NASA Project Cost Estimating Capability (PCEC) version 2.4

Presented by

Engineering Cost Team (CS50)

NASA Marshall Space Flight Center

Richard Webb	**Shawn Hayes**
Mark Jacobs	**Nathan Snyder**

PCEC
Outline

- **Overview of PCEC**
  - **Description: What is PCEC?**
  - **Background: Why PCEC?**
  - **Tool Overview**

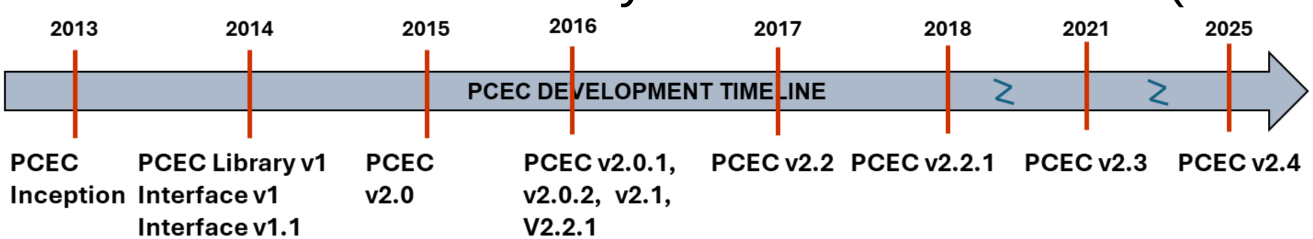
- **Robotic Spacecraft Model**
  - **Format, structure, CERs, database**

- **Crew and Space Transportation Systems (CASTS) Model**
  - **Format, structure, CERs, database**
  - **Addon Models: PCM, OCM**

- **Conclusion**
  - **REDSTAR, ONCE**
  - **PCEC access information**

What is PCEC?
Summary Description

- PCEC is a ***CAPABILITY*** including parametric cost models *and supporting data*
  - Developed and maintained by the MSFC Engineering Cost Office (ECO)
  - Replaced the NASA Air Force Cost Model (NAFCOM) circa 2013-2014
- Excel Add-in
  - Open Architecture and Code
  - Provides Full Visibility into all Calculations and Statistics
  - Meets all NASA Information Technology Security Requirements
- Two primary ‘models’, provided as part of a single, integrated tool
  - Robotic Spacecraft (Robotic SC)
  - Crewed and Space Transportation Systems (CASTS)
- Source and supporting data, normalizations, and CER workbooks are stored in MSFC REDSTAR Library and ONCE database (NASA users)



Moving to a Data Centric Approach

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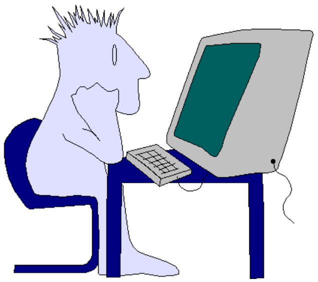
PCEC Approach was/is a response to what was perceived to have become a general problem with NASA cost estimating approaches.

FROM



TO

Model Centric

- Focus is on how to use the model
- Model becomes a medium for communication with the technical community
- Model gets all the credit (or blame) for the estimate
- **Estimate becomes an evaluation of the present, rather than a prediction of the future**

Data Centric

- Focus is on the relationship of the data to the estimating problem
- Analyst must access and know the underlying data
- Puts onus for the quality of the estimate on the estimator
- **Done properly, can lead to value-added solutions**

Why PCEC?
PCEC Model Philosophy

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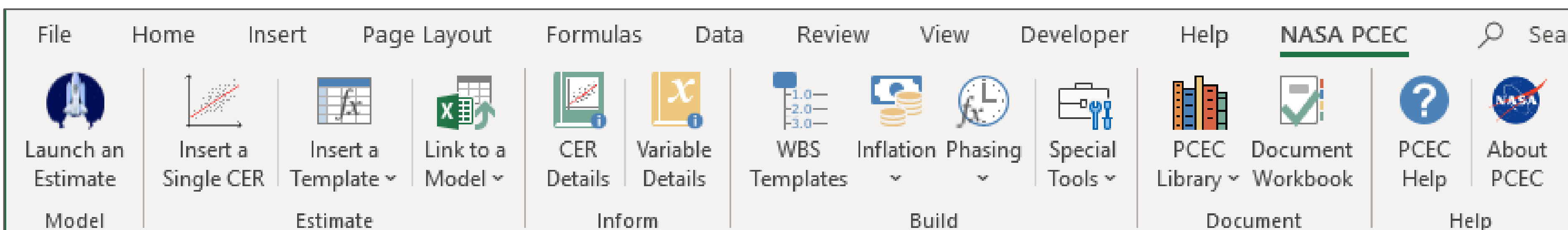
- **Use the Best Data Possible**
  - Verified and Validated CASTS Data
  - CADRe Data for Spacecraft Model
- **Total Transparency in the Analysis of the Data and the Development of the CERs**
- **No Cherry Picking the Data Points**
- **Minimize or Eliminate Subjective Inputs**
  - Follow a Data Driven Process for the Derivation of Subjective Inputs
  - Allow the User to Follow the same Process for Determining Input Values
- **Emphasize Quality of Input Parameters over Quantity**
- **Expect the User to Develop the Rationale for the Estimate**
  - Know the Data

Traceable → Defendable → Credible

What is PCEC? Tool Overview

Engineering Cost Office

- The Project Cost Estimating Capability (PCEC) is the primary NASA in-house developed parametric tool for estimating the cost of robotic missions, launch vehicles, crewed vehicles, etc.
  - Overarching tool for creating an estimate that spans the full NASA WBS
  - CERs included out-of-the-box for estimating the costs of a flight system (e.g., thermal) and support functions (e.g., project management)
  - Connects to other NASA-sponsored specialized tools to cover the complete NASA WBS (e.g., NICM, MOCET, PCM, OCM)
  - Excel-based (presented as add-in in the Ribbon) with completely visible calculations and code
  - Available to the General Public



The PCEC Architecture

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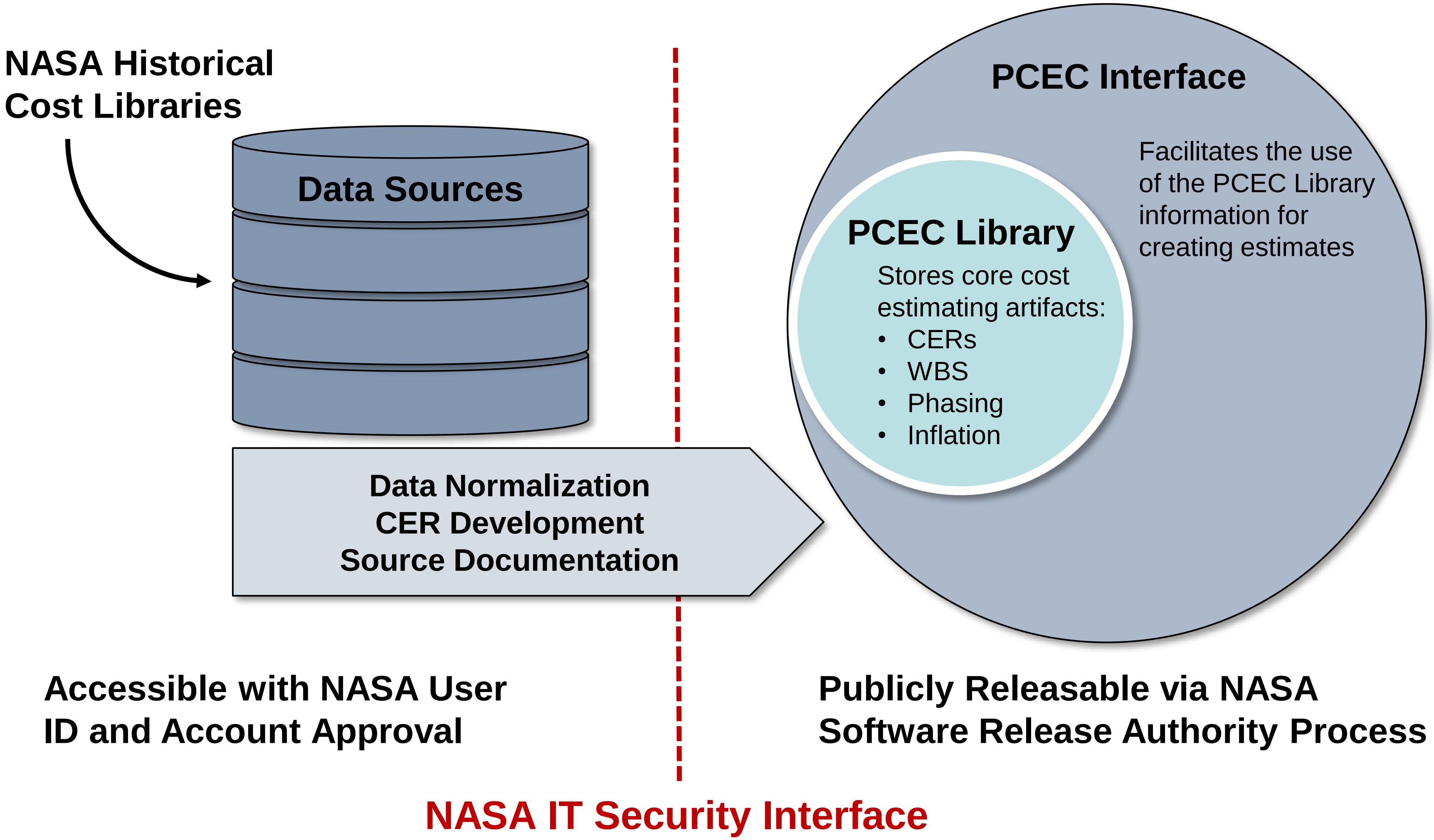
Key Elements of the PCEC Architecture



ROBOTIC SPACECRAFT MODEL

NASA PCEC
Robotic Missions Summary

Engineering Cost Office

NAFCOM
NASA – Air Force Cost Model
1990 – 2013

PCEC Robotic Missions
Project Cost Estimating Capability
2014 – Present

- Included 149 NASA and Air Force missions
- CERs at the subsystem-level (with some component-level CERs)
- Project Support Functions (PM/SE/MA/MOS) treated as “wraps”
- Covers Development costs only
- Limited visibility into data normalization effort and basis for CERs

NAFCOM	NASA WBS		PCEC
Historical-based Wrap Factors	1	**Program Management**	Separate CERs for each Function
	2	**Systems Engineering**	
	3	**Mission Assurance**	
Pass-thru	*4*	***Science Team***	*Pass-thru*
	5	**Payload**	
Historical-based Wrap Factors	5.1	P/L Management	Separate CERs for each Function
	5.2	P/L Systems Engineering	
	5.3	P/L Mission Assurance	
Instrument CERs	5.4	Instruments	Instrument CERs and/or NICM
	5.4.1-n	Instrument #1-n	
Historical-based Wrap Factors	5.5	P/L Integration, Assembly, & Test	I&T Recurring & Non-recurring CERs
	5.6	P/L GSE	
	6	**Spacecraft**	
Historical-based Wrap Factors	6.1	S/C Management	Separate CERs for each Function
	6.2	S/C Systems Engineering	
	6.3	S/C Mission Assurance	
Multivariable Subsystem-level CERs & Some Component CERs	6.4	Flight Elements	Multivariable Subsystem-level CERs & Some Lower-Level CERs
	6.4.1	Flight Element #1-n	
	6.4.1.1	Structure & Mech	
	6.4.1.2	Thermal	
	6.4.1.3	Power	
	6.4.1.4	Command & Data	
	6.4.1.5	Attitude Control	
	6.4.1.6	Propulsion	
Historical-based Wrap Factors	6.5	S/C Integration, Assembly, & Test	I&T Recurring & Non-recurring CERs
	6.6	S/C GSE	
Historical-based Wrap Factors	7	**MOS**	Multivariable CER
	9	**GDS**	
	10	**System IAT**	Multivariable CER
Pass-thru	*8*	***Launch Services***	*Pass-thru*
Pass-thru	*11*	***E/PO***	*Pass-thru*

