Final Cassini Propulsion System In-Flight Characterization

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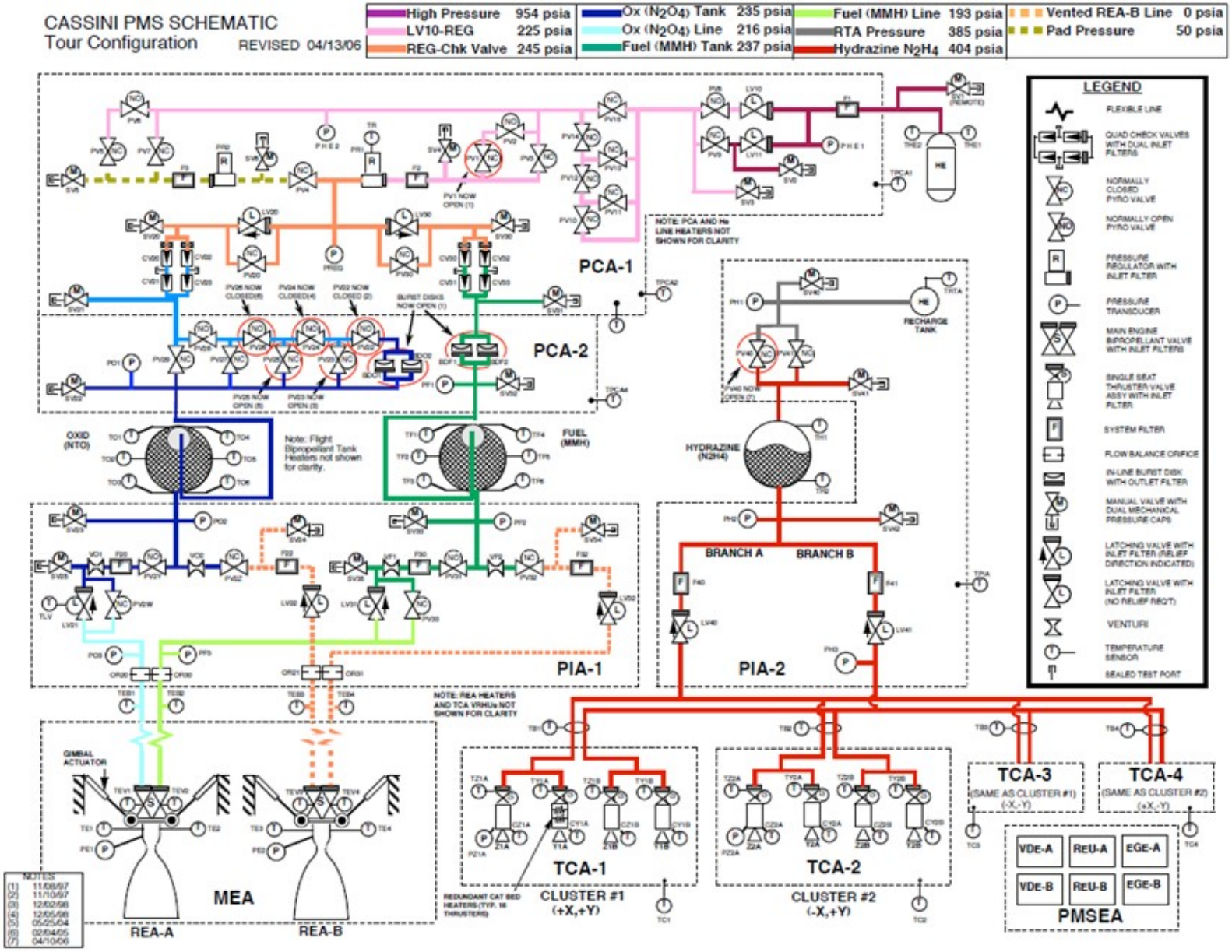
Topics Covered

- CPMS Schematic Refresher
- R-4D (REA-A Only) Operating Box History
