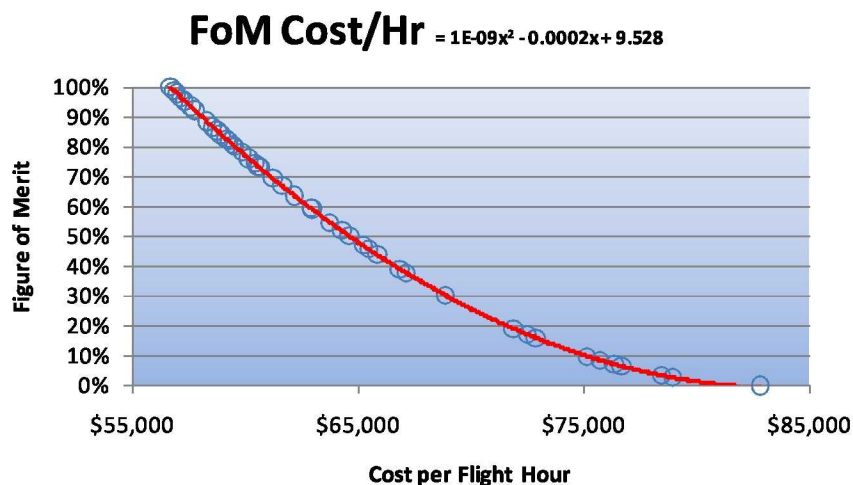Spiral 1 Avg Unit Prod Cost

Spiral1 O&S COST

www.nasa.gov

- A second decision approach was investigated using surrogate FoM "utility curves" and weighting criteria derived from the Analytic Hierarchy Process (AHP).

- The basis of cost benefit in this approach allows for consideration of variation in value referred to as a Figure of Merit (FoM) utility score (worst within dataset = 0 %*weighting score, best within dataset = 100%*weighting score).

			Weightings				
			15%	28%	28%	28%	
SPIRAL	FPR	CONFIG	COST/FLT-HR	EMISSIONS	BLOCK TIME	NOISE	Final FoM
S1	FPR1.4	HI DD VAN	0.4%	12.5%	16.0%	26.5%	47.8%
S1	FPR1.5	HI DD FIXED	7.0%	21.8%	23.7%	27.1%	84.3%
S1	FPR1.6	HI DD FIXED	11.0%	24.5%	19.2%	27.7%	88.5%
S1	FPR1.7	HI DD FIXED	13.8%	26.8%	11.9%	28.3%	86.2%
S1	FPR1.3	HI G VAN	2.4%	12.2%	28.3%	24.7%	66.1%
S1	FPR1.4	HI G VAN	7.5%	19.0%	22.5%	27.7%	80.0%
S1	FPR1.5	HI G FIXED	11.7%	24.0%	27.2%	27.1%	100.0%
S1	FPR1.6	HI G FIXED	13.3%	24.9%	20.3%	27.7%	94.3%
S1	FPR1.4	LO DD VAN	0.9%	11.9%	11.9%	26.5%	41.5%
S1	FPR1.5	LO DD FIXED	8.9%	19.1%	22.5%	27.1%	81.4%
S1	FPR1.6	LO DD FIXED	13.0%	21.1%	18.1%	27.7%	84.8%
S1	FPR1.7	LO DD FIXED	14.7%	22.3%	10.9%	27.7%	78.2%
S1	FPR1.3	LO G VAN	1.0%	8.3%	22.5%	24.7%	49.5%
S1	FPR1.4	LO G VAN	5.9%	15.9%	14.9%	27.7%	61.3%
S1	FPR1.5	LO G FIXED	10.4%	19.3%	21.4%	27.1%	82.2%
S1	FPR1.6	LO G FIXED	11.4%	19.8%	16.0%	27.7%	77.3%
S2	FPR1.4	HI DD VAN	0.4%	0.5%	6.3%	26.5%	15.0%
S2	FPR1.5	HI DD FIXED	6.6%	7.6%	14.9%	27.1%	49.0%

▶ The shape of each utility curve was derived from engineering judgment and warrants further investigation as to it's impact on the decision results.