- Started with a blank sheet
- Includes 62 NASA missions (59 for v2.4 CERs)
- CERs at the subsystem-level (with some lower-level CERs)
- CERs for all Project Support Functions (except Science Team)
- Covers Development & Operations
- Maximum visibility into data normalization effort and basis for CERs

NASA PCEC Robotic Mission Data Sets

Engineering Cost Office

MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
Missions for PCEC v2.3					
1 TDRSS K-L	1/23/14	GSFC	Boeing	Space Comm	Class A
2 MAVEN	11/18/13	GSFC	LMA	Planetary	Class C/D
3 LADEE	9/6/13	GSFC	ARC	Planetary	Class B
4 IRIS	6/27/13	GSFC	LMMS	Astrophysics/SMEX	Class C/D
5 Van Allen Probes	8/30/12	GSFC	APL	Heliophysics/LWS	Class B
6 NuSTAR	6/13/12	JPL	OSC	Astrophysics/Explorer	Class C/D
7 MSL	11/26/11	JPL	JPL/LMA	Planetary/Mars Expl	Class B
8 GRAIL	9/10/11	JPL	LMA	Planetary/Discovery	Class C/D
9 Juno	8/5/11	JPL	LMA	Planetary/New Frontiers	Class B
10 Glory	3/4/11	GSFC	OSC/Swales	Earth Sciences	Class C/D
11 GOES (-P)	3/4/10	GSFC/NOAA	Boeing/SGT	Earth Sciences	Class A
12 SDO	2/11/10	GSFC	GSFC	Heliophysics	Class B
13 WISE	12/14/09	JPL	BATC	Astrophysics/Explorer	Class C/D
14 LCROSS	6/18/09	ARC	NG	Planetary/Discovery	Class C/D
15 LRO	6/18/09	GSFC	GSFC	Planetary	Class B
16 KEPLER	3/6/09	JPL	BATC	Astrophysics/Discovery	Class C/D
17 OCO	2/24/09	JPL	OSC	Earth Science	Class C/D
18 IBEX	10/19/08	SwRI	OSC	Astrophysics/Explorer	Class C/D
19 Dawn	9/27/07	JPL	OSC/JPL	Planetary/Discovery	Class B
20 Phoenix	8/4/07	JPL	LMA	Planetary	Class B
21 AIM	4/25/07	LASP	OSC	Heliophysics	Class C/D
22 THEMIS	2/17/07	UCB	Swales	Astrophysics/Explorer	Class C/D
23 STEREO	10/26/06	GSFC	APL	Heliophysics	Class B
24 CLOUDSAT	4/28/06	GSFC	BATC	Earth Sciences	Class C/D
25 NEW HORIZONS	1/19/06	APL	APL	Planetary/New Frontiers	Class B
26 MRO	8/12/05	JPL	LMA	Planetary/Mars Expl	Class B
27 DEEP IMPACT	1/12/05	JPL	BATC	Planetary/Discovery	Class B
28 Swift	11/20/04	GSFC	Spectrum Astro	Astrophysics/Explorer	Class C/D
29 MESSENGER	8/3/04	APL	APL	Planetary/Discovery	Class B
30 Spitzer	8/25/03	JPL	LMA	Astrophysics	Class A
31 MER	6/10/03	JPL	JPL	Planetary/Mars Expl	Class B
32 GALEX	4/28/03	JPL	OSC	Astrophysics/Explorer	Class C/D
33 RHESSI	2/5/02	UCB	Spectrum Astro	Heliophysics	Class C/D
34 TIMED	12/7/01	APL	APL	Earth Sciences	Class C/D
35 GENESIS	8/8/01	JPL	LMA	Planetary/Discovery	Class C/D
36 Mars Odyssey	7/7/01	JPL	LMA	Planetary/Mars Expl	Class C/D
37 WMAP	6/30/01	GSFC	GSFC	Astrophysics/Explorer	Class C/D
38 WIRE	3/5/99	GSFC	GSFC	Astrophysics/Explorer	Class C/D
39 TRACE	4/2/98	GSFC	GSFC	Astrophysics/Explorer	Class C/D
40 Cassini	10/15/97	JPL	JPL	Planetary/Outer Planets	Class A
41 Mars Global Surveyor	11/7/96	JPL	LMA	Planetary/Mars Expl	Class B
42 NEAR	2/17/96	APL	APL	Planetary/Discovery	Class B
43 GPM	2/27/14	GSFC	BATC	Earth Sciences	Class B
44 OCO-2	7/2/14	JPL	OSC	Earth Sciences	Class C/D
45 MMS	3/12/15	GSFC	GSFC	Astrophysics/Explorer	Class C/D
46 OSIRIS-REx	9/8/16	GSFC	LMA	Planetary/New Frontiers	Class B
47 GOES-R	11/19/16	GSFC/NOAA	Boeing/SGT	Earth Sciences	Class B
48 CYGNSS	12/15/16	SwRI	SwRI	Earth Sciences	Class C/D
49 InSight	5/5/18	JPL	LMA	Planetary/Discovery	Class B

PCEC v2.3 included 49 Missions

PCEC Robotic Missions includes a mix of Programs and Mission Risk Classes

PCEC v2.4 CERs include 59 Missions

MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
Added Missions for PCEC v2.4					
50 SMAP	1/31/15	JPL	JPL	Earth Sciences	Class C/D
51 JPSS-1	11/10/17	GSFC	BATC	Earth Sciences	Class B
52 Solar Probe	8/6/18	GSFC	APL	Heliophysics	Class B
53 Mars 2020	7/30/20	JPL	JPL	Planetary	Class B
54 TESS	3/20/18	GSFC	OSC	Astrophysics/Explorer	Class C/D
55 IXPE	12/9/21	MSFC	Ball	Astrophysics/Explorer	Class C/D
56 DART	11/23/21	APL	APL	Planetary	Class C/D
57 JWST	12/25/21	GSFC	NG	Astrophysics	Class A
58 Lucy	10/16/21	GSFC	LMSS	Planetary	Class B
59 GOES-T	3/1/22	GSFC	LMSS	Earth Sciences	Class B

Current database includes 62 Missions

MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
Normalized for PCEC Future Versions					
60 Psyche	10/13/23	JPL	SSL	Planetary	Class B
61 Europa Clipper	10/10/24	JPL	JPL	Planetary	Class A
62 SPHEREx	2/27/25	JPL	Ball	Astrophysics	Class C

Identified Future Mission Candidates

MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
New Missions Candidates					
N-1 IMAP	Aug/Sep 2025	APL	APL	Heliophysics	Class C
N-2 PUNCH	2/27/25	SwRI	SwRI	Heliophysics	Class D
N-3 Carruthers	Aug/Sep 2025	UCB	BAE	Heliophysics	Class D
N-4 JPSS-2	11/10/22	GSFC	OATK	Earth Sciences	Class B
N-5 NEA Scout	11/16/22	MSFC	JPL	Planetary	Class D
N-6 PACE	2/8/24	GSFC	GSFC	Earth Sciences	Class C
N-7 PREFIRE	5/25/24	JPL	SDL	Earth Sciences	Class D
N-8 GOES-U	6/25/24	GSFC	LMSS	Earth Sciences	Class B
N-9 Lunar Trailblazer	2025	JPL	JPL	Planetary	Class D
N-10 VIPER	2025	ARC	JSC	Planetary	Class D

PCEC Robotic Mission Database Statistics

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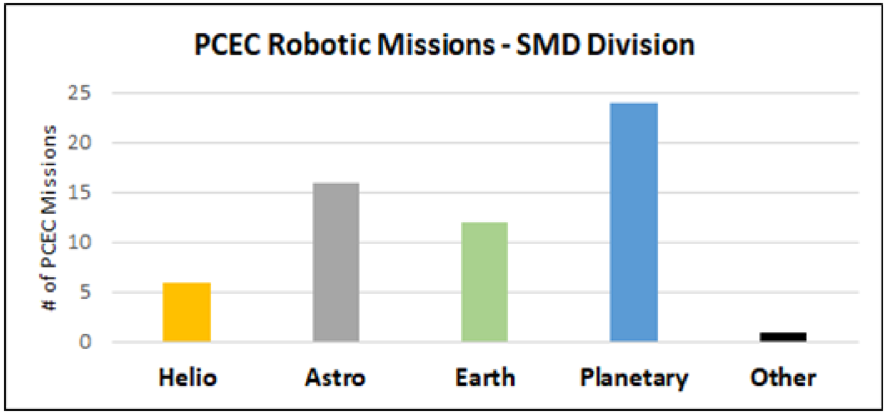
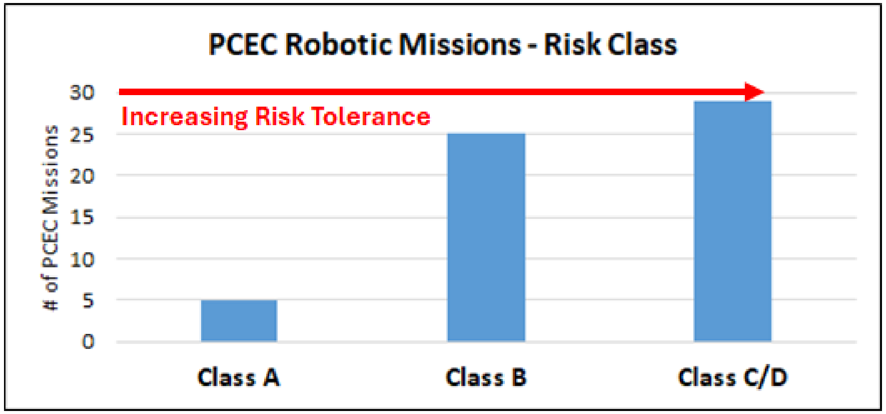
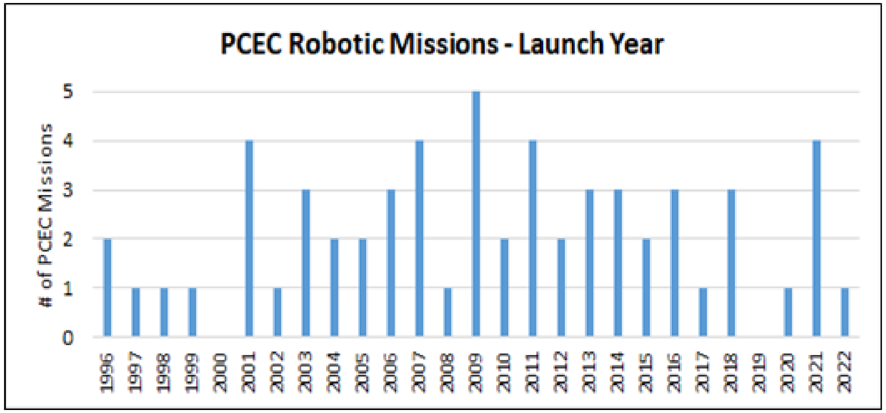
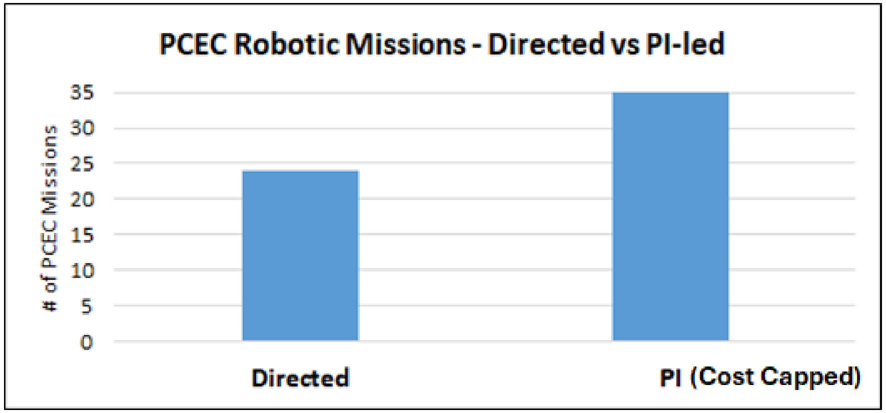
- Distributions of missions across SMD Division Launch Year, Risk Class, and Directed vs PI-led are shown here









