

Propulsion Cost Model (PCM) Update

Presented to:
NASA Cost & Schedule Symposium

Presented by:
Richard Webb
KAR Enterprises

May 3, 2023



**Engineering
Cost
Office**





Propulsion Cost Model Update Outline



- Propulsion Cost Model Overview
- Solid Rocket Motor Module
 - Categories Definitions
 - Boosters
 - Stages
 - Upper Stages
 - Kick Motors
 - Sounding Rockets
 - Solid Rocket Motor Cost Database and Cost Estimating Relationships (CERs) for each Category
 - Historical Cost Database
 - DDTE and Flight Unit CERs
- Next Steps
 - Relationship to CASTS Solid CERs
 - Spreadsheet development and release
 - Documentation: User Guides and Virtual Black Books



Propulsion Cost Model Update

OVERVIEW



- What is PCM?
 - A parametric cost model for use in estimating the life cycle cost of different earth-to-orbit and in-space transportation propulsion systems
 - Add-on model to Crew And Space Transportation Systems (CASTS) portion of Program Cost Estimating Capability (PCEC) that can be:
 - Standalone model to PCEC/CASTS
 - Linkable to PCEC estimate; similar to other specialized NASA models
 - Suite of tools: model + historical data (Unrestricted & Restricted versions)
 - Spreadsheet-based cost model plus documentation
 - Historical data
 - Technical and programmatic data (Unrestricted)
 - Non-recurring development and recurring production cost data (Restricted)
 - Non-Recurring Development (DDTE) + Flight Unit (FU) cost
 - All cost data normalized to Constant Year 2015 \$'s

