Propulsion Cost Model
(PCM)

Presented to:

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NASA

TIME COST TECHNICAL

Engineering
Cost
Office

Victory Solutions
NASA MSFC
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Team
SB Diversity

Outline

- PCM as part of Project Cost Estimating Capability (PCEC)
- Propulsion Cost Model
  - Overview
  - Liquid Rocket Engines
  - Nuclear Thermal Rocket
  - Solid Rocket Motors
- Summary and Next Steps

What is PCEC?

- The Project Cost Estimating Capability (PCEC) is the primary NASA-sponsored parametric cost tool for space system estimates
  - Developed and maintained by NASA at MSFC beginning in late 2013
  - Excel Add-in that provides capabilities and cost estimating artifacts used to build a spacecraft cost estimate in Excel
  - Based on more than 70 missions/system elements, but with separate approaches for modeling different types of systems
    - Robotic Spacecraft (Robotic SC)
    - Crewed & Space Transportation Systems (CASTS)
  - Completely transparent tool: no code passwords, protected sheets, etc.
  - Available to the general public via ONCE and the NASA Software Catalog (https://software.nasa.gov/)

PCEC Email Contact:	MSFC-PCEC@mail.nasa.gov
Application Website(s):	ONCE (NASA Civil Servants) https://software.nasa.gov/ , search for PCEC

Propulsion Cost Model (PCM) Overview

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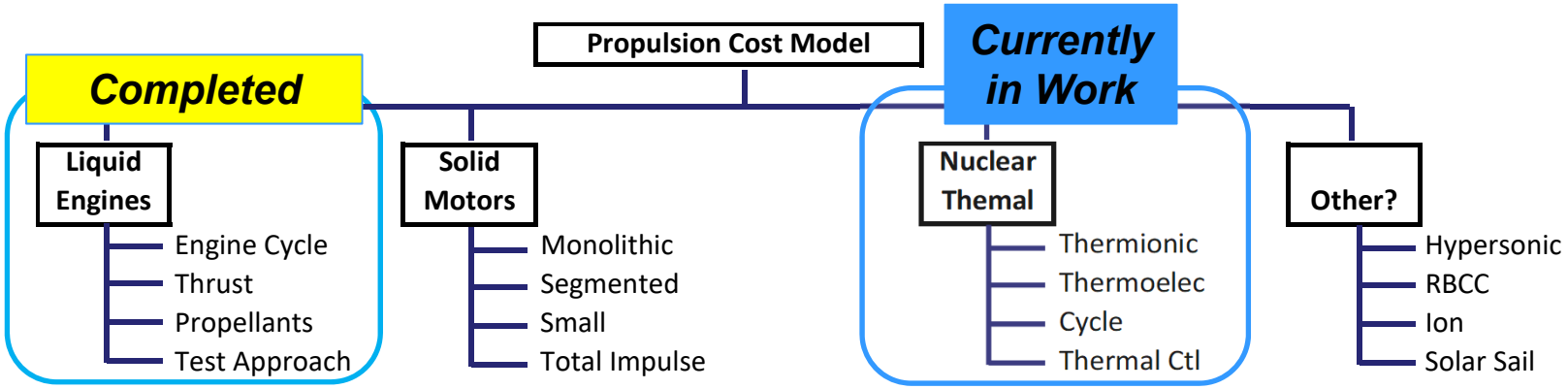
- What is PCM?
  - A new model for use in estimating the life cycle cost of different earth-to-orbit and in-space transportation propulsion systems
  - Add-on model to CASTS PCEC Model
    - Standalone model to PCEC/CASTS
    - Linkable to PCEC estimate similar to other specialized NASA models
    - Suite of tools: model + historical data (Unrestricted and Restricted versions)
    - Spreadsheet-based cost model plus documentation
    - Historical data
      - Technical and programmatic data (Unrestricted)
      - Non-recurring development and recurring production cost data (Restricted)
- Why PCM?
  - Plato: “Necessity is the mother of invention”(?)
  - Or not . . .

I don’t think necessity is the mother of invention. Invention, in my opinion, arises directly from idleness, possibly also from laziness—to save oneself trouble. — Agatha Christie

PCM Capability

PCM Capability

- Ultimately: Liquid Rocket Engines, Solid Rocket Motors, Nuclear Thermal Propulsion, . . .
- Current near term release = Liquid Rocket Engines



Availability

- Similar approach to PCEC/CASTS
- General Public (Unrestricted) model (spreadsheet) + documentation
- NASA-approved Users (Restricted) model + documentation
  - Manual and Historical Technical data sheets plus (restricted) source cost database/calibrations

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Liquid Engines Summary

- Parametric model built on non-cost technical and programmatic characteristics
  - Engine cycle, propellants, thrust, production rates and quantities, etc.
  - Certification testing approach, design maturity, state of the art, etc.