▶ As related to cost, the first dollar of cost reduction is always easier to obtain that the last dollar of cost reduction and as such might be considered as having less value or utility.

▶ As related to noise, the utility curve concavity shows less benefit for "over achieving" and also demonstrates the pitfalls of using combined FoMs (noise certification is regulated at 3 prescribed points rather than the overall cumulative).
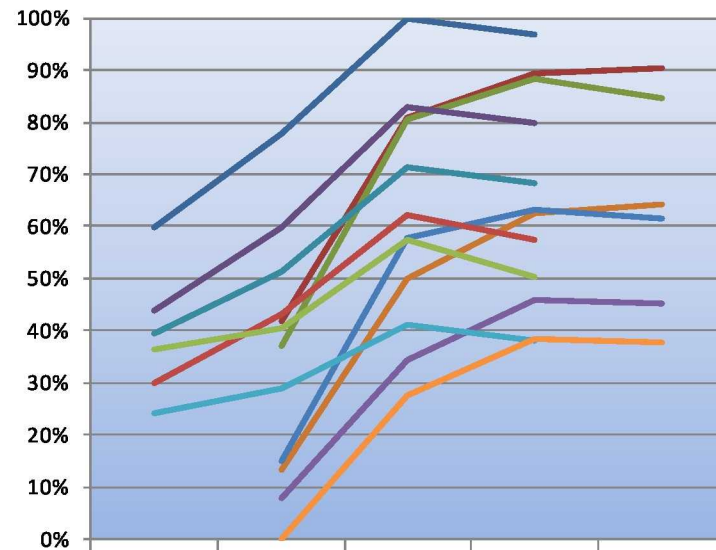
FoM Cost/Hr $= 1E\text{-}09x^2 - 0.0002x + 9.528$

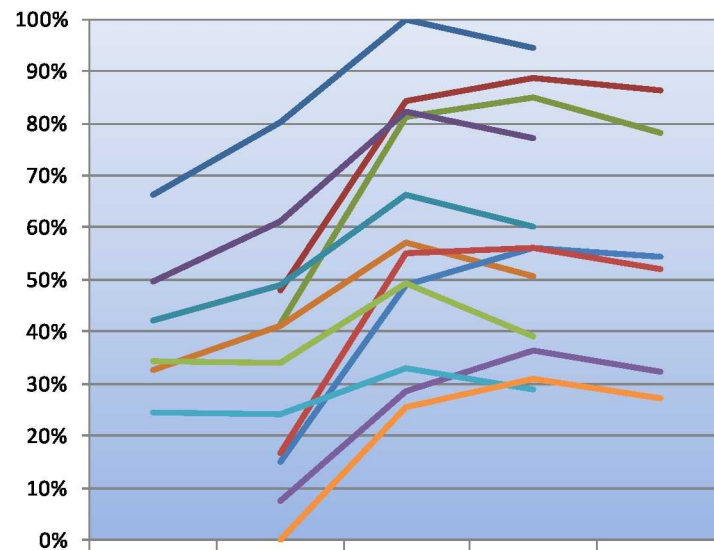**FoM NOISE** $= -0.0002x^2 + 0.0396x + 0.6584$

11

www.nasa.gov

PBEAT Application & Decision Analysis using NASA's Subsonic Engine Concept Study for an Advanced Single-Aisle Transport

- Cost weighted @ 25%
- Emission weighted @ 25%
- Block Time weighted @ 25%
- Noise weighted @25%

▌ The trade space plotted – Illustrating the Spiral 1 Hi G FPR15 configuration as the highest rated.