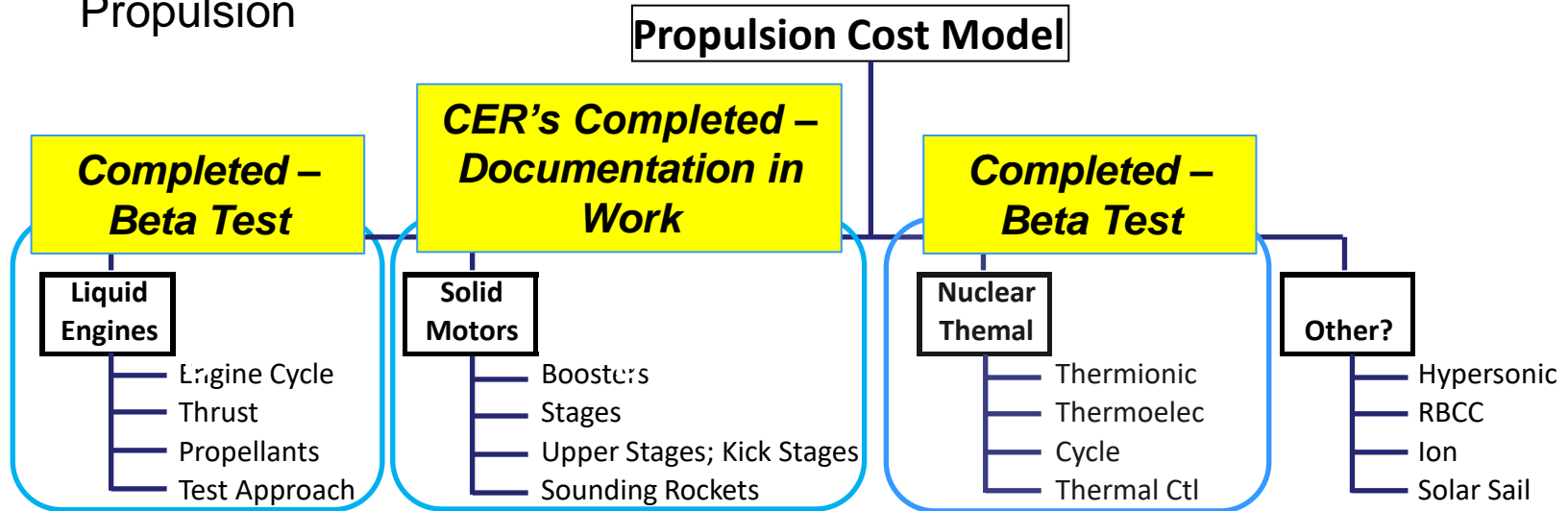


Propulsion Cost Model Update ORGANIZATION



PCM Capability

- Liquid Rocket Engines, Solid Rocket Motors, Nuclear Thermal Propulsion



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



Propulsion Cost Model Update STATUS



- Organized in 3 “Modules”
 - Liquid Rocket Engines (LRE), Solid Rocket Motors (SRM), Nuclear Thermal Propulsion (NTP)
- LRE and NTP (*essentially*) completed
 - LRE: model + user guide + Virtual Black Books (VBBs) for each engine in historical database
 - Available in hard-copy or via on-line REDSTAR Repository
 - NTR: model CER’s completed, *user guide and VBB data in work*
- **SRM: CER’s initial version completed – primary focus of this update**
 - CER’s finalized subsequent to peer review updates
 - *User guide and VBB data in work*



Propulsion Cost Model Update

SOLID ROCKET MOTOR OVERVIEW



- Primary Changes from CASTS CERs
 - Significantly expanded depth and breadth of historical database relative to PCEC ver. 2.3 CASTS SRM CERs
 - CASTS CERs included large earth-to-orbit launch vehicle boosters only
 - Depth: increased total number of historical datapoints
 - REDSTAR, Missile Defense Agency (MDA) data-sharing, other
 - Breadth: expanded database to include much wider range of solids – both size and type
 - Segregated database into 5 different categories by type/use of SRM
 - Created Non-Recurring and/or Flight Unit CERs for each category
 - Boosters, Stages, Upper Stages, Kick Motors, Sounding Rockets
 - Changed primary independent variable from Total Impulse to Gross Weight
 - Data easier to obtain; more applicable to all SRM categories
 - Total Impulse vs. Gross Weight very highly correlated (.99+ R²)

	Non Recurring	Flight Unit
WAS	6	18
IS	30	55

MDA Data = 11 new datapoints; all Flight Unit \$'s (no Non-Recurring)



Propulsion Cost Model Update

SRM DEFINITIONS (1 of 2)



- Solid Rocket Motors Category Definitions
 - Boosters
 - Provide thrust at liftoff to earth-to-orbit launch systems in addition to first stage. All boosters in historical database are side-mounted to primary first stage. Database consists primarily of segmented cases, with two monolithic cases booster datapoints. Minimal avionics, some with thrust vector control. Shuttle Solid Rocket Booster (SRB) is reusable/manned, all others are expendable/unmanned.
 - Stages
 - In-line first, second, or third stages for earth-to-orbit or ballistic launch systems. Ballistic systems include land and sea-based intercontinental ballistic missiles.
 - Upper Stages
 - Stages designed to be ignited in-space. Lifted from earth to an in-space destination (e.g. Low Earth Orbit) by an earth-to-space launch system. Typically deployed by launch system as integrated unit with payload, after separation is then ignited to boost the payload to the desired orbit/destination.



Propulsion Cost Model Update

SRM DEFINITIONS (2 of 2)



- Solid Rocket Motors Category Definitions
 - Kick Motors
 - Similar to Upper Stages but generally with less propulsive power, Kick Stages are designed to be ignited in-space. Also known as “apogee kick motors”, they are lifted from earth to an in-space destination (e.g. Geosynchronous Transfer Orbit) by an earth-to-space launch system. Typically deployed by the launch system as an integrated unit with the payload, and is then ignited to boost the payload to the desired orbit.
 - Sounding Rockets
 - A Sounding Rocket is a suborbital rocket used to launch upper atmosphere, exoatmospheric, and microgravity sondes or probes. It can propel payloads into space, but cannot establish them in orbit. Usually used to place scientific payloads into space for short periods of time (e.g. 30 minutes) before the payload falls back to earth.