- Based on Liquid Rocket Engine Cost Model (LRECM)
  - Developed by Rocketdyne (circa 1992-2003)
  - "Bought" by NASA mid-90's; updated mid '00's
  - "Engineering" model – limited number data points

- Modifications for PCM version
  - Adding additional data points
    - Propellant combinations, pressure (versus pump) – fed
  - Modifying/changing CER's
  - Calibration of historical engine data points
  - Fixed/variable production cost as function of production rate

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Liquid Engines Cost Elements

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- OUTPUT: Cost Elements/Work Breakdown Structure
  - Model Base = constant Millions of Dollars, 2015 (M 2015$)
  - Escalation using NASA New Start or user-input indices

LIQUID ROCKET ENGINES
OUTPUTS

COST SUMMARY

Raw Output | Escalated Value

Design, Development, Test, & Engineering

	2015 $M	2020 $M
Design / Development Engineering Labor	$ 694.92	$ 783.59
Development Test Hardware	$ 1,847.03	$ 2,082.73
System Test Hardware	$ 1,754.68	$ 1,978.59
Integration, Assembly, Checkout	$ 92.35	$ 104.14
System Test Operations	$ 1,332.03	$ 1,502.01
System Test Labor	$ 896.21	$ 1,010.58
Development/Qualification Test Propellants	$ 435.82	$ 491.43
Tooling and Ground Support Equipment	$ 414.17	$ 467.02
Tooling	$ 41.42	$ 46.70
Mechanical/Electrical GSE	$ 372.75	$ 420.32
System Engineering & Integration	$ 44.36	$ 50.02
Program Management	$ 116.90	$ 131.82
DDT&E Total	**$ 4,449.41**	**$ 5,017.18**
DDT&E PRIME Total	***$ 4,013.59***	***$ 4,525.75***

Production

	2015 $M	2020 $M
Average Unit Hardware	$ 28.00	$ 31.57
Integration, Assembly, Checkout	$ 2.92	$ 3.29
System Engineering & Integration	$ 2.06	$ 2.32
Program Management	$ 1.37	$ 1.55
Average Unit Cost	**$ 34.35**	**$ 38.73**
Total Production Quantity	98	
Total Production Cost	**$ 3,366.35**	**$ 3,795.92**
T1,1	$ 84.92	$ 95.76
Variable Cost per Engine*	$ 29.32	$ 33.06
Fixed Cost per Year *	$ 87.75	$ 98.95

** Estimated based on Steady State Production*

Operations and Support

	2015 $M	2020 $M
Ops and Support Cost per Engine per Flight	$ 0.39	$ 0.44
Ops and Support Cost per Flight	$ 1.95	$ 2.19
Total Ops and Support Cost per Year	**$ 3.89**	**$ 4.39**

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Liquid Engines Source Database

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Added to LRECM Data Set	Engine	Cycle	Propellants	Reusable /Expendable	Thrust (klbf)	Launch System(s)
	F1	Gas Generator	RP/LOX	Expend	1,522	Saturn V
O	MA5	Gas Generator	RP/LOX	Expend	490	Atlas II
O	RS27	Gas Generator	RP/LOX	Expend	237	Delta II
	J2	Gas Generator	LH2/LOX	Expend	230	Saturn II
X	J2X	Gas Generator	LH2/LOX	Expend	294	not apply
X	RL10A3	Split Expander*	LH2/LOX	Expend	15	Multiple
O	RS68	Gas Generator	LH2/LOX	Expend	797	Delta IV
X	LR87	Gas Generator	Hypergolic	Expend	543	Titan IV
X	LR91	Gas Generator	Hypergolic	Expend	105	Titan IV
X	Viking VI	Gas Generator	Hypergolic	Expend	171	Ariane 4, 5
	SSME	Stg Combustion (2 shaft)	LH2/LOX	Reus	512	Shuttle
X	RD180	Stg Combustion (1 shaft)	RP/LOX	Expend	930	Atlas V
X	LM Ascent	Pressure-Fed	Hypergolic	Expend	3.5	Lunar Module
X	LM Descent	Pressure-Fed	Hypergolic	Expend	10	Lunar Module
X	OMS	Pressure-Fed	Hypergolic	Reus	6	Shuttle
X	RL10C1	Split Expander*	LH2/LOX	Expend	22.9	Multiple