FoM Cost = 25%, Emissions = 25%, Block Time = 25%, & Noise = 25%

	FRP1.3	FRP1.4	FPR1.5	FPR1.6	FPR1.7
S1 Hi G	0.599	0.779	1.000	0.969	
S1 Hi DD		0.418	0.810	0.893	0.905
S1 Lo DD		0.370	0.806	0.883	0.846
S1 Lo G	0.440	0.598	0.831	0.800	
S2 Hi G	0.393	0.514	0.715	0.682	
S2 Hi DD		0.134	0.499	0.626	0.643
S2 Lo DD		0.150	0.577	0.632	0.617
S2 Lo G	0.298	0.431	0.623	0.575	
S3 Hi G	0.363	0.403	0.575	0.504	
S3 Lo DD		0.078	0.343	0.458	0.452
S3 Lo G	0.243	0.288	0.411	0.379	
S3 Hi DD		0.000	0.274	0.383	0.378

12 Distribution Statement A: Approved for Public Release www.nasa.gov

- Cost weighted @15%
- Emission weighted @ 28.3%
- Block Time weighted @ 28.3%
- Noise weighted @ 28.3%

- The trade space plotted – Illustrating the Spiral 1 Hi G FPR15 configuration as the highest rated.
- With only slightly increased noise weighting, lower FPR engines begin to rise in utility

FoM Cost = 15%, Emissions = 28%, Block Time = 28%, & Noise = 28%

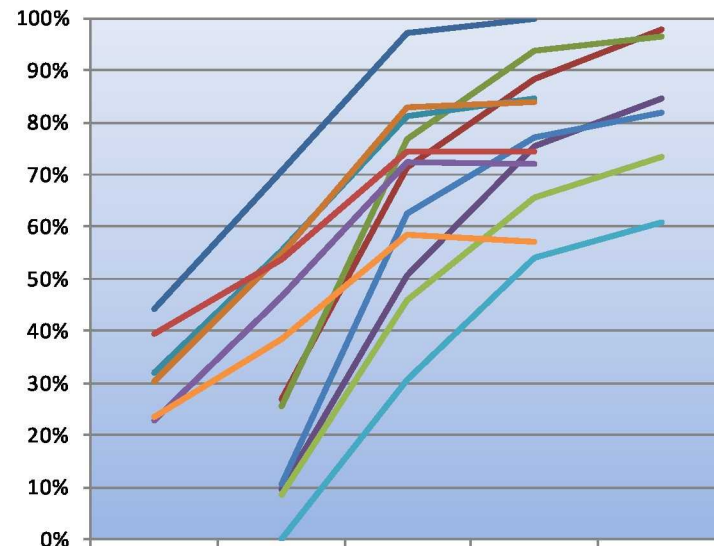|	FRP1.3	FRP1.4	FPR1.5	FPR1.6	FPR1.7
S1 Hi G	0.661	0.800	1.000	0.943	
S1 Hi DD		0.478	0.843	0.885	0.862
S1 Lo DD		0.415	0.814	0.848	0.782
S1 Lo G	0.495	0.613	0.822	0.773	
S2 Hi G	0.420	0.491	0.662	0.601	
S2 Lo G	0.326	0.410	0.572	0.505	
S2 Hi DD		0.150	0.490	0.562	0.545
S2 Lo DD		0.166	0.549	0.562	0.520
S3 Hi G	0.344	0.339	0.494	0.391	
S3 Lo DD		0.074	0.287	0.365	0.322
S3 Lo G	0.243	0.241	0.328	0.289	
S3 Hi DD		0.000	0.257	0.308	0.271

www.nasa.gov

PBEAT Application & Decision Analysis using NASA's Subsonic Engine Concept Study for an Advanced Single-Aisle Transport

- Cost weighted @ 50%
- Emission weighted @ 16.6%
- Block Time weighted @ 16.6%
- Noise weighted @ 16.6%

- The trade space plotted – Illustrating the Spiral 1 Hi G FPR16 configuration as the highest rated.
- With decreased noise weighting, higher FPR engines show greater utility (due to reduced ramp weight)