Propulsion Cost Model Update

SRM DATABASE (1 of 2)



- Historical Database (1 of 2)
 - Sorted by Gross Weight (Low to High)

Category

BO	Booster
KS	Kick Stage
SR	Sounding Rocket
ST	Stage
US	Upper Stage

Database Weight Range

From: 277 lbs

To: 1.4M lbs

Cat	Vehicle	Stage
KS	Delta/Atlas AKM	Star 17A
KS	Delta	Star 24
ST	MDA	Trident C4 Stage 3
KS	Delta/Atlas/NII	Star 27
SR	Orion	Orion
ST	MDA	THAAD Booster
ST	MDA	Orion 38
KS	Shuttle/Ariane/Delta	Star 37XFP
KS2	Shuttle/Ariane/Delta	Star 37XFPV
US	MDA	ASAS
KS	Delta	Star 37FM
SR	Black Brant V	Black Brant V
SR	BBVA	Black Brant V A
SR	Terrier	Terrier Orion
US	MDA	Talos
SR	Terrier	Terrier Malamute
ST	Minuteman	MMI, II Stg 3: M57A1
US	Shuttle	PAM-D Star 48 short
KS	Shuttle (PAM)/Delta	Star 48B short
KS2	Shuttle (PAM)/Delta	Star 48B long
US	Delta II	PAM-D Star 48 long
KS2	Conestoga	Star 48V
KS2	Conestoga	Star 48 BV
SR	Terrier	Terrier-Black Brant VC
SR	Black Brant X	Black Brant X
US	Shuttle	PAM-DII Star 63
ST	MDA	Castor IA
ST	Minuteman	MMII, III Stg 3: SR73AJ1
US1	Shuttle	IUS-2 Orbus 6
ST	MDA	Orion 50XL



Propulsion Cost Model Update

SRM DATABASE (2 of 2)



- Historical Database (2 of 2)
 - Sorted by Gross Weight (Low to High)

Category

BO	Booster
KS	Kick Stage
SR	Sounding Rocket
ST	Stage
US	Upper Stage

Database Weight Range

From: 277 lbs

To: 1.4M lbs

Cat	Vehicle	Stage	Gross Weight (lbs)
SR	Black Brant XI	Black Brant XI	11,600
SR	Black Brant XII	Black Brant XII	13,888
ST	Minuteman	MMI Stg 2: M56A1	15,502
ST	Minuteman	MMII, III Stg 2: SR19AJ1	15,502
SR	Aries	Aries-MM I	15,760
ST	Peacekeeper	PK Stg 3 (HER SR-120)	16,962
US1	Shuttle/Athena	IUS-1 Orbus 21	23,953
ST	MDA	Castor IVB	25,445
BO	Atlas IIAS	Atlas IIAS Castor 4A	25,737
SR	Joust	Prospector/Joust (Castor IVA)	27,000
US	Shuttle/Athena	IUS Multi Stage	32,418
ST	MDA	Trident C4 Stage 2	35,972
ST	MDA	Orion 50XSL	36,153
ST	MDA	Trident C4 Stage 1	42,508
ST	Minuteman	MMI, II, III Stg 1: M55E1	50,400
ST	Peacekeeper	PK Stg 2 (AGC SR-119)	60,874
BO	Atlas V	Atlas V AGC AJ-60A SRM	102,949
ST	Peacekeeper	PK Stg 1 (MTI SR-118)	107,778
ST	Athena	Castor 120 - LLV1 1st Stg	117,014
BO	Ariane V	Ariane V EAP-P230	610,785
BO	Titan IV	Titan IV CSD SRM	704,000
BO	Titan IV	Titan IV SRMU	776,038
BO	Shuttle	Shuttle RSRM	1,255,334
BO1	Shuttle	Shuttle ASRM	1,345,807
BO1	Ares 1	Ares 1 FSB	1,377,000