NASA WBS for Robotic Missions

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- The NASA Work Breakdown Structure (WBS)used for Robotic Missions is shown here
- The PM/SE/MA and I&T functions are not consistently book-kept between Project level and S/C or Payload level (and are moved from WBS 5/6 to WBS 1/2/3/10 for PCEC analyses)

These I&T efforts are distributed across WBS 10 and 5/6 but combined for this analysis

NASA WBS (augmented)

WBS #	*Item*
1.0	**Program Management**
2.0	**Systems Engineering**
3.0	**Mission Assurance**
4.0	**Science**
5.0	**Payload**
5.1	P/L PM
5.2	P/L SE
5.3	P/L MA
5.4	Instrument #1
5.xx	Instrument *n*
5.70	P/L Software
5.80	P/L IAT
5.90	P/L GSE
6.0	**Spacecraft**
6.1	S/C PM
6.2	S/C SE
6.3	S/C MA
6.4	Structure & Mech. (SC 1)
6.5	Thermal (SC 1)
6.6	Power (SC 1)
6.7	C&DH (SC 1)
6.8	Communications (SC 1)
6.9	ACS (SC 1)
6.10	Propulsion (SC 1)
6.11	Harness (SC 1)
6.12-6.43	Repeat 6.4-6.11 for each Flt Element
6.70	S/C Software
6.80	S/C IAT
6.90	S/C GSE
7.0	**MOS**
8.0	**Launch Services**
9.0	**GDS**
10.0	**System Level IAT**
11.0	**E/PO**

These PM/SE/MA efforts are distributed across WBS 1/2/3 and 5/6 but combined for this analysis

PCEC Robotic Mission Data Normalization from CADRe*

Normalization Process Steps

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START
Raw (Unadjusted) Project Data

STEP 1
Inflate to Common Fixed Year $

STEP 2
Allocate to NASA WBS

STEP 3
Account for Mgmt, Fees, & Burdens

OUTPUT A
NASA WBS by Yr w/o Fees or Burdens

STEP 4
Full Cost Accounting Adjustments

STEP 5
Account for Contributions

OUTPUT B
NASA WBS by Yr w/ FCA & Contributions but w/o Fees or Burdens

STEP 6
Development Profile Phasing - *Schedule & Long Lead Items*

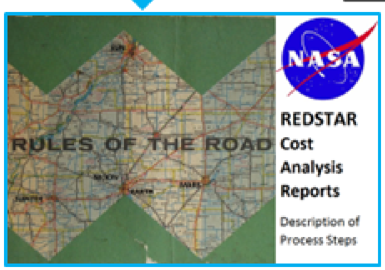
STEP 7
Removal of Costs for Multiple Units

OUTPUT C
NASA WBS by Phase (*normalized to a single protoflight unit*)

STEP 8
Removal of Costs from External Impacts

OUTPUT D
NASA WBS by Phase w/o External Impacts

Additional detail covering each process step is documented in the "Rules of the Road"



* Cost Analysis Data Requirement (CADRe) is NASA's system to collect technical, schedule, cost, and other data for each major milestone of a project

Cost Analysis Figures-of-Merit (FOMs)

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- **Developed four supplemental analyses to facilitate using data analysis results for cost modeling - Objective is to provide analysts with additional details that can be used to improve cost models**
- **Data Quality Assessment**
  - A score sheet has been included to capture uncertainty related to data interpretation due to lack of details - this provides a measure of confidence in the results and provides direction for future improvements
- **Spacecraft Heritage Assessment**
  - A rating sheet has been included to capture the level of spacecraft heritage associated with each project. The rating uses in-depth knowledge of the "as-launched" spacecraft configuration as the heritage basis (which is often less than pre-Phase B predictions)
- **Prototypes & Spares Assessment**
  - This rating captures prototype/spare quantities and prototype utilization plan details
- **Parts & Redundancy Assessment**
  - This rating captures the quality and type of parts and redundancy within each subsystem

Efforts to Capture Payload Accommodations Requirements

PCEC Payload Accommodations Database

- PCEC input candidates include several Payload inputs: Total Mass, Total Power, # of Instruments
- These inputs do not seem to adequately capture complexity of supporting the payload for I&T and other Project Support functions
- Additional Payload characteristics may better capture Accommodations complexity
- Enhanced insight into Payload Accommodations impacts on I&T, PM/SE/MA, and MOS/GDS development could improve PCEC CER performance

Mass
- Individual Instruments
- Total Mass

Power
- Individual Instruments
- Total Power

Volume
- Individual Instruments
- Total Volume

Thermal
- Instr-specific Min Op T
- Lowest Op T

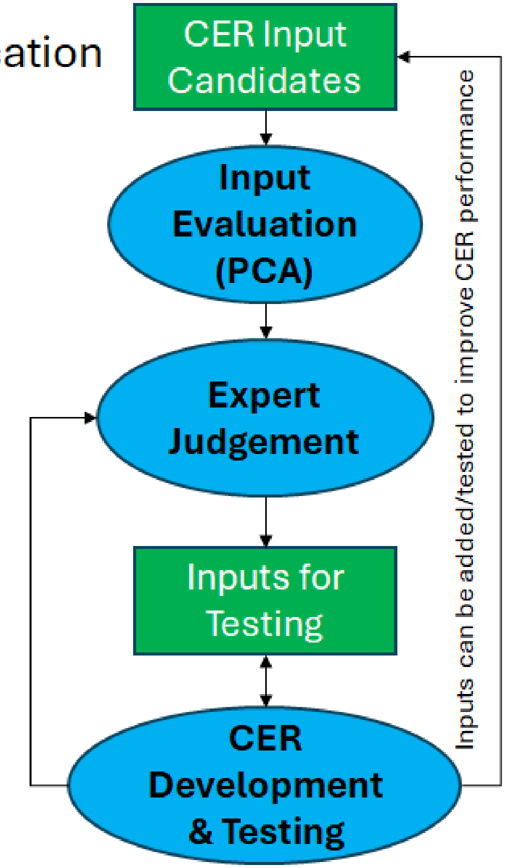
Data Rate
- Individual Instruments
- Total Data Rate

Pointing
- Individual Instruments
- Most Precise Reqt

PCEC Robotic Mission CER Development Database

Engineering Cost Office

- PCEC's CER Development Database includes over 500 data fields for 72 flight elements including normalized costs and technical/schedule input candidates; Includes all data needed to run PCEC (and SOCM)
- CER development is an iterative process with significant identification and testing of new input candidates



PCEC CER DATABASE CONTENTS

	DEVELOPMENT DATA	OPERATIONS DATA
COST	Normalized Development Costs for S/C Subsystems and Project Support (Non-Recurring & Recurring)	Normalized Operations Costs for Cruise & Encounter (Planetary) or Prime & Extended (Earth)
TECHNICAL	S/C System and Subsystem Technical Characteristics (includes all PCEC CER inputs)	Mission Operations Technical Characteristics (includes all NASA SOCM inputs)
SCHEDULE	S/C Subsystem-specific Schedule	Cruise, Encounter, Prime, Extended Mission Operations Durations

PCEC Robotic CERs Development Input Candidates

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- Multiple information sources have been reviewed to generate the initial input candidate list, including mass & performance metrics from:
  - CADRe: Fields in Part B (technical)
  - Cost Models: Aerospace Corp SSCM & COBRA, PRICE Space Missions (update of SAIC/Chicago Cost Model), and NAFCOM

INPUT CANDIDATES

PROJECT/MISSION
- Mission Risk Class
- Mission Target/Type
- Lead Organization
- Flight System Lead Organization
- Payload Lead Organization
- Flight System Lead Experience
- Payload Lead Experience
- # of Key S/C Contractors
- # of Key Payload Contractors
- Degree of In-House Scope
- International HW Participation
- Directed or AO
- Subsystem Lead Organization
- Subsystem Lead Experience
- # of Key Subcontractors
- Degree of In-House Scope

SCHEDULE
- Design Time (ATP-CDR)
- Fabrication Time (CDR-SIR)
- I&T Time (SIR-Ship)
- LO Time (Ship-Launch)
- CO Time (Launch-On-orbit CO)

FLIGHT SYSTEM
- Flight System Type
- Flight System Mass
- Flight System Power
- Flight System Heritage
- Flight System Advanced Technology
- Flight System New Design
- Flight System Design Modifications
- Parts Rating
- Payload Mass
- Payload Power
- # of Payload Elements
- # of flight system elements
- Operating Environment
- Radiation Environment

STRUCTURES & MECHANISMS
- Mass
- Load Carrying Shell/Truss Material
- # of Articulated Structures
- # of Deployed Structures

THERMAL
- Mass
- Thermal Operating Environment
- Thermal Control Type
- Radiator Material
- Insulation Type
- Power, Heaters (W)

PROPULSION/RCS
- Mass
- Engine 1 Thrust
- Engine 2 Thrust
- Engine 3 Thrust
- Ion PPU Power
- Ion Engine Thrust
- Tank Material
- Type of Propulsion System
- Propellant Mass
- Number of Thrusters

COMMAND & DATA HANDLING
- Mass
- Board Form Factor
- # of Boards
- Data Storage Capacity
- Onboard FSW, SLOC
- FSW Reuse
- Processor Type

COMMUNICATIONS
- Mass
- Uplink Band
- Downlink Band
- # of Bands
- Transmitter Power
- Max. Instrument Data Output
- Peak Uplink Data Rate
- Peak Downlink Data Rate
- Average Downlink Data Rate
- Average Uplink Data Rate
- HGA Assembly Material
- HGA Diameter (m)
- Max. Distance from Sun (AU)

GUIDANCE, NAV, & CONTROL
- Mass
- Pointing Accuracy
- Pointing/Knowledge Requirements
- Pointing Stability, Jitter
- Reaction Wheel Torque
- Slew Rate
- Control Type (3 Axis, Spinner, other)