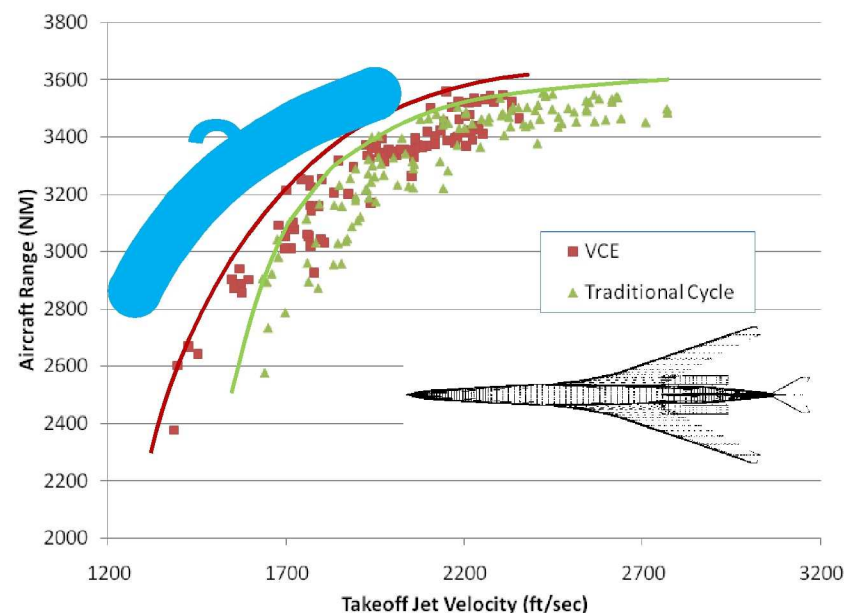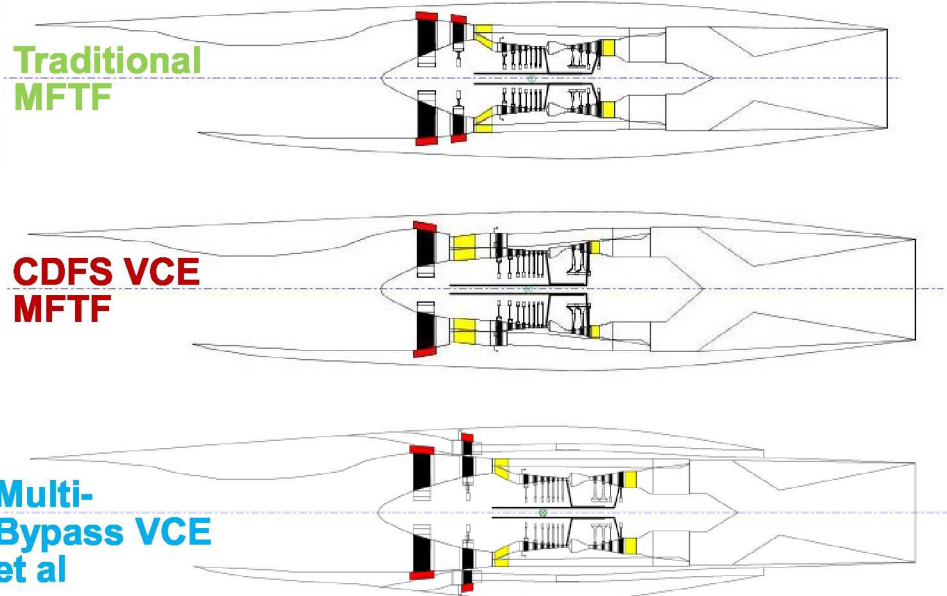**FoM** Cost = 50%, Emissions = 17%, Block Time = 17%, & Noise = 17%