- R-4D Performance History in ME TCMs/OTMs
  - ΔV Error vs. ΔV Magnitude
  - Burn Time Prediction Error vs. ΔV Magnitude
  - REA-A Pc Roughness (or lack thereof) over 183 ME burns
- RCS TCM/OTM Performance History
  - ΔV Error vs. ΔV Magnitude (A-Branch & B-branch Maneuvers)
  - Z1A-Z4A Pc Roughness History
  - B-Branch Line Pressure & N_2H_4 Outlet Tank Pressure Roughness History
- Pressure Transducer Drift History

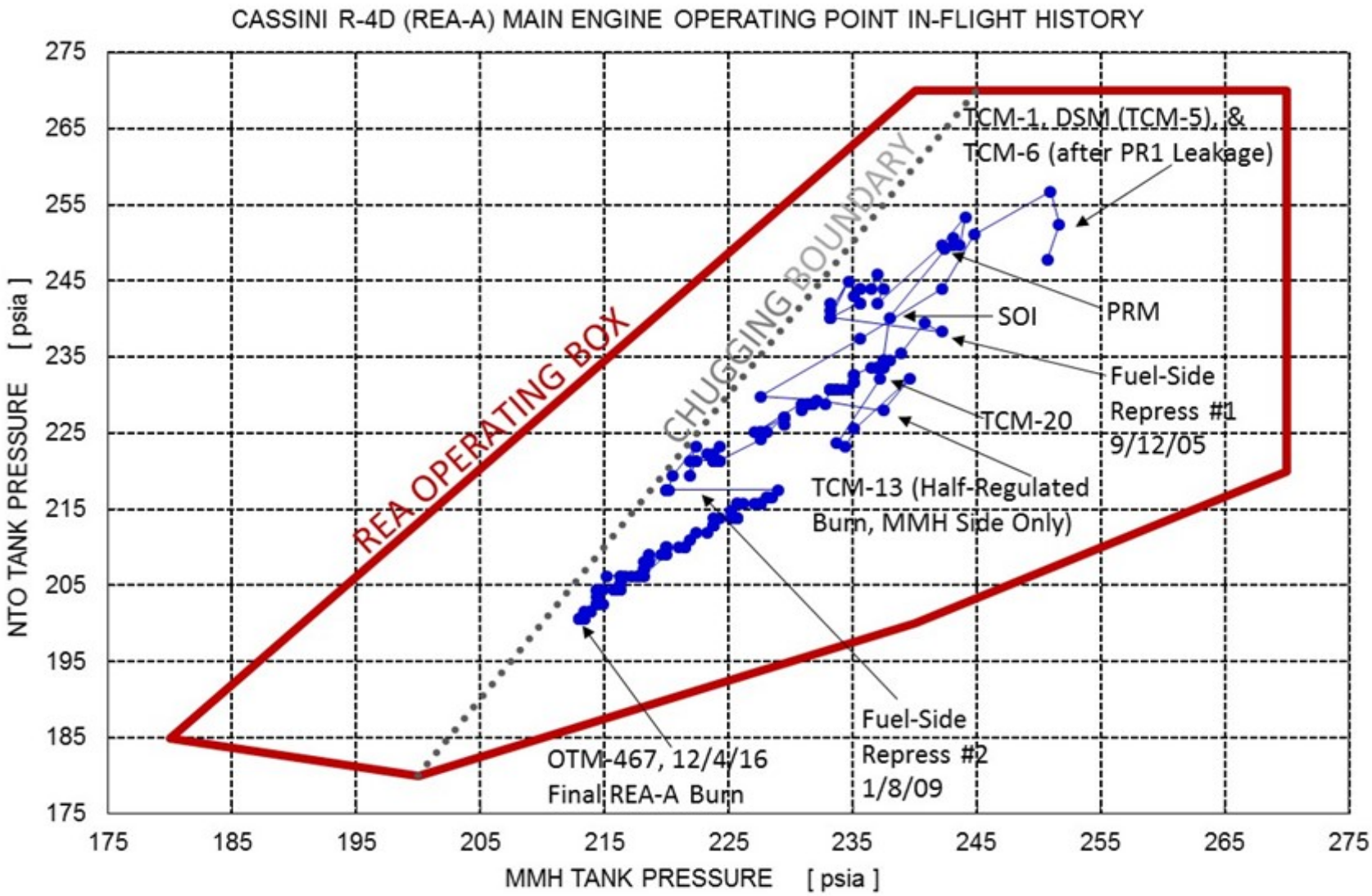
Topics Covered (continued)

- N_2H_4 Mass History
- NTO/MMH Mass History
  - Plot vs. Mission Time
  - Helium Budget Results
- CPMS Bipropellant Pressurization System Analyses