POWER
- Mass
- Battery Capacity
- Battery Type/Chemistry
- Average Payload Power
- Peak Payload Power
- OSRs Needed?
- BOL Power @ 1 AU
- Array Area (m^2)
- Active Cell Area (m^2)
- End of Life Power

HARNESS
- Mass
- Additional EMI/Radiation Shielding
- End of Life Power

PCEC Robotic CERs
Operations Input Candidates

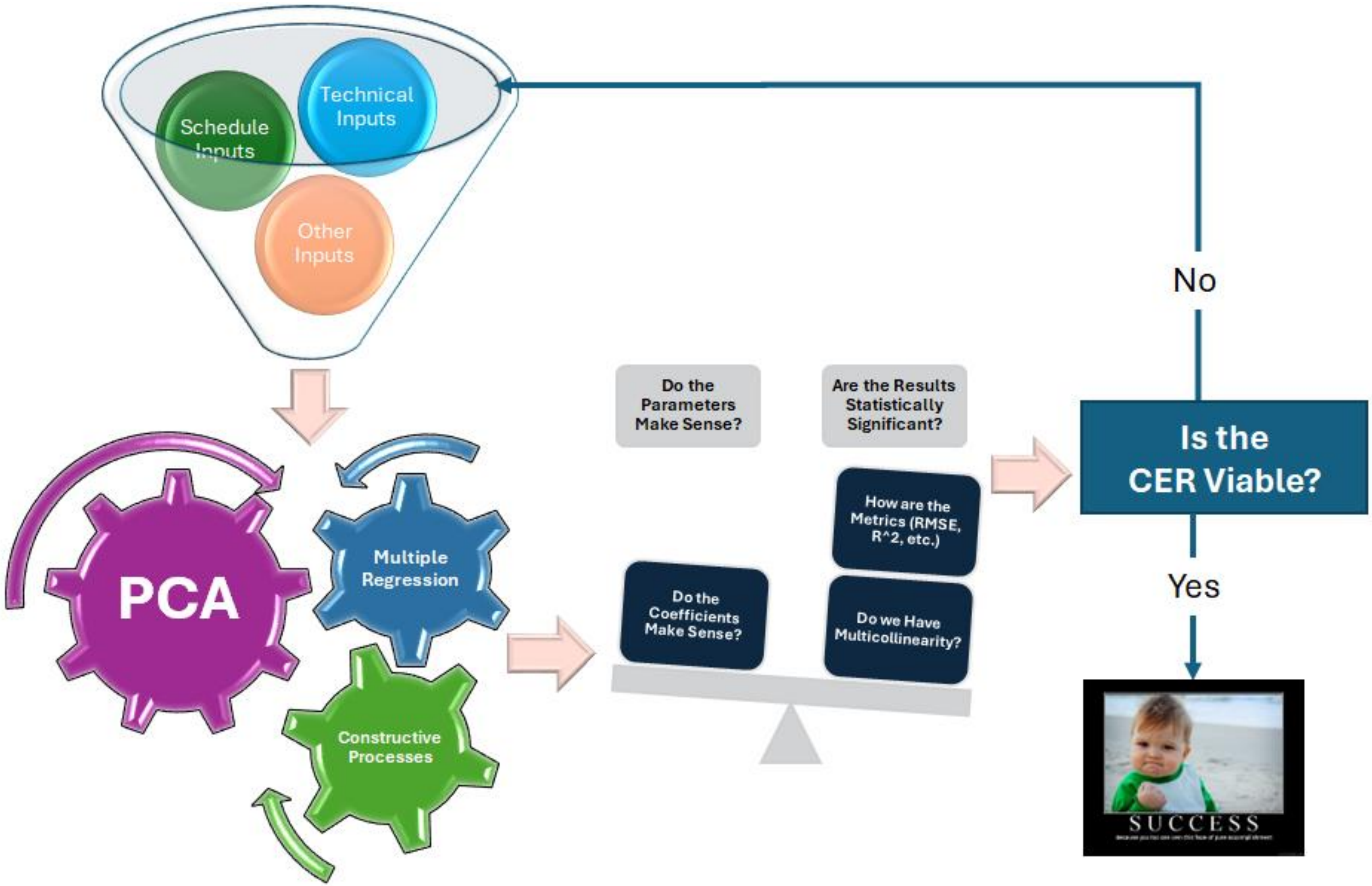
- **Multiple information sources have been reviewed to generate the initial input candidate list:**
  - CADRe: Fields in Part B (technical)
  - Cost Models: Space Operations Cost Model (SOCM), PCEC Normalized Data Library, MOCET
  - Over 150 input candidates were identified for each mission

INPUT CANDIDATES

SOCM (1)	SOCM (2)	SOCM (3)	PCEC Data Library	MOCET
# of Identical Flight Systems	# of Imaging Instruments	Instrument/Payload Operating Modes	Launch Date	Number of Instruments
# of Separate Science Investigations	# of Non-Imaging Instruments	Maneuver Frequency	Mass	Orbiting Body
# of Supporting Organizations	Command Frequency - Generation Time	Memory Margin	Power (EOL)	Cruise Checkout?
Architecture Design	Command Frequency - Real-Time Commands	MOS Autonomy	Heritage	Quiescent Cruise?
Conflicts Among Instruments	Command Frequency - Sequences	MOS Flexibility	Parts Rating	Mission Type
Contract Type	Crosstraining/Staffing Overlaps	MOS Heritage - %	# of Flight Elements	Mission Class
Design Complexity	Cruise Mission Duration (mo)	Nominal Mission Duration (mo)	Radiation Environment	
Development Schedule	Data Processing - Autonomy	Payload Flight Heritage	Data Storage Capacity, GB	
Lead Organization Level of Experience	Data Processing - Data Completeness	Post-Flight Data Analysis Duration (mo)	Peak U/L Rate, kbps	
Management Mode	Data Processing - Data Delivery Time	Power Margin	Peak D/L Rate, Mbps	
Mission Risk Class	Data Processing - Heritage/Reuse	Propulsion Margin - %	Daily D/L Volume, GB/day	
Mission Type	Data Processing - Max. Downlink Rate Mbps	Risk Plan - GDS/MOS	Flight System Type	
MOS s/W Maturity/Heritage	Data Processing - Max. Gb/Day	Risk Plan - Instruments/Payload	Mission Target/Type	
Operations Approach	Data Processing - On-Line Storage, GB	Risk Plan - S/C	Mission Risk Class	
Orbit	Data Processing - Storage/Playback Frequency	S/C Complexity	Project Lead Organization	
Pointing Requirements	Data Return Margin	S/W Redundancy	S/C Lead Organization	
S/C Design Implementation	Design Complexity	Science Event Complexity	S/C Lead Experience	
Science Team Location/Distribution	Downlink Data Rate (kbps)	Staff Experience	Operating Environment	
Science Team Role	Encounter Criticality	Targeted Observations	U/L Band	
Science Team Size (not all FT)	Encounter Mission Duration (mo)	Verification Requirements	D/L Band	
Scope of Guest Investigator Program	Engineering Event Complexity			
SOCM Instrument Score	Extended Mission Duration (mo)			
Target	H/W Redundancy			
Tracking Network	Instrument Support Complexity			

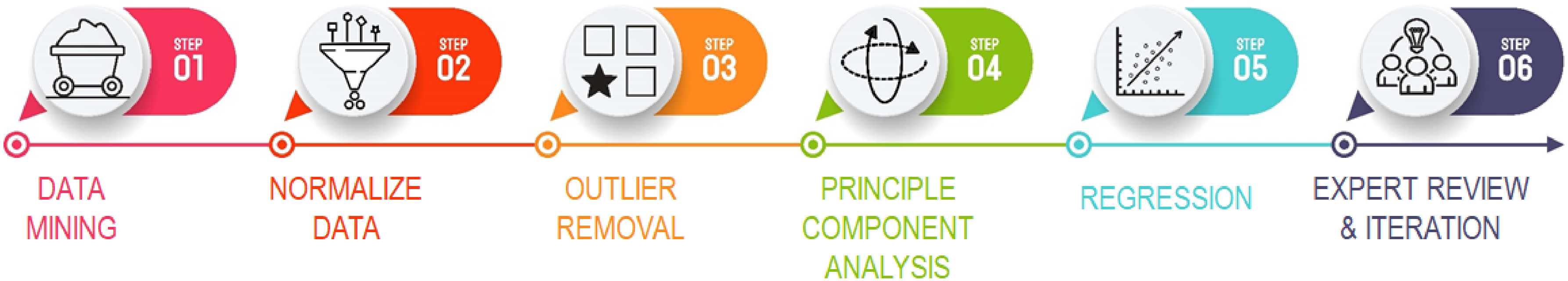
PCEC Robotic Mission CER *“Sausage Maker”*
Iterative Process for Generating CERs

Engineering Cost Office



PCEC Robotic Mission CER Development Process (1 of 3)

- A 6-step process for CER development has been utilized in the creation of the v2.4 robotic spacecraft model



Data Mining & Preprocessing

- CADRe & Supporting Data provide the foundation supporting all PCEC CER development (8-Step Cost Normalization Process, Technical Characteristics, Schedules, Derived Metrics)
  - Strive to identify reasonable and high-quality input candidates
- Remove outliers as necessary using boxplot analysis

CER Creation

- PCA is mathematical process that helps to identify CER input parameters that drive cost (results are not always intuitive)
- The PCEC regression process was implemented using a Python routine that includes log transformation of the data and uses a standard backward stepwise approach

CER Testing & Evaluation

- Preliminary CERs are evaluated by SMEs and are iterated until each CER demonstrates acceptable performance
- Additional post processing analysis includes:
  - Examination of Residuals/Outliers
  - K-Fold Cross Validation
  - Input Sensitivity Testing
  - Overall model performance

PCEC Robotic Mission CER Development Process (2 of 3)

Engineering Cost Office

STEP 01
DATA MINING

- Ongoing mission data collection effort since FY 2015
- Main sources of data used to support CER development include:
  - LRD CADRes and their supporting documentation
  - REDSTAR library resources at MSFC

STEP 02
NORMALIZE DATA

- To date, 62 missions have been normalized using an 8-step process which aligns each mission's cost data using the NASA standard WBS as a unifying framework
  - Adjustments for inflation, fees/burdens, contributions, etc.
- Each mission's normalization workbook can be found in the REDSTAR library along with supporting documentation

STEP 03
OUTLIER REMOVAL

- Mission outliers were identified using box plot analysis for each CER
- Impact of outlier removal on model performance was tested and shown to be necessary for the greater good
  - JWST, MSL Rover and Cassini are examples of recurrent outliers
- No single unifying element could be found to link outlier missions together given the variation in mission destination and purpose

PCEC Robotic Mission CER Development Process (3 of 3)

Engineering Cost Office

STEP 04
PRINCIPLE COMPONENT ANALYSIS

- PCA is mathematical process that transforms a data set into a smaller one that still contains most of the information contained in the larger set.
- PCA effectively reduces the number of variables while preserving as much information as possible

STEP 05
REGRESSION

- The PCEC regression process was implemented using a Python routine that includes log transformation of the data and uses a standard backward stepwise approach
- Variables were limited to no more than 10% of the number of observations
  - Most CERs have less than five independent variables
- Model selection criteria relies on error minimization metrics (RMSE) and SME judgement