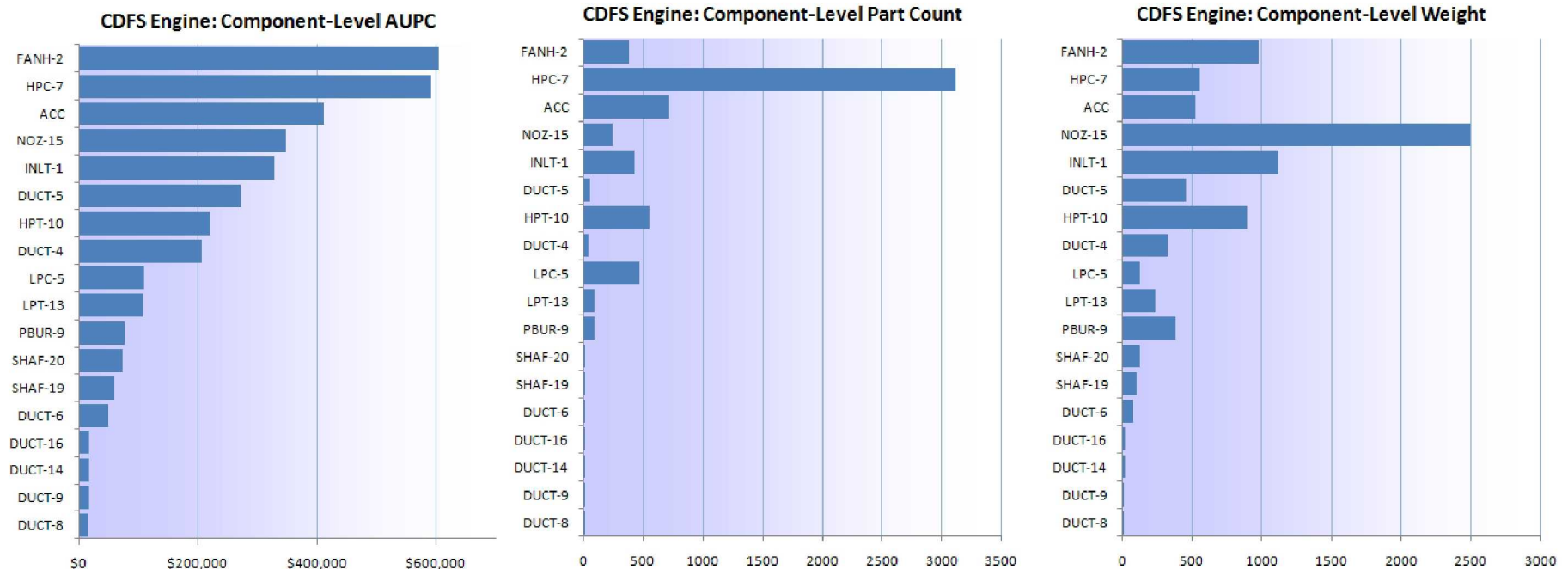|	FRP1.3	FRP1.4	FPR1.5	FPR1.6	FPR1.7
S1 Hi G	0.441	0.708	0.972	1.000	
S1 Hi DD		0.269	0.712	0.885	0.977
S1 Lo DD		0.257	0.766	0.939	0.966
S2 Hi DD		0.094	0.507	0.754	0.846
S2 Hi G	0.319	0.553	0.814	0.846	
S1 Lo G	0.303	0.546	0.828	0.839	
S2 Lo DD		0.107	0.626	0.772	0.819
S3 Hi G	0.396	0.538	0.743	0.745	
S3 Lo DD		0.086	0.460	0.655	0.733
S2 Lo G	0.228	0.465	0.722	0.719	
S3 Hi DD		0.000	0.306	0.541	0.609
S3 Lo G	0.236	0.386	0.585	0.573	

www.nasa.gov

▸ Performance studies are underway examining the impact of variable cycle engine architecture for reconciling supersonic cruise performance with acoustically low takeoff jet velocity.

▸ Using the same/similar tools as the previous subsonic example, a sparse pareto frontier was assembled from performance results of two engine architectures

▸ For two of these engines meeting a desired jet velocity, engine cost estimates were generated at a subcomponent/part-level using the same attributes formulae derived for the previous subsonic example.

Traditional MFTF

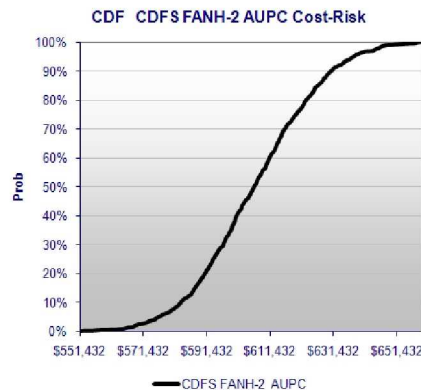**CDFS VCE MFTF**

Multi-Bypass VCE et al

15

www.nasa.gov

▸ The sample results show the Average Unit Production Cost impact of two cost complexity drivers from these subcomponent results which have been aggregated to the component-level for comparison.