  - Primary Pressure Regulator (PR1) Leakage History
  - NTO Diffusion Modeling
  - MMH and NTO Low-Pressure Latch Valves (LV30 & LV20) Leakage History
  - LV10 “Leakage” History (really Helium Diffusion)
- Unusable N_2H_4 and MMH/NTO Assessment
- Favorite Cassini Image from 20 Years of Operations

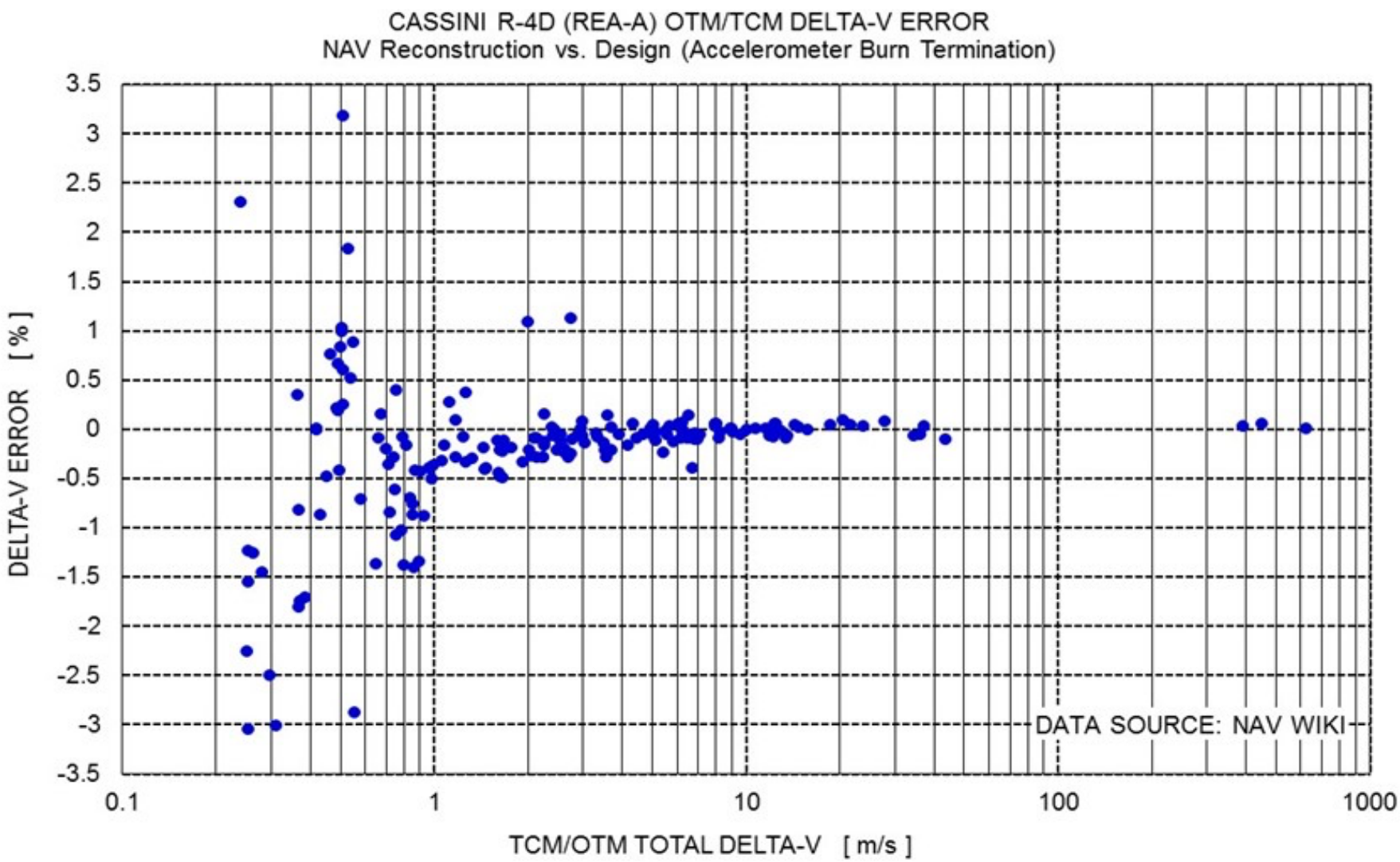
CPMS Schematic



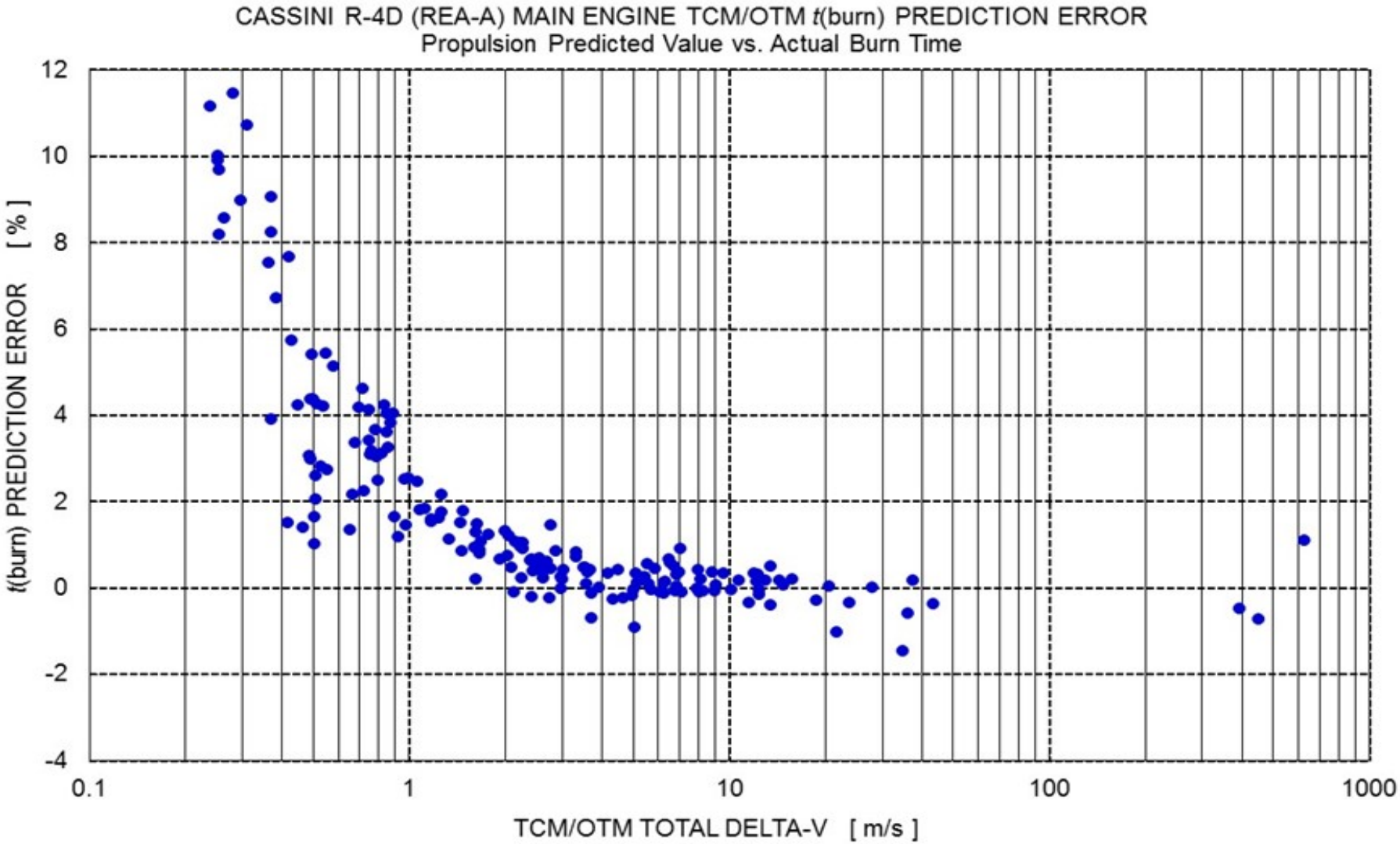
REA-A (R-4D) Operating Box History



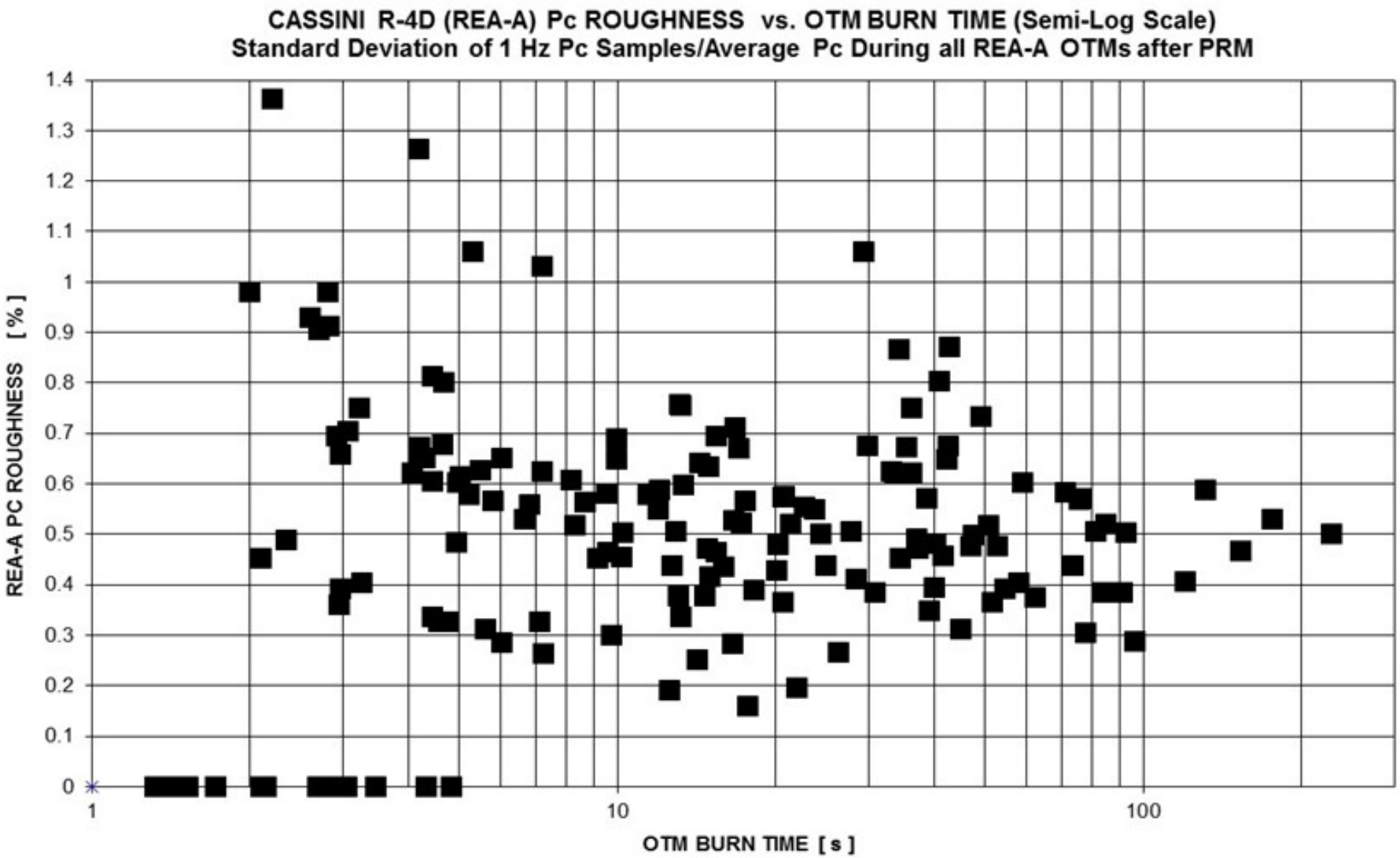