STEP 06
EXPERT REVIEW & ITERATION

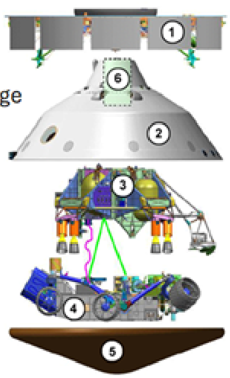
- Although mathematical methods can produce an array of CERs with low error that appear reasonable, care must be taken to sanity check the results
- Model input parameters must make intuitive sense
- PCEC preliminary CERs were reviewed by subject matter experts and iterated until a mathematically viable and intuitive results were obtained for each CER

PCEC Robotic Missions Unique Items

Multiple items require unique handling:

- **Aerodeceleration**
  - PCEC has CERs for Parachutes and Thermal Protection Systems (and Airbags)
- **Ion Propulsion**
  - COTS models for PPU (driven by max power) and Ion Thrusters (driven by screen voltage/ISP); CERs built on NSTAR and early ion propulsion efforts and refined with recent experience
- **Secondary Flight Elements**
  - PCEC s/c subsystems have a flag to identify if a subsystem is reliant on a different flight system for a primary function

MSL
1) Cruise Stage
2) Backshell
3) EDL
4) Rover
5) TPS
6) Parachute



Secondary Flight Elements

Mission	Flight Element
MSL	Carrier
MSL	EDL
Phoenix	Cruise Stage
Phoenix	ED
THEMIS	Probe Carrier
MER	Cruise Stage
MER	EDL
InSight	Carrier
InSight	ED

Secondary Flight Elements Subsystem Definitions

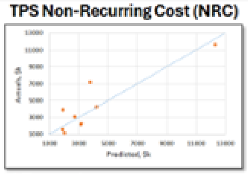
Subsystem	Secondary Subsystem Definition
Structures	Doesn't fly independently or carry primary load
Thermal	Doesn't fly independently
Power	Doesn't include solar array or RTG
GN&C	Doesn't fly independently
Propulsion	Doesn't fly independently
Telecomm	Doesn't include Xmtr/Receiver or Amps
C&DH	Doesn't include primary processor

"Secondary" flight elements mainly apply to Mars landed missions

THERMAL PROTECTION SYSTEM

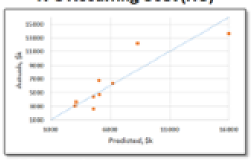
- Definition: Covers design, fabrication, and I&T for all TPS material; Includes TPS on Heat Shield, Backshell, and Parachute; Does not include structure, adhesive, or other supporting elements

TPS Non-Recurring Cost (NRC)



- **Input Parameters:**
  - PD - Peak Deceleration (g)
  - MPS - Mean Pressure at the Surface (kPa)
- **Cost Estimating Relationship (CER):** $1236 \times (PD)^{0.3761} \times (MPS)^{-0.1847}$
- **Adjusted R^2:** 0.52
- **Range of Error:** -51 to 73%

TPS Recurring Cost (RC)

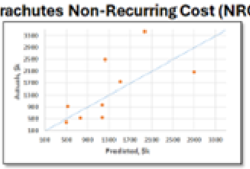


- **Input Parameters:**
  - PD - Peak Deceleration (g)
  - HD – Heatshield Diameter (m)
  - HPU – Heatshield Production Units
- **Cost Estimating Relationship (CER):** $1437 \times (HPU) \times (PD)^{0.2625} \times (HD)^{0.6068}$
- **Adjusted R^2:** 0.70
- **Range of Error:** -32 to 77%

PARACHUTES

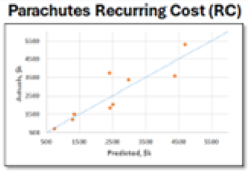
- Definition: Covers design, fabrication, and I&T for the Parachute System; Includes all flight parachutes, lines, and mortar; Does not include support structure

Parachutes Non-Recurring Cost (NRC)



- **Input Parameters:**
  - MPD: Main Parachute Diameter (m)
- **Cost Estimating Relationship (CER):** $8.5 \times (MPD)^{1.9641}$
- **Adjusted R^2:** 0.50
- **Range of Error:** -51 to 119%

Parachutes Recurring Cost (RC)



- **Input Parameters:**
  - PSM - Parachute System Mass (Chutes, Mortar) (kg)
  - MPS - Mean Pressure at the Surface (kPa)
  - PPU – Parachute Production Units
- **Cost Estimating Relationship (CER):** $564 \times (PPU) \times (PSM)^{0.4983} \times (MPS)^{-0.0880}$
- **Adjusted R^2:** 0.83
- **Range of Error:** -36 to 32%

PCEC Robotic Missions Recent Improvements for v2.4

Engineering Cost Office

IMPROVED CERs

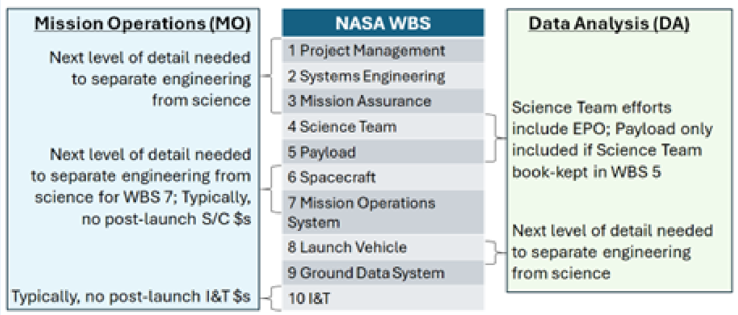
- Includes 10 new missions (w/ 12 flight systems)
- Enhanced diversity between NASA Programs and Mission Risk Classes
- Enabled CER improvements with refined input drivers, especially for System I&T that now includes Non-Recurring and Recurring CERs

MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
Added Missions for PCEC v2.4					
50 SMAP	1/31/15	JPL	JPL	Earth Sciences	Class C/D
51 JPSS-1	11/10/17	GSFC	BATC	Earth Sciences	Class B
52 Solar Probe	8/6/18	GSFC	APL	Heliophysics	Class B
53 Mars 2020	7/30/20	JPL	JPL	Planetary	Class B
54 TESS	3/20/18	GSFC	OSC	Astrophysics/Explorer	Class C/D
55 IXPE	12/9/21	MSFC	Ball	Astrophysics/Explorer	Class C/D
56 DART	11/23/21	APL	APL	Planetary	Class C/D
57 JWST	12/25/21	GSFC	NG	Astrophysics	Class A
58 Lucy	10/16/21	GSFC	LMSS	Planetary	Class B
59 GOES-T	3/1/22	GSFC	LMSS	Earth Sciences	Class B

OPERATIONS CERs

- Significant improvements for Operations
- Separate estimates are supported for MO and DA and for Planetary Cruise & Encounter and Near-Earth Primary Mission

- To provide enhanced insight into Phase E costs, separate CERs for Mission Operations and Data Analysis were developed but not yet adopted
  - CERs cover Planetary Cruise & Encounter phases and Near-Earth Primary Mission



EXCELLENT PERFORMANCE

- Excellent performance testing results w/ new Missions (not used for the CERs)

MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
Normalized for PCEC Future Versions					
60 Psyche	10/13/23	JPL	SSL	Planetary	Class B
61 Europa Clipper	10/10/24	JPL	JPL	Planetary	Class A
62 SPHEREx	2/27/25	JPL	Ball	Astrophysics	Class C

PCEC Robotic Missions Future Plans

Engineering Cost Office

- **New Missions**
  - 10 new mission candidates (+ 3 recent missions post-v2.4) with normalized data

	MISSION	Launch Date	Lead Org PM	Lead Org Flt Sys	NASA Program	Mission Risk Class
New Missions Candidates						
N-1	IMAP	Aug/Sep 2025	APL	APL	Heliophysics	Class C
N-2	PUNCH	2/27/25	SwRI	SwRI	Heliophysics	Class D
N-3	Carruthers	Aug/Sep 2025	UCB	BAE	Heliophysics	Class D
N-4	JPSS-2	11/10/22	GSFC	OATK	Earth Sciences	Class B
N-5	NEA Scout	11/16/22	MSFC	JPL	Planetary	Class D
N-6	PACE	2/8/24	GSFC	GSFC	Earth Sciences	Class C
N-7	PREFIRE	5/25/24	JPL	SDL	Earth Sciences	Class D
N-8	GOES-U	6/25/24	GSFC	LMSS	Earth Sciences	Class B
N-9	Lunar Trailblazer	2025	JPL	JPL	Planetary	Class D
N-10	VIPER	2025	ARC	JSC	Planetary	Class D

- **CER Improvements**
  - Continue to explore alternative approaches, new input candidates, and derivation of Figure of Merit input candidates

- **Leveraging database-enable capabilities**
  - Explore ways to maximize utilization of the large PCEC Robotic Mission Database

PCEC Robotic Missions Lessons Learned

Engineering Cost Office

- **More data doesn't always help**
  - CER performance initially was not improved after new missions were added, although the new missions helped reduce the number of outlier points
  - New input candidates and other modifications were needed to improve performance
- **Significant expert judgement is needed to choose the best CERs**
  - PCA & Regression can identify good statistical correlations, but the inputs are sometimes counter-intuitive
  - Good inputs should be "causal" not "associative"
  - Understanding why outlier data points are outliers is the key to finding the best CERs
- **Understanding the data is essential to cost normalization & CER development efforts**
  - Normalization efforts need to account for "External" impacts outside project's direct control
  - CER development needs to account for unique project experiences & cost book-keeping oddities

CREW AND SPACE TRANSPORTATION SYSTEMS MODEL

PCEC CASTS Overview

Engineering Cost Office

- **Based on data from 30 historical launch vehicle stages, crewed vehicles, and related space transportation systems/subsystems**
  - Plus 16 Liquid Rocket Engines (LRE) and 50+ Solid Boosters/Motors (SRM)
    - ***Including data from MDA as part of data exchange agreement (June 2021)***
- **One set of CERs for estimating subsystem-level costs of Design and Development (D&D) and Flight Unit (46 CERs)**
  - Primarily single-variable power CERs; some multi-variable power CERs
  - Includes Prime contract cost (excludes Civil Service, non-prime Support); **CY 2015 $M**
- **Plus set of CERs for estimating support costs (e.g., PM, ground support equipment, tooling) at the spacecraft level (9 CERs)**
- **Fixed/Variable equation estimates**
  - Production cost per year as f(rate)

<u>Letter of Intent</u>

Between

NASA Marshall Space Flight Center
Engineering Cost Office

And

Missile Defense Agency
Cost Estimating Directorate

SUBJECT: Cost Estimating and Analysis Knowledge and Data Sharing

The purpose of this Letter of Intent (hereafter referred to as the "LOI") is to facilitate cooperation between Engineering Cost Office located at the National Aeronautics and Space Administration (NASA) George C. Marshall Space Flight Center (MSFC) and the Missile Defense Agency (MDA) Cost Estimating Directorate. Both parties recognize that mutual benefit will result from such cooperation. <u>This LOI is not to be construed as a legally binding agreement nor as a commitment of resources by either party.</u>

Under this LOI both
cost analysis knowle
standards. This coop

The parties declare th

- Share non-cla
- Assist the oth
- Exchange kno
  and models
- Cooperate as

It is further understoo
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shared data. Therefor

- Acknowledge
  regulations (i.
  Export Admin
  implementing
  (ITAR)(22 CF
  (EAR)(15 CF

- Acknowledge that an unlawful export occurs if there is a release of export-controlled information in the United States with knowledge or intent that the information will be shipped or transmitted out of the United States. Furthermore, a release to a foreign national or foreign representative within the U.S. is also an export.
- Acknowledge our responsibility to protect export-controlled information (ECI) and actively restrict the access of the public at large to ECI. Under the AECA, civil and criminal penalties apply to anyone who exports ECI without proper permission. "Export" is defined to include the transfer of such data to any Foreign National, Foreign Representative, or to a U.S. citizen overseas.
- Acknowledge our responsibility to comply with limited rights notices and other restrictive markings applicable to data being exchanged, or considered for exchange.
- Understand that civil servants may face criminal prosecution for release of proprietary contractor data in violation of the Trade Secrets Act (18 U.S.C § 1905). Proprietary data, i.e., trade secrets, includes business and confidential financial data received from a contractor such as overhead rates, overtime, fully burdened labor rates, subcontracting plans, OCI plans, G&A rates and percentages, potential award fee, key personnel names and position titles, contract innovations, etc.
- Understand that contractor employees who are given access to shared data are required to comply with their respective OCI plans, nondisclosure agreements, and applicable clauses of their respective contracts related to access to and protection of data, as well as applicable markings on the documents or data.
- Acknowledge that access to data shared by the parties pursuant to this LOI is authorized for U.S. Government employees and approved support service contractor employees only, unless the parties agree otherwise or the data rights involved require greater restrictions.