▸ Results indicate generally acceptable results in applying "subsonic" attribute formulae to very different turbine engine architectures using PBEAT (though Turbines, and Controls & Accessories warrant further discussion/investigation).

▸ Interrogation of subcomponent details highlights some areas requiring refinement, such as manufacturing processes assumed for the cooled turbine components

CDFS Engine: Component-Level AUPC

CDFS Engine: Component-Level Part Count

CDFS Engine: Component-Level Weight

www.nasa.gov

- Refined formulae for variance (least, likely, most) on a subcomponent basis may be required rather than uniform +/- 10%, impacting cumulative distribution.

- Controls & Accessories is too broad a category in NASA's current conceptual design (high part count overly inflates "off-the-shelf" items), though large amount of electronics rightfully contributes to the high cost.

- Manufacturing processes need greater user specification using PBEAT (e.g. Turbine et al processes should be tied to conceptual design code WATE++).

CDF CDFS FANH-2 AUPC Cost-Risk

	Least	Likely	Most
FANH-2 Duct & Inlet Guide Vane (Stage#0)	$7,202	$9,185	$11,460
FANH-2 (Stage#1) Stage, Shaft-drum & Rotating Seals	$8,451	$10,596	$13,085
FANH-2 (Stage#2) Stage, Shaft-drum & Rotating Seals	$8,448	$10,781	$13,392
FANH-2 (Stage#2) Stage, Casing Outer Wall (cooling)	$13,630	$16,964	$21,217
NH-2 (Stage#2) Stage, Stator, Case & Stationary Seals	$16,143	$20,428	$25,561
FANH-2 (Stage#2) Stage, Rotor, Case & Rub-seals	$16,091	$20,585	$25,550
FANH-2 (Stage#1) Stage, Casing Outer Wall (cooling)	$16,693	$20,956	$26,134
FANH-2 (Stage#1) Stage, Rotor, Case & Rub-seals	$20,116	$25,800	$31,827
NH-2 (Stage#1) Stage, Stator, Case & Stationary Seals	$20,174	$25,881	$32,397
FANH-2 (Stage#1) Stage, Rotor, Disk	$20,054	$25,974	$32,387
FANH-2 (Stage#2) Stage, Rotor, Blades	$26,769	$33,902	$42,528
FANH-2 (Stage#2) Stage, Rotor, Disk	$30,983	$39,024	$49,135
FANH-2 (Stage#2) Stage, Stator, Vanes	$31,090	$39,494	$49,491
FANH-2 (Stage#1) Stage, Rotor, Blades	$43,933	$56,029	$70,149
FANH-2 (Stage#2) Stage, Blade Containment	$57,611	$73,214	$92,767
FANH-2 (Stage#1) Stage, Stator, Vanes	$62,001	$78,899	$99,925
FANH-2 (Stage#1) Stage, Blade Containment	$77,491	$97,553	$122,551
Sum Total =	$605,266		