R-4D ΔV Error vs. ΔV Magnitude



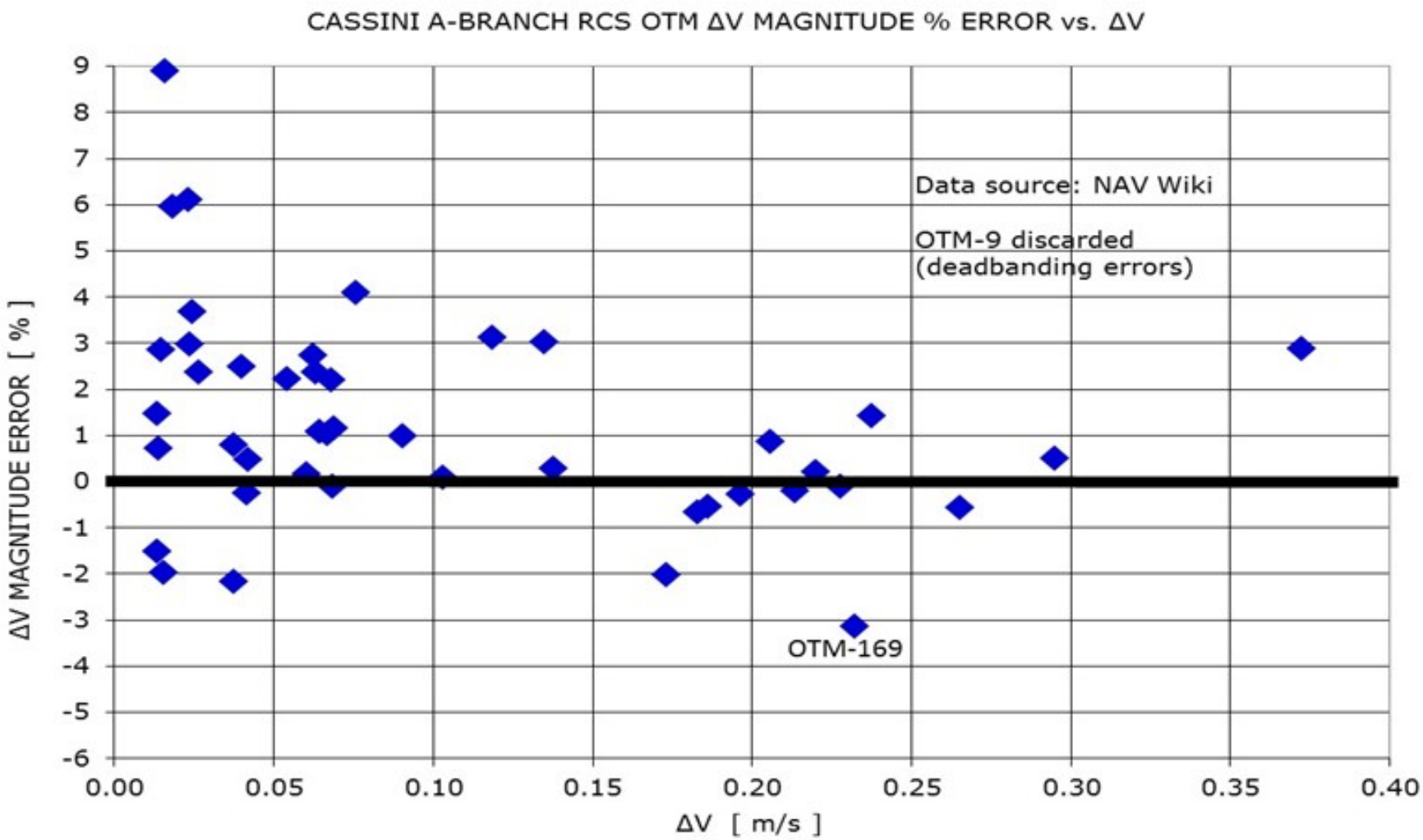
R-4D Burn Time Prediction Error vs. ΔV Magnitude



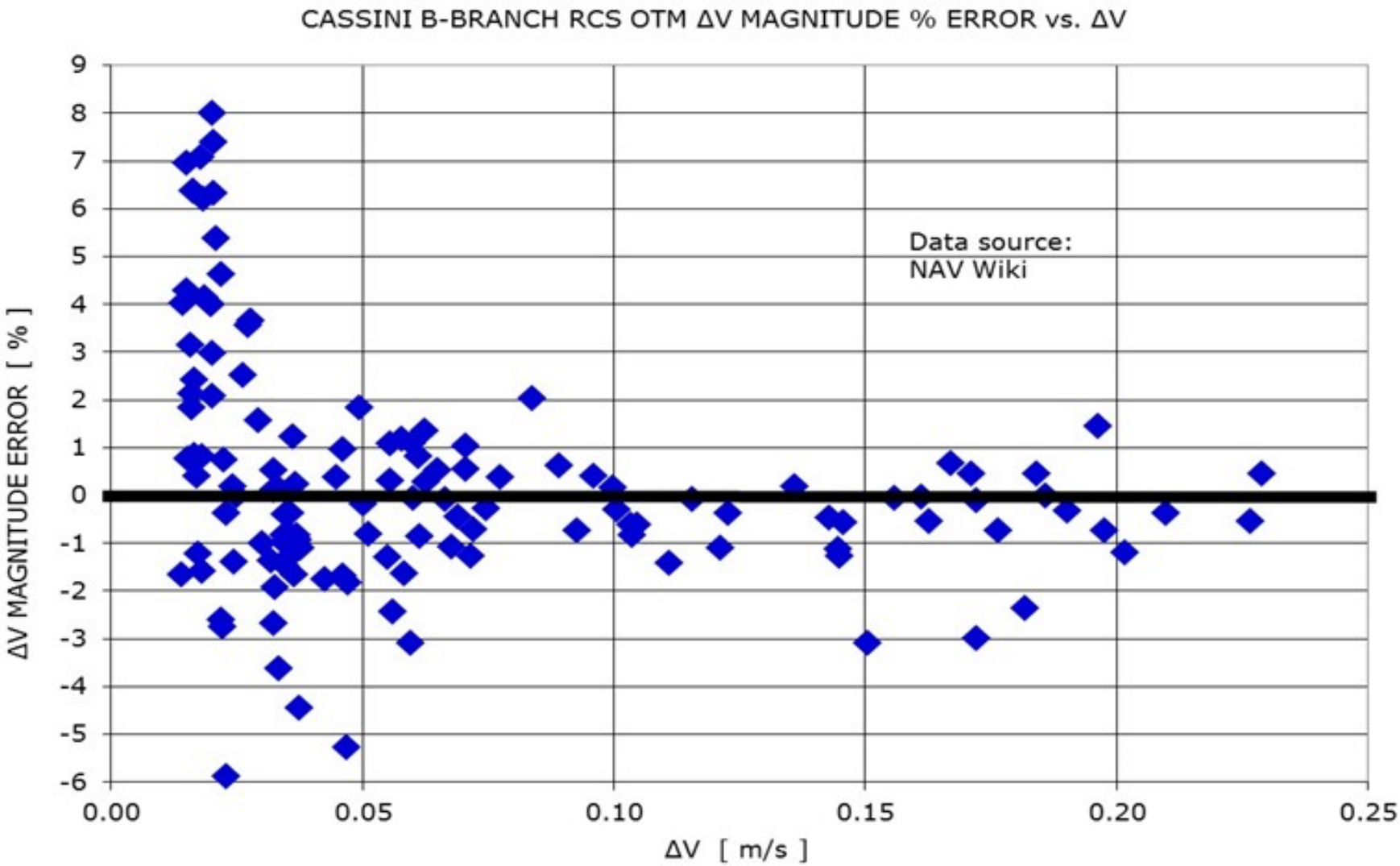
R-4D (REA-A) Pc Roughness vs. Burn Time