This LOI may be modified at any time by mutual agreement of the parties, or terminated by either party upon reasonable notice to the other party.

FRANK PRINCE   Digitally signed by FRANK PRINCE Date: 2021.06.29 09:00:08 -05'00'

Frank A. Prince
Manager, Engineering Cost Office
NASA Marshall Space Flight Center

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Paul E. Tetrault
Director, Cost Estimating
Missile Defense Agency

PCEC CASTS
CER Development Process

- CASTS CER's reflect general PCEC development approach
- Ramifications to CASTS CER's? Significant data "clutter"
  - Minimal number data points with multiple potential independent variables ("over fitting")
  - Lack of/dissimilar definitions between sources
  - Poor predictive value (P-values >> .05)
  - Counter-intuitive results (cost > over time, cost < increased complexity)
  - Conflicting/countervailing influences between potential variables
    - Time vs. degree of new design vs. technology level vs. SOA vs. etc.
- Calculated "adjustment factor" for each data point
  - Not a "complexity" factor – says nothing about why value is what it is

- Identify Source Data
  - NAFCOM-heritage systems: Trace back to original sources; re-evaluate using common definitions/assumptions; fit to CASTS WBS
  - New systems: Understand/analyze source data; evaluate using common definitions/assumptions; fit to CASTS WBS
- Normalize Source Data
  - Convert to common year & units
  - Separate out elements of cost: Design & Development, First Unit, System Test Hardware, etc.
- Assign to Appropriate CASTS WBS Elements
- Develop CASTS CERs
  - Identify potential independent variables
  - Develop CER equations
  - Evaluate CER "goodness"
- Document Analysis

PCEC CASTS WBS & CERs

Engineering Cost Office

- CASTS Work Breakdown Structure – Cost Estimating Relationships
  - Developed WBS specifically for CASTS
    - NASA Standard WBS Launch Vehicle = 1 line
    - Breadth to handle all LV configurations; Depth to subsystem level

Program Segment		
1	Program Mgt & Support	
1	Systems Engr & Integ	
Vehicle Segment		
1	Integration, Ass'y, Checkout	
2	Crew Structures	
3		Wing
3		Tail
3		Fuselage/Body
3		Capsule Structures
2	Thrust Structure	
2	Adapters	
2	Secondary/Support Structs	
2	Tanks	
2	Intertank	

Vehicle Segment (cont'd)		
	Mechanisms	
2		Thrust Vector/Flight Control
2		Separation
2		Recovery
2		Other
2	Main Propulsion Systems	
	Thermal Protection	
2		Passive
3		Re-Entry Leading Edges
3		Re-Entry Heat Shield
	Propulsion	
4		Liquid Engines
4		Solid Motors
2		Reaction Ctl/Orb Maneuv Sys

Vehicle Segment (cont'd)		
	Avionics & Power	
4		Guidance, Nav, & Control
4		Telemetry & Tracking
4		Command, Ctl, Data Handling
2		Range Safety/Flt Termination
2	Electric Power	
2	Shroud/Fairing	
2	Crew Systems	
3		Environ Ctl & Life Supt
3		Displays/Controls
Software Segment		
2	Flight Software	
3	Ground Software	
Test Segment		
1	System Test Operations	
1	System Test Hardware	
Ground Segment		
1		Ground/Test Support Equip
2		Tooling

	CER Type
1	Cost-to-Cost
2	Des & Dev + Flt Unit (wt/other)
3	Adjustment Factor
4	Multi Var CER (DD & FU)

PCEC CASTS
Historical Data Set

Engineering Cost Office

Launch/Crew Vehicles

Apollo Command/Service Module (CSM)
Apollo Lunar Module (LM)
Atlas II
Atlas V 5m Fairing
Atlas V Centaur
Atlas V Common Core Booster (CCB)
Centaur D
Centaur G' (Shuttle Centaur)
Centaur G' CISS (Centaur Integ Supt Sys) - ASE
Inertial Upper Stage
Int'l Space Station Oxygen Generation Sys (OGS)
Int'l Space Station Water Recovery Sys (WRS)
Orbit Maneuvering Vehicle
Orion Crew Module
Orion Integrated Vehicle
Orion Launch Abort System
Orion Service Module
Saturn V 1st Stage (SIC)
Saturn V 2nd Stage (SII)
Saturn V 3rd Stage (SIVB)
Shuttle External Tank (ET)
Shuttle Orbiter
Shuttle Solid Rocket Booster (SRB)
Shuttle Solid Rocket Motor (SRM)
Skylab Airlock
Skylab Orbital Work Station (OWS)
Space Launch System (SLS)
Spacelab
Titan Centaur
Titan IV 5m Fairing

Added v.2.4

Software

SSME Adv Health Mgt Sys
Orbiter Cockpit Avionics Upgrade
Orbiter Primary Avionics Software Sys
Orbiter Backup Flight Software
BRAHMS
DART
X33
Centaur G' (Shuttle Centaur)
Inertial Upper Stage
Orbit Maneuvering Vehicle
Atlas II
Atlas V

Liquid Engines

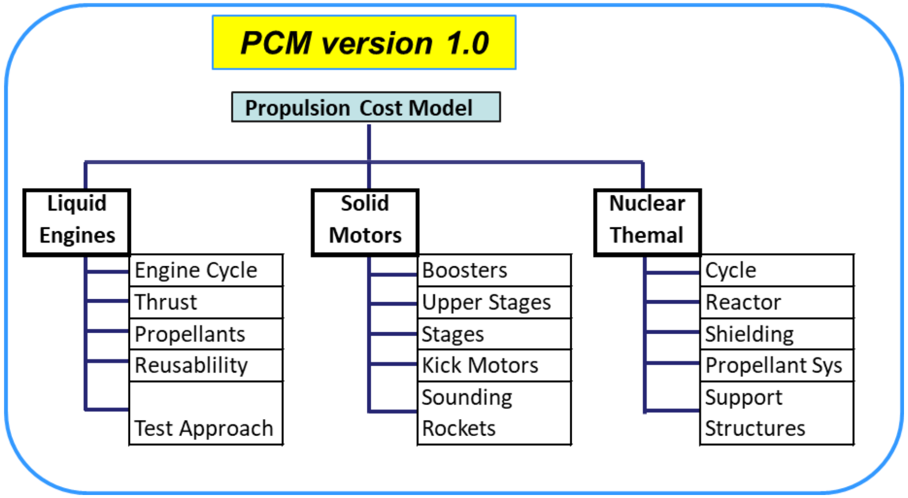
F1
J2
J2X
RS27
RD180
RS68
SSME
OMS
LM Ascent
LM Descent
MA5
Viking VI
LR87
LR91
RL10A3
RL10C1

	Mass (Lbs)	First Flight Year - DDTE	First Flight Year - Flt Unit
BOOSTERS			
Titan IV SRMU	776,038		
Titan IV CSD SRM	704,000		
Shuttle RSRM	1,290,513		
Atlas IIAS Castor 4A	25,737		
Atlas V AGC AJ-60A SRM	102,949		
Ariane V EAP-P230	610,785		
Shuttle ASRM	1,345,807		
Ares 1 FSB	1,616,125		
STAGES			
PK Stg 1 (MTI SR-118)	107,778	1986	1986
PK Stg 2 (AGC SR-119)	60,874	1986	1986
PK Stg 3 (HER SR-120)	16,962	1986	1986
MMI, II, III Stg 1: M55E1	50,400	1961	1961
MMI Stg 2: M56A1	15,502	1961	1961
MMI, II Stg 3: M57A1	4,100	1961	1961
MMII, III Stg 2: SR19AJ1	15,502	1964	1964
MMII, III Stg 3: SR73AJ1	7,900	1969	1969
Castor 120 - LLV1 1st Stg	117,014	1969	1969
THAAD Booster	1,894	1995	1995
Trident C4 Stage 1	42,508	1977	1977
Trident C4 Stage 2	35,972	1977	1977
Trident C4 Stage 3	711	1977	1977
Orion 50XSL	36,153	1994	1994
Orion 50XL	9,494	1994	1994
Orion 38	1,924	1994	1994
Castor IVB	25,445	1989	1989
Castor IB	7,875	1961	1961
Trident D5	130,000	1990	1990
Trident C4 TOTAL	79,191	1977	1977
Pegasus XL	47,571	1990	1990

	Mass (Lbs)	First Flight Year - DDTE	First Flight Year - Flt Unit
UPPER STAGES			
PAM-D Star 48 short	4,705		
PAM-DII Star 63	7,716		
PAM-D Star 48 long	4,721		
Talos	2,869		
ASAS	2,512		
Trident C4 Stage 3	711		
IUS Multi Stage	32,418		
IUS-1 Orbus 21	23,953		
IUS-2 Orbus 6	8,465		
KICK MOTORS			
Star 17A	277		
Star 24	481		
Star 27	796		
Star 37FM	2,531		
Star 37XFP	2,105		
Star 48B short	4,708		
Star 48B long	4,721		
Star 37XFPV	2,105		
Star 48V	4,772		
Star 48 BV	4,800		
SOUNDING ROCKETS			
Black Brant V	2,639		
Black Brant X	5,700		
Black Brant XI	11,600		
Black Brant XII	13,888		
Terrier-Black Brant VC	4,900		
Black Brant V A	2,639		
Terrier Malamute	3,456		
Terrier Orion	2,800		
Orion	880		
Prospector/Joust (Castor IVA)	27,000		
Aries-MM I	15,760		

PCEC CASTS Add-in Models

- **Propulsion Cost Model – v.1.0**
  - Three separate spreadsheet models – similar to CASTS: DDTE + FU M2015$'s
    - Liquid Rocket Engines (LRE) + Solid Rocket Motors (SRM) + Nuclear Thermal Propulsion (NTP)
  - Restricted and Unrestricted versions – includes User Guides and VBBs
  - To be released this month (July 2025) – same access as PCEC



- **Operations Cost Model**
  - Spreadsheet-based model completed 2006
  - Estimates recurring Earth-To-Orbit launch vehicle cost not covered by hardware-based models (Launch & Flight/Mission Ops+); fixed/variable cost estimates