Sample of Controls & Accessories subcomponents

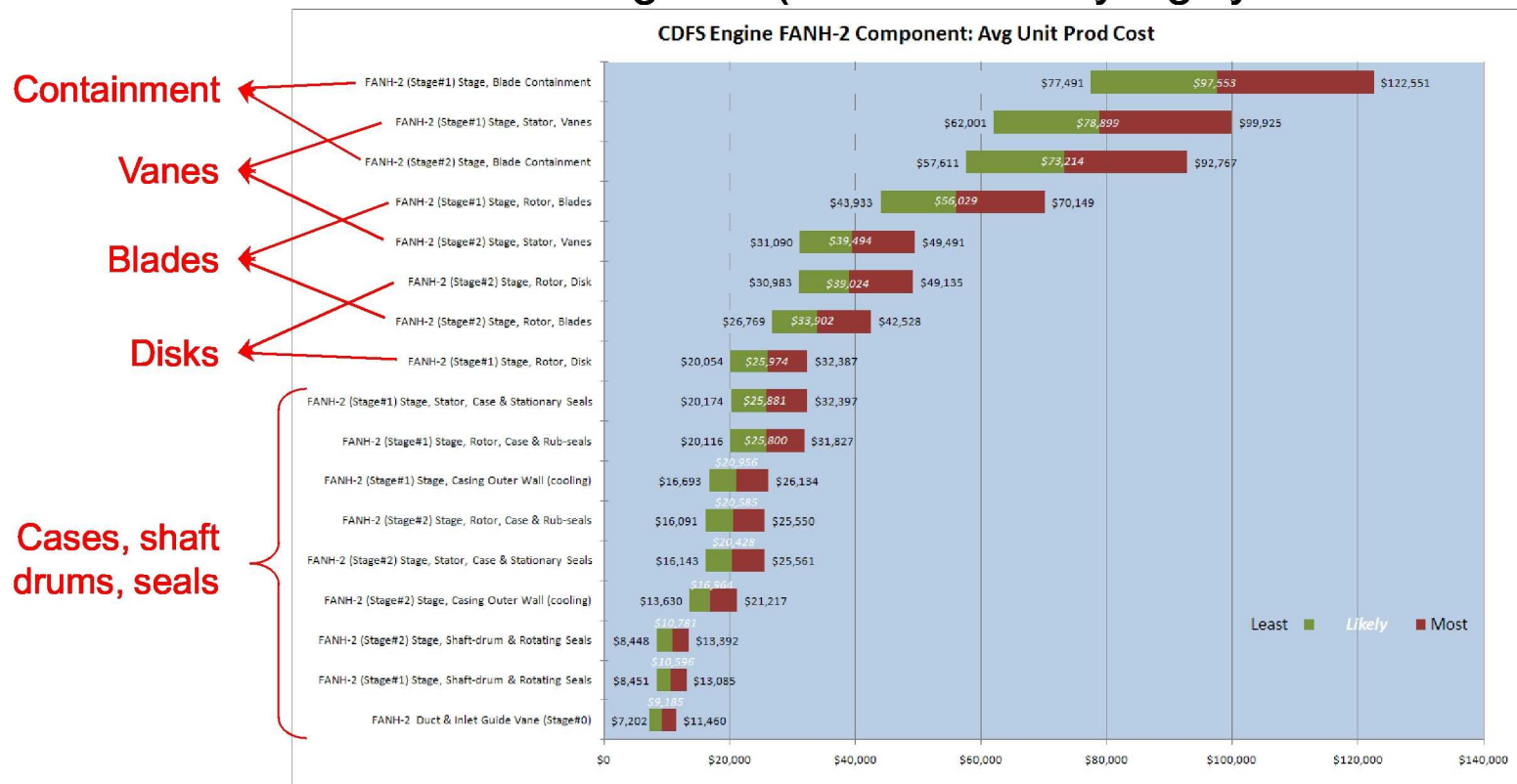| ACC	ACC Accessories Unit & Gearbox, HPC Tower shaft + Bearing/Sump
ACC	ACC Accessories Unit & Gearbox, Torque Converter (Customer Horsepower Extraction)
ACC	ACC Accessories Unit & Gearbox, Fuel Boost Pump (Electronic)
ACC	ACC Accessories Unit & Gearbox, Lube Pump (Mechanical)
ACC	ACC Accessories Unit & Gearbox, Electric Generator Unit
ACC	ACC Accessories Unit & Gearbox, Electric Starter Unit
ACC	ACC Accessories Unit & Gearbox, Fire Suppression Unit
ACC	ACC Propulsion Electrical, FADEC/ECUnit
ACC	ACC Propulsion Electrical, Electrical Wiring
ACC	ACC Propulsion Electrical, Lighting
ACC	ACC Propulsion Electrical, Sensors