**Split Expander = use Gas Generator*

O	Included in original LRECM data but not documented
X	Added to LRECM data set

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Liquid Engines Key Variables

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- Key Variables
  - Technical & Programmatic Characteristics
    - Thrust, Chamber Pressure (Pc), Total and Average Production Rates/Year, etc.
  - "K1" Variable value = f(Engine Cycle + Propellants)
    - Engine Cycle: Gas Generator, Staged Combustion (1, 2-shaft), Pressure Fed
    - Reusable/Expendable
    - Propellants: Fuel (RP, LH2, A-50) + Oxidizer (LO2, N2O4)
  - Subjective Variables
    - Manufacturing Maturity, Design Maturity, Certification Approach, etc.
- CER Example: Flight Average Unit Cost (AUC)

AUC = K1 Factor x Thrust Factor x Pc Factor x Mfg Factor x Constant x Adjustment Factor

Where…

- K1 Factor = from lookup table; f(Cycle, Propellant)
- Thrust Factor = $0.2455 \times \text{Thrust}^{0.54}$
- Pc Factor = multi-order polynomial: f(Pc, K1)
- Manufacturing Factor = lookup table; Mfg Maturity Level, Mfg Automation Level
- Constant = 3.000 (M 15$'s)
- Adjustment Factor = (restricted version only), value at which AUC = historical calibrated data

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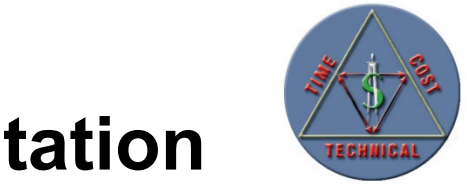
Liquid Engines Documentation



- Available Documentation
  - Unrestricted
    - General User's Guide
    - Specific (e.g. LRE) Guide
    - Historical Database Technical Data Sheets
  - Restricted
    - Unrestricted documentation
    - + Historical Database Source Cost Data and DDTE and AUC Adjustment Factors

- Technical Data Sheets
  - Part of CASTS "Virtual Black Books" data set
    - Modeled after NASA Cost Analysis Data Requirement (CADRe) historical project data sets
  - One for each member of LRE historical data set
  - Contents: Overview, development and production history, primary technical parameters, engine description

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Nuclear Thermal Rocket Overview

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- Why a Nuclear Thermal Rocket (NTR) parametric cost model?
  - Necessity (again) – inquiring minds want to know
  - More efficient than chemical propulsion for interplanetary travel (and beyond)
  - Nuclear Thermal and Nuclear Electric are two primary Nuclear Thermal Propulsion (NTP) concepts
    - Nuclear materials heat/expand working fluid (usually liquid hydrogen) – no combustion
    - Replaces combustion/expansion of chemical fuel and oxidizer

- PCM NTR cost model is based on work done by Rocketdyne for NASA Glenn (then Lewis) Research Center circa 1992
  - Original work defined two models:
    - 1) In-situ nuclear power generation (e.g. located on Moon for Moon-base power generation)
    - 2) NTR propulsion for in-space transportation

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NTR Source Data and CERs

Engineering Cost Office

- PCM model currently focused on Nuclear Thermal in-space propulsion
  - In-situ power model not included with PCM at present
- Primary NTR model source data
  - Nuclear Engine for Rocket Vehicle Applications (NERVA)
    - Plus preceding ROVER program
  - Systems for Nuclear Auxiliary Power (SNAP) series
  - Space Station Freedom (SSF) power studies – Rocketdyne
- Primary independent variables
  - Reactor Thermal Power (MWth: megawatts thermal)
  - Weight: CERs for non-nuclear subsystems