PCEC CASTS Data Documentation

- User Guides + Virtual Black Books + CER Documentation
  - Restricted and Unrestricted versions
- Integrated collection of accessible source information
- Available online through REDSTAR

PCEC CASTS DOCUMENTATION in REDSTAR

- **CASTS Virtual Black Books**
  - Apollo Command Module
  - Saturn IC (SIC)
  - Saturn II (SII)
  - Saturn IVB (SIVB)
  - Shuttle Orbiter
  - Shuttle External Tank
  - Atlas I, II, IIA, IIAS, V
  - …
- **PCEC Library v2.4**
  - **User's Guides**
    - Unrestricted
    - Restricted
  - **CER Documentation**
    - Adapters
    - Avionics
    - …

For Each System Element

1. Cost Analysis Workbook: Excel workbook with calculations and derivations to get source data to CER input data
2. Technical Resume: PDF file with summary technical descriptions & schedules
3. REDSTAR Bibliography: List of source documents and "cream of the crop" references in REDSTAR

PCEC CASTS User's Guide (1 of 2)

- Two versions of User's Guide:
  - Unrestricted: Includes model overview, definitions, description of modeling processes, and for each WBS element: CER equations, descriptions, data set of Adjustment Factors
  - Restricted: Includes all information in Unrestricted version plus scatter plots and CER source dataset

CASTS User's Guide - Unrestricted
PCEC version 2.4
May 2025

5.12 Main Propulsion Systems (MPS)

CER Equations

$$[MPS\ DD\ Cost] = 0.6779 * [WeightPerUnit]^{0.6339}$$

$$[MPS\ FU\ Cost] = 0.0099 * [WeightPerUnit]^{0.8555}$$

Inputs

Dry Weight (Weight) per unit (lbs.)

Description

This CER estimates the DD and FU costs of the MPS of a launch vehicle element and includes (as applicable) feed lines, fill and drain, purge and vent, and pressurization subsystems. The Apollo CSM and LM data points were excluded from the CER calculation data set base due to the significant difference in requirements, design, complexity, and overall nature of those subsystems relative to the rest of the data set. As such the Apollo adjustment factors are essentially factors to adjust for analogous MPS systems comparable to the Apollo systems.

Main Propulsion Systems - Adjustment Factors			
Mission	WBS Item	DD	FU
Apollo CSM	Main Propulsion	11.75208	11.59137
Apollo LM	Ascent	6.90673	10.60289
Apollo LM	Descent	5.87273	10.55784
Atlas V CCB	RP1	1.59983	0.40220
Atlas V Centaur	LH2	2.86189	3.14819
Centaur D	LH2	2.22051	1.97783
Centaur G'	MPS-CISS LH2	0.40378	0.51210
Centaur G'	MPS-G' LH2	0.33024	1.90702
External Tank	LH2	0.74657	0.42641
Orbiter	LH2	1.18034	4.09338
Orion	SM Hypergolic	3.30695	3.51465
S-IC	RP1	0.75476	0.94008
S-II	LH2	1.26489	1.57654
S-IVB	LH2	2.16697	0.52857
Titan Centaur	LH2	0.40462	0.29903

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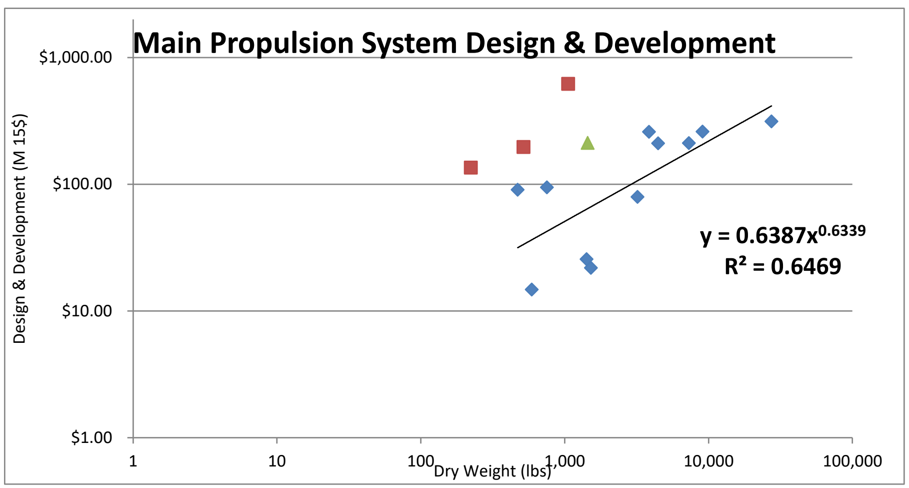
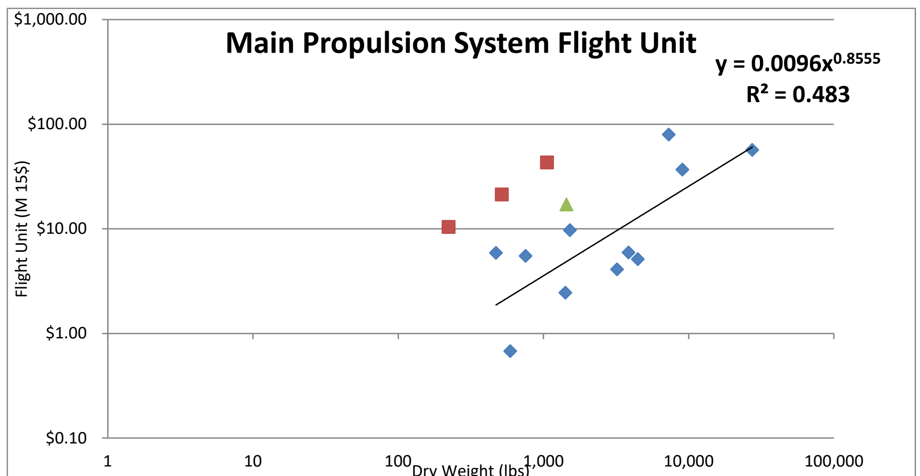
User's Guide (2 of 2)

- Restricted versions include CER source data set and scatter plots

Main Propulsion Sys		Source Data					CER Data	
		Wt	DD	TFU	YR $	Escal	DD	TFU
AV CCB	RP1	4,467	$ 181.38	$ 4.43	2007	1.1599	$ 210.39	$ 5.14
ET	LH2	3,213	$ 21.50	$ 1.11	1979	3.7057	$ 79.67	$ 4.11
SIC	RP1	27,418	$ 42.08	$ 7.62	1970	7.4507	$ 313.49	$ 56.77
C D	LH2	754	$ 15.07	$ 0.88	1973	6.2736	$ 94.54	$ 5.52
Orbiter	LH2	7,298	$ 98.35	$ 36.98	1988	2.1542	$ 211.87	$ 79.67
AV Cent	LH2	472	$ 78.04	$ 5.07	2007	1.1599	$ 90.52	$ 5.88
SIVB	lh2	3,854	$ 32.58	$ 0.75	1969	7.9648	$ 259.50	$ 5.96
Titan Cent	LH2	591	$ 6.85	$ 0.31	1988	2.1542	$ 14.76	$ 0.68
CG'	MPS-G' LH2	1,522	$ 11.15	$ 4.93	1990	1.9671	$ 21.94	$ 9.71
CG'	MPS-[illegible] LH2	1,420	$ 13.05	$ 1.2[illegible]	1990	[illegible]671	$ [illegible]67	$ 2.46
SII	lh2	[illegible]	[illegible]	[illegible]	1967	[illegible]	[illegible]	$ 36.97
Orion	SM Hy[illegible]	[illegible]	[illegible]	[illegible]	2012	[illegible]	[illegible]	$ 17.10
Apollo CSM	Main Propulsion	1,058	$ 66.64	4.65	1966	9.3082	$ 620.30	$ 43.24
Apollo LM	Ascent	223	$ 48.13	$ 3.70	1982	2.8204	$ 135.74	$ 10.43
Apollo LM	Descent	518	$ 69.85	$ 7.58	1982	2.8204	$ 197.01	$ 21.36

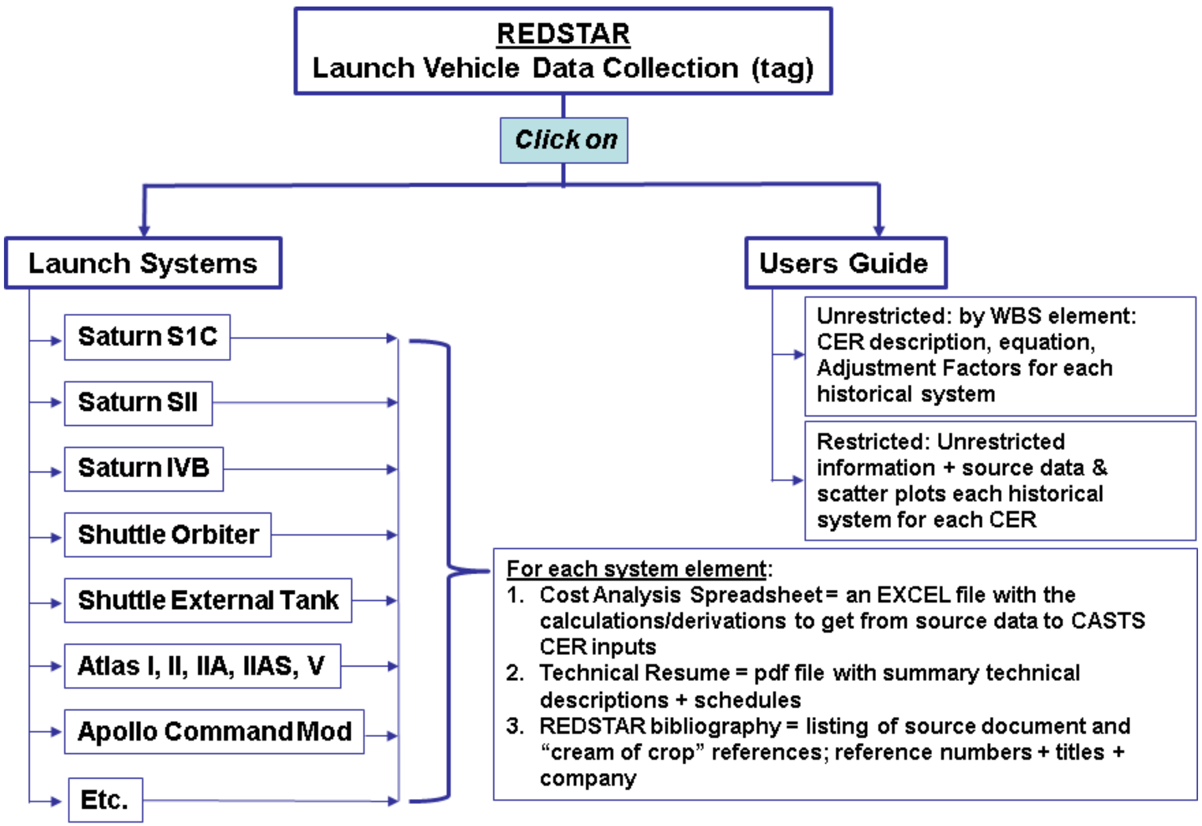




PCEC CASTS
Virtual Black Books

Engineering Cost Office

- CADRe-like – not a CADRe, but same type of information
- Integrated collection of accessible source information
- Restricted available online through REDSTAR
- Unrestricted available upon request – (technical data only)



PCEC CASTS
VBB – F-1 Engine Example

Engineering Cost Office

- Virtual Black Book (CASTS and PCM) Example
  - F-1 Liquid Rocket Engine

Technical Data Sheet

CASTS TECHNICAL DATA SHEET

Liquid Rocket Engines

F-1

Summary

The F-1 engine is the most powerful single-nozzle rocket engine ever built. The F-1's million-and-a-half pounds of thrust per engine at liftoff (quintupled in a cluster of 5) lifted men to the moon as the booster engine for the Saturn V first stage (S1C). The F-1 is a single start, fixed thrust, engine. It is turbopump fed and is a gas-generator cycle engine. It is gimbaled and uses RP-1 (kerosene) as fuel and liquid oxygen as oxidizer. RP-1 is also used as the turbopump lubricant and control system fluid.