Sample of Variable Nozzle subcomponents

NOZ-15	NOZ-15 Nozzle (Bypass), Outer Wall Panels & Stiffeners
NOZ-15	NOZ-15 Nozzle (Bypass), Convergent Inner Wall Panels & Stiffeners
NOZ-15	NOZ-15 Nozzle (Bypass), Divergent Inner Wall Panels & Stiffeners
NOZ-15	NOZ-15 Nozzle (Bypass), 2D Sidewall Panels & Stiffeners
NOZ-15	NOZ-15 Nozzle (Bypass), 2D Transition Panels & Stiffeners
NOZ-15	NOZ-15 VAR AREA C & A
NOZ-15	NOZ-15 VAR AREA MISC
NOZ-15	NOZ-15 Nozzle (Bypass), Plug Panels & Stiffeners
NOZ-15	NOZ-15 Nozzle Thrust Reverser (Bypass), Clamshell Frames & Skeleton
NOZ-15	NOZ-15 Nozzle Thrust Reverser (Bypass), Reverse Flow Chutes
NOZ-15	NOZ-15 Nozzle Thrust Reverser (Bypass), Crank &Linkage Arms
NOZ-15	NOZ-15 Nozzle Thrust Reverser (Bypass), Nozzle Outer & Inner Panels Lap Seals
NOZ-15	NOZ-15 Nozzle Thrust Reverser (Bypass), Actuation

www.nasa.gov

▸ The general ranking of Fan subcomponents costs are as expected.

▸ Fan containment, though a complex Kevlar material system, has excessive production cost prompting more refined specification of manufacturing maturity in the supplemental formulae.

▸ Similarly, highly variable components, such as the vanes, exhibit excessive production cost and warrant investigation (corroborated by highly variable nozzle).

CDFS Engine FANH-2 Component: Avg Unit Prod Cost

18

www.nasa.gov

Summary Observations

▸ No cost estimate is "right", though some techniques are better than others. Cost confidence and managing to cost are what matters most, and requires integration with conceptual design tools where ~70% of cost-impacting decisions are made.

▸ Estimates aggregated from decompositions deeper than 2 or 3 levels below aren't worth the time and effort to create them (co-variance argument). Furthermore, decompositions without some accompanying engineering for complexities (e.g. TRL, manufacturing maturity, etc.) can confuse results and undermine cost confidence (witness "Fan Containment" and "Controls & Accessories").

▸ Decision Analysis is not a robot optimizer. Robust, flexible solutions are better than true optimums, especially during conceptual design phases of a program when requirements and engineering uncertainties are greatest.

▸ Demonstrated versatility of PBEAT is suited to NASA's broad charter (aeronautical systems, space launch & satellite systems, green energy, etc.).

- Refinement of supplemental formulae (attribute characterization) continues, to better address Turbine Engine specifics and enforce user-consistency without degrading PBEAT versatility
- Automated linking between improved fidelity Aircraft/Engine design codes and the PBEAT code (via autodata sheets) continues to reduce estimation time/effort and accelerate cost as a decision criteria.

www.nasa.gov

References

1. "Ultra-high Bypass Ratio (UHB) Engine Concept Cost Study for an Advanced Single-Aisle Transport"; NASA TM pending publishing; *Ajit K. Sil, Jonathan A. Seidel, John Reynolds (NASA Glenn Research Center, Cleveland, Ohio)*

2. "Engine Concept Study for an Advanced Single-Aisle Transport"; NASA TM pending publishing; M*ark D. Guynn (NASA Langley Research Center, Hampton, Virginia),Jeffrey J. Berton, Kenneth L. Fisher, Douglas R. Thurman, and Michael T. Tong (NASA Glenn Research Center, Cleveland, Ohio)*

3. "Benefits of a Variable Cycle Engine with a Core Driven Fan Stage on Supersonic Business Jet Performance"; NASA TM pending publishing; Justin Gray and Scott Jones *(NASA Glenn Research Center, Cleveland, Ohio)*

4. *"PROCESS-BASED ECONOMIC ANALYSIS TOOL: Users Guide"; (NASA Glenn Research Center, Updated 16 August, 2010)*

www.nasa.gov