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NTR Example Output/CER

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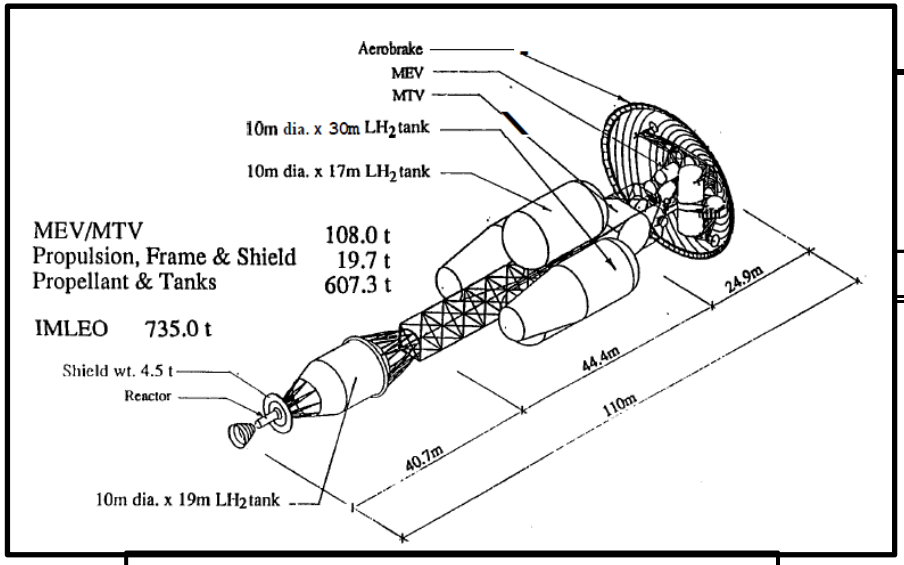
- Example input/output for NTR system



Thrust	**75 klbf**
Reactor Power	**1600 MWth**
Reactor Temp	**2700 K**

	Dev	Unit	TOTAL
Propellant Supply	$ 435.10	$ 355.05	$ 790.15
Thruster	$ 2,029.17	$ 360.00	$ 2,389.17
Structures	$ 116.47	$ 15.53	$ 132.00
Control/Condition Monitor	$ 68.02	$ 24.00	$ 92.02
SUBTOTAL	$ 2,648.76	$ 754.58	$ 3,403.34
Ground Test Hardware	$ 830.04		$ 830.04
Ground Test	$ 695.76		$ 695.76
SEI	$ 834.91		$ 834.91
Assembly		$ 75.46	$ 75.46
Acceptance Test		$ 124.51	$ 124.51
PM&S		$ 47.73	$ 47.73
TOTAL	$ 5,009.47	$ 1,002.27	$ 6,011.74

- Example CER: Nuclear Reactor (portion of Thruster subsystem)

Reactor Development M15$ = [376 + (880 x MWth^.07)] x 3.000 x NERVA Inheritance Factor

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Solids Overview

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- Why a Solid Rocket Motor (Booster) parametric cost model?
  - Expand basis of current CASTS top-level CER for large-diameter SRMs
  - Adds small-diameter SRM data set
  - Expands large-diameter data set
    - More data points + greater insight/depth
      - E.g. end item + activity level CERs
      - Case, propellant, nozzle; mix/cast, QA/Xray, nozzle buildup, integration, etc.
      - Reusable versus expendable recurring cost contributors
- Enable “better” SLS + other launch systems non-recurring and recurring cost analyses
- Provide additional insight to understand/address solid industry issues
- Current PCM Status: next on the list

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SRM Basic CASTS CER

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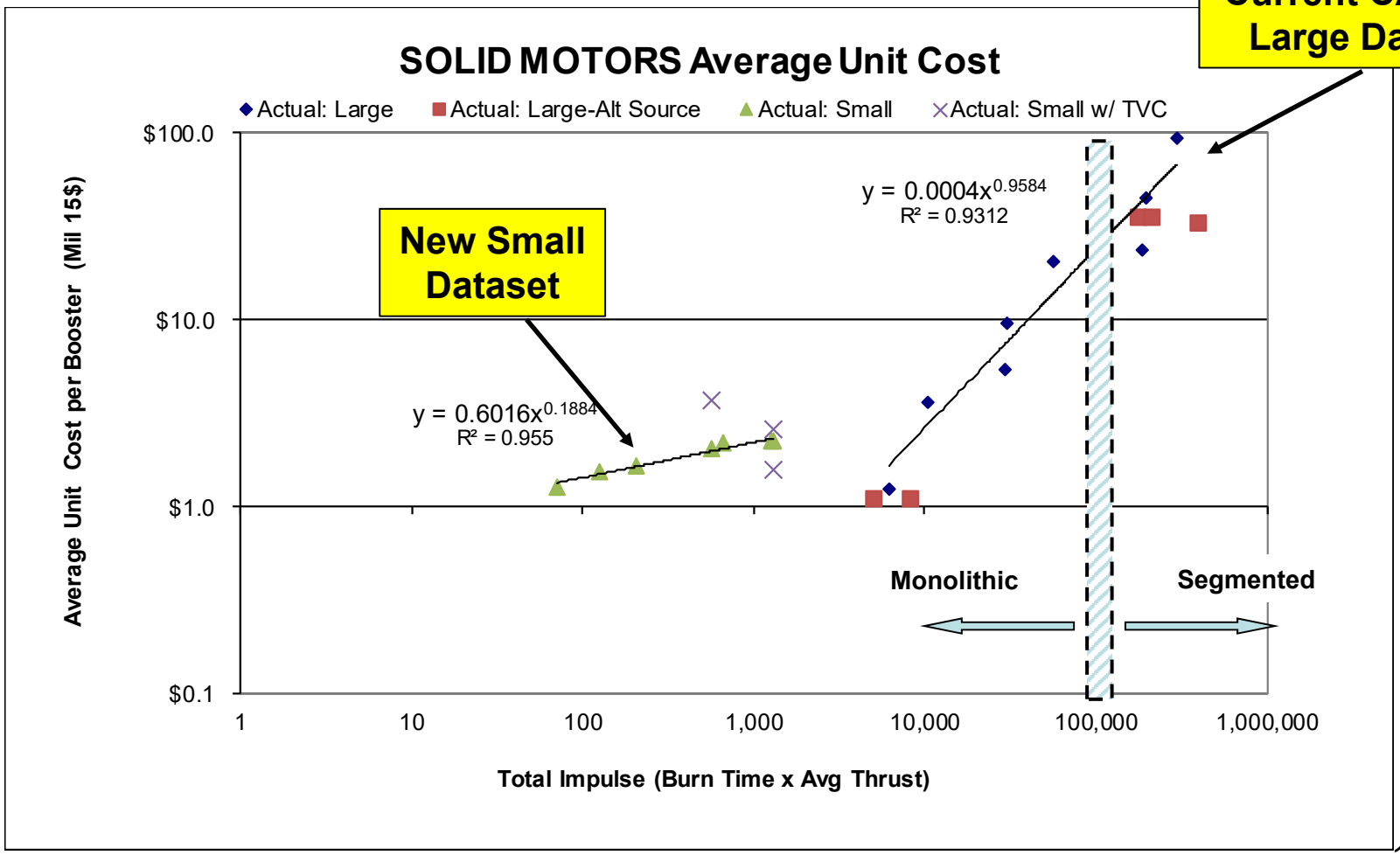
- CASTS provides point-of-departure CER and data set
  - Unit Cost versus Total Impulse = Average Thrust x Burn Time



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Solids Issues (1 of 2)

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- Sustainability of large-diameter solid motor industrial base
- Cost/pound of solid propellant (Ammonium Perchlorate (AP)) vs. demand

Comparing Space Shuttle RSRM to other SRMS		
Missile Program	**Pounds of Propellant**	**Equivalent # of SRMS to Equal One Space Shuttle RSRM**
Space Shuttle RSRM	1,106,059	1
Trident II D-5	110,200	10
Minuteman III (MM III)	66,642	17
Ground Missile Defense (GMD)	43,469	25
Kinetic Energy Interceptor (KEI)	20,026	55
Patriot Advanced Capability-3 (PAC-3)	350	3,160
Guided Multiple Launch Rocket System (GMLRS)	216	5,121
Advanced Medium-Range Air-to-Air Missile (AMRAAM)	113	9,788
Hellfire	20	55,303
Javelin	3	368,686

NASA man-launched space systems represented ~70% of the demand base – that is now gone

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Solids Issues (2 of 2)

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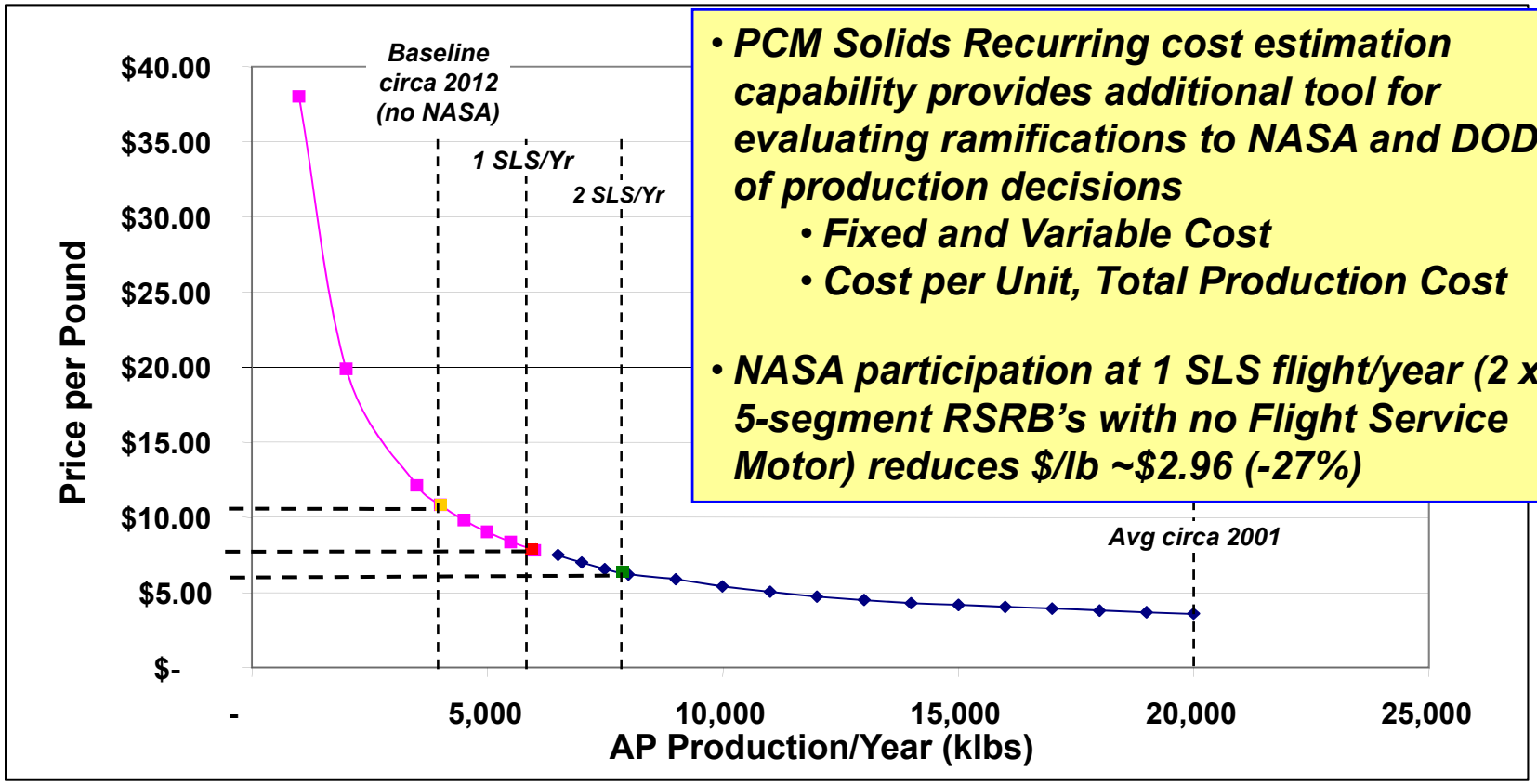
- AP Production pricing per pound very sensitive to quantity procured
  - Reflects significant fixed cost to maintain production capability (~$50M/yr)
- NASA decisions impact recurring cost of many DOD agencies/programs



- ***PCM Solids Recurring cost estimation capability provides additional tool for evaluating ramifications to NASA and DOD of production decisions***
  - ***Fixed and Variable Cost***
  - ***Cost per Unit, Total Production Cost***
- ***NASA participation at 1 SLS flight/year (2 x 5-segment RSRB's with no Flight Service Motor) reduces $/lb ~$2.96 (-27%)***

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Summary & Next Steps

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- PCM Summary
  - PCM development is “demand driven”
    - Addresses liquid, nuclear, solid propulsion systems
  - Provides top level insight into non-recurring and recurring cost of alternative propulsion options for ballistic, earth-to-orbit, and in-space transportation systems
  - Unrestricted version available for general distribution
    - Restricted version available to TBD NASA-approved personnel

- PCM Next Steps
  - Release Liquid model and documentation
    - Selected beta-testing
  - Finalize, then release NTR model and documentation
  - Develop, Document, Release SRM model
  - Potential Enhancements: Decomposition of cost estimates to lower level end-item and activity-based cost elements