NASA made the initial contract award for development of the F-1 engine to Rocketdyne in 1959. The contract was for an engine with 1.5 million pounds of thrust, which was an approximately 7.5 times greater thrust level than its predecessor operational engine, the H-1 and previous Air Force development efforts on large liquid engines. While the F-1 required no new state-of-the-art technology developments, the enormous increase in size and thrust relative to previously developed engines introduced many engineering and facility/equipment challenges. Among the primary difficulties encountered during F-1 development were combustion instability, turbopump development, and regenerative cooling metallurgical and manufacturing approaches.

F-1 full-scale development involved a substantial amount of development and qualification testing, including component, subsystem, and integrated engine tests. The engines for the Apollo Saturn V launch system required qualification at the engine component and engine system level with a formal demonstration of the 0.99 reliability goal at 50% confidence. As a result, there were over 50 equivalent new test engines produced and over 2,000 tests performed, including over 1,000 full duration tests.

NASA Management Center: MSFC
Prime Contractor: Rocketdyne (Rockwell)
ATP: January 1959
Development (Qualification) Complete: December 1966
Initial Delivery: November 1963 (first ground test engine)
January 1965 (first flight engine)
Last Delivery: November 1969
Equivalent Development Engines: 53 to 56 (depending on source)
Production Engines: 98 total

Parameters

Engine Cycle: Gas-Generator
Propellants: RP-1 (Kerosene) / Liquid Oxygen
Thrust: 1.522 klbf sea level;

...ICAL DATA SHEET

...level)
...15 = 159 sec)
...tion)

...livered from 1963-64 through 1969-70. The engines ...cts, NAS8-5604 and NAS8-18734. 65 engines were ...% reliability. Figure F1-1 provides a summary of F-1

F1 Engines Delivered

Number Engines	Year	R&D	roduction
76	TOTAL	85	98
22	61	1	
98	62	8	
	63	11	
75	64	10	2
14	65	15	15
1	66	16	23
4	67	9	23
2	68	7	19
2	69	5	12
98	70	3	4

...pection

...F-1 engine production summary

Description

The F-1 is a gas-generator cycle, turbopump driven, LOX/RP expendable engine which produced approximately 1.5 mlbf at liftoff of the Saturn V launch system. It is a single-start, fixed thrust, gimballed engine. The nozzle is regeneratively cooled through 178 tubes down the length of the thrust chamber.

A gas-generator was used to drive a turbine which in turn drove separate fuel and oxygen pumps, each feeding the thrust chamber assembly. The turbine was driven at 5,500 RPM by the gas-

...CAL DATA SHEET

...US gallons of RP-1 per minute while the oxidizer ...n per minute. Environmentally, the turbopump was ...m input gas at 1,500 °F (820 °C) to liquid oxygen ...d to lubricate and cool the turbine bearings.

...ension, roughly half the length of the engine. This ...e engine from 10:1 to 16:1. The exhaust from the ...y a large, tapered manifold; this relatively cool gas ...nsion from the hot (5,800 °F (3,200 °C)) exhaust ...gine.

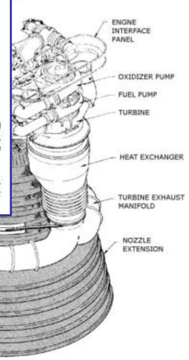


Figure F1-2. F-1 engine view

Cost & Sources

0121-01403

F-1 Engine Production Cost History

Number Engines:		98 TOTAL	76 NAS8-5604	22 NAS8-18734B	0 NAS8-18734F
Deliverable Hardware					
1st 14 engines	$	[redacted]			
1st 76 Engines	$				
Engine Systems	$				
Engr Support	$				
Maint engr	$				
Misc	$				
Thrust Chambers	$				
Gas Generators	$				
Turbopumps	$				
Feed Systems	$				
Hydr Control Sys	$				
Pressurization	$				
Elec & Instr	$				
Thermal Insul	$				
Tooling	$				
STE	$				
Engines	$				
Parts	$				
Mockups	$				
GSE	$				
Long Lead Hdw	$				
Total Hardware	**$**				
Site Assoc. Support					
Field Engineering	$				
Supt Parts Sers	$				
Training	$				
Manuals	$				
Other	$				
Total Support	**$**				
Total Prod Cost	**$**				
Fee	$				
Total Production	**$**				

		NAS8-18734A Ops & Flt Supt 1967-1970
Flt Supt & Anomaly Res	$	[redacted]
Ops Supt	$	
Improvements	$	
Simplicity	$	
Studies	$	
Total Ops & Flt Supt	**$**	
F-1 Prod Subtotal	$	
Propellants	$	
TOTAL F1 Production	**$**	
$/Engine TY$	$	
Prod Sched midpoint		
Escalation to 92$		
F1 AUC 92$	**$**	

REDSTAR Analysis Center

Engineering Cost Office

REDSTAR Analysis Center

REDSTAR is both a physical analysis center and an online searchable database maintained in Microsoft SharePoint

REDSTAR contains over 43,000 documents of which over 17,000 are available electronically as pdf, Word, Excel, and PowerPoint files

Founded in 1971
Some of the notable greats:
Bill Rutledge
Gene Austin
Joe Hamaker
Steve Creech
Andy Prince

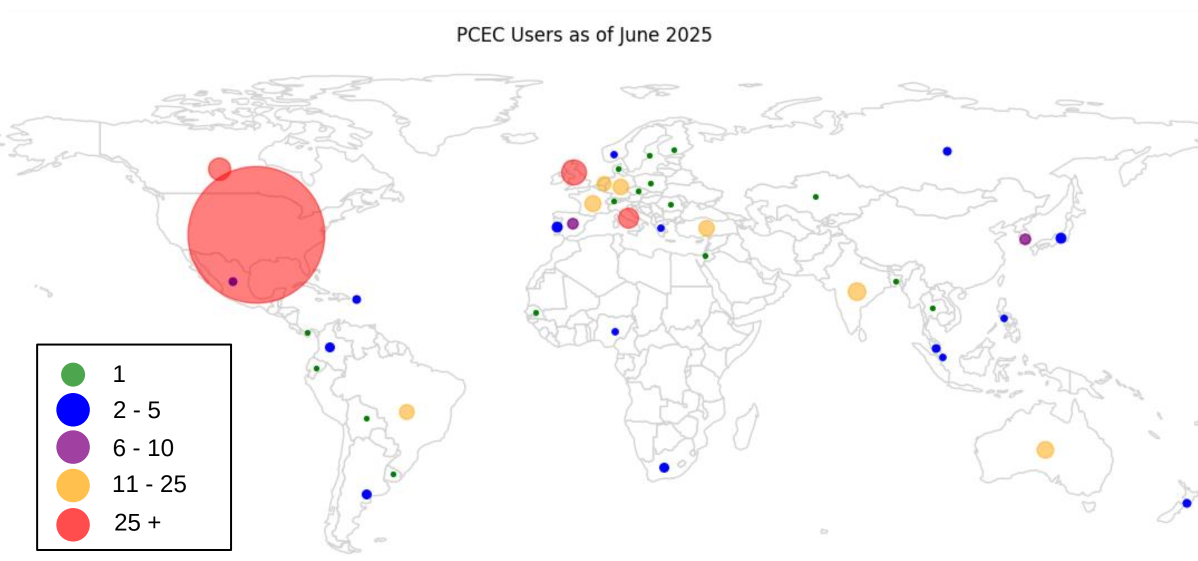
REDSTAR Analysis Center
MSFC Building 4494, Room 2

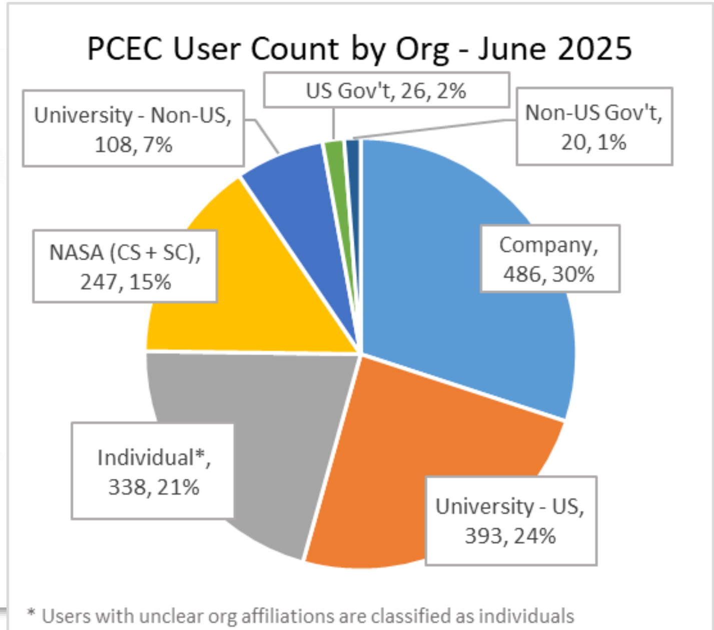
"Attempting to plan for the future without a sense of history is like trying to plant cut flowers."
Dr. D. Boorstin – Librarian Emeritus of Congress

Contact Melissa Roberts, REDSTAR Research Manager
melissa.e.roberts@nasa.gov
256-544-2320

PCEC Distribution

- PCEC v2.4 was released May 2025
  - E-mail announcement went out to latest user list
  - Available on both the ONCE Database (for both CS and SC ONCE users) and the NASA Software Catalog (for all others)
  - Software Catalog Users: Go to https://software.nasa.gov/app/
- As of June 2025, 1600+ ‘Downloaders’ spread across 44 Countries





PCEC
Status - Today

- PCEC v2.4 is the latest version available (released in May 2025), which includes enhancements for estimating more elements across the NASA Standard WBS
- The general public can obtain PCEC (with some export restrictions) via the NASA Software Repository
  - DoD, Prime Contractors, Universities, citizens of many foreign countries
- Where/How to get PCEC

PCEC Email Contact: MSFC-PCEC@mail.nasa.gov
Application Website: https://software.nasa.gov/ , search for PCEC

- Contact Information:

Nathan Snyder (Primary)
NASA MSFC
256-544-1842
nathan.j.snyder@nasa.gov

Stanley McCaulley
NASA MSFC
256-544-0618
stanley.c.mccaulley@nasa.gov

Mark Jacobs
Space Systems Analysts, LLC
813-839-5476
mkjacobs@att.net

Shawn Hayes
Space Systems Analysts, LLC
630-797-5018
shawn.hayes@ssanalysts.com

Richard Webb
KAR Enterprises, LLC
661-547-7632
richard.webb@karenterprises.net