	Pegasus XL	47,571.0
	Trident C4 TOTAL	79,191.0
Trident	D5	130,000
Pegasus	Orion 50(2)+Pegasus 3	50,990



Propulsion Cost Model Update

COST ESTIMATING RELATIONSHIPS



- CER's by Category
 - Mil Constant Year 2015\$'s
 - GW = Gross Weight (pounds)

Category	DDTE	Flight Unit
Booster	$.00018 \times GW^{1.1402}$	$.00006 \times GW^{1.0049}$
Stages	$23.38455 \times GW^{.4929} \times (\text{Year of First Flight} - 1960)^{-.4186}$	$.02532 \times GW^{.4417} \times (\text{Year of First Flight} - 1960)^{.2802}$
Upper Stages	Not Apply	$.0011 \times GW^{.1201}$
Kick Motors	Not Apply	$.4354 \times GW^{.1928}$
Sounding Rockets	Not Apply	$.0068 \times GW^{.5777}$

- NOTES
 - As with many CASTS CERs, absence of datapoints limits CER statistical significance
 - No DDTE CERs calculated for Upper Stages, Kick Motors, Sounding Rockets - Primarily due to lack of data
 - OBSERVATION: Almost every SRM is a modification/derivative of at least one, usually more, previous motors – development cost is not available or represents modifications to previous motors
 - Some historical datapoints included in source data provided with model, but excluded from CER calculations
 - Reasons described in documentation (User Guides, Virtual Black Books)



Propulsion Cost Model Update

PCEC Ver 2.3.1 CASTS CER CHANGES



- **Replacement of current CASTS Solid Motors CERs**
 - Current CERs (DDTE & Flight Unit) are very limited in scope
 - Essentially just “Boosters” historical database
 - No small solids (Sounding Rockets, Kick Motors, Upper Stages)
 - Stages not included in CER calculations – data provided for information purposes
 - Independent Variable is Total Impulse, not Gross Weight
 - PCEC CASTS Version 2.3.1 Replacement
 - Develop 2 “all in” CERs using all datapoints in updated PCM Solids database (one each for DDTE and Flight Unit)
 - Include all source data in Restricted documentation for user-based analyses



Propulsion Cost Model Update

PCEC Ver 2.3.1 CASTS SOLIDS CERs



- **CASTS “all in” DDTE CER**

- For slightly better fit - Segregate into two separate CERs based on input Gross Weight (GW)
- Essentially divides database into segmented vs. monolithic motors

- **If $GW < 500k \text{ lbs} = 6.07 \times 10^{-5} \times GW^{1.4977}$**
- **If $GW \Rightarrow 500k \text{ lbs} = 2.7 \times 10^{-7} \times GW^{1.6126}$**

- **CASTS “all in” Flight Unit CER**

- No segregation between size motors
 - If segregated, CERs are essentially non-predictive ($R^2 < .2$)

- **Flight Unit = $.0142 \times GW^{.5886}$**



Propulsion Cost Model Update

NEXT STEPS



- **Complete development and dissemination of all three PCM modules**
 - Complete testing (as necessary) of LRE and NTP module spreadsheets
 - Complete SRM PCM spreadsheet
 - Complete SRM Documentation and Virtual Black Books (VBB)
 - Same format and content as LREs
 - Documentation: Restricted and Unrestricted versions
 - VBB: By historical system, resides in REDSTAR
 - » Cost data available to Restricted users only
 - **Update CASTS SRM CERs as part of PCEC ver. 2.3.1**
 - Update Restricted and Unrestricted User Guides
 - Includes historical datapoints' DDTE and Flight Unit Costs and Adjustment Factors (Restricted Version)



QUESTIONS?

Contact Information:

Richard Webb

KAR Enterprises

richard.webb@karenterprises.net

richard.l.webb@nasa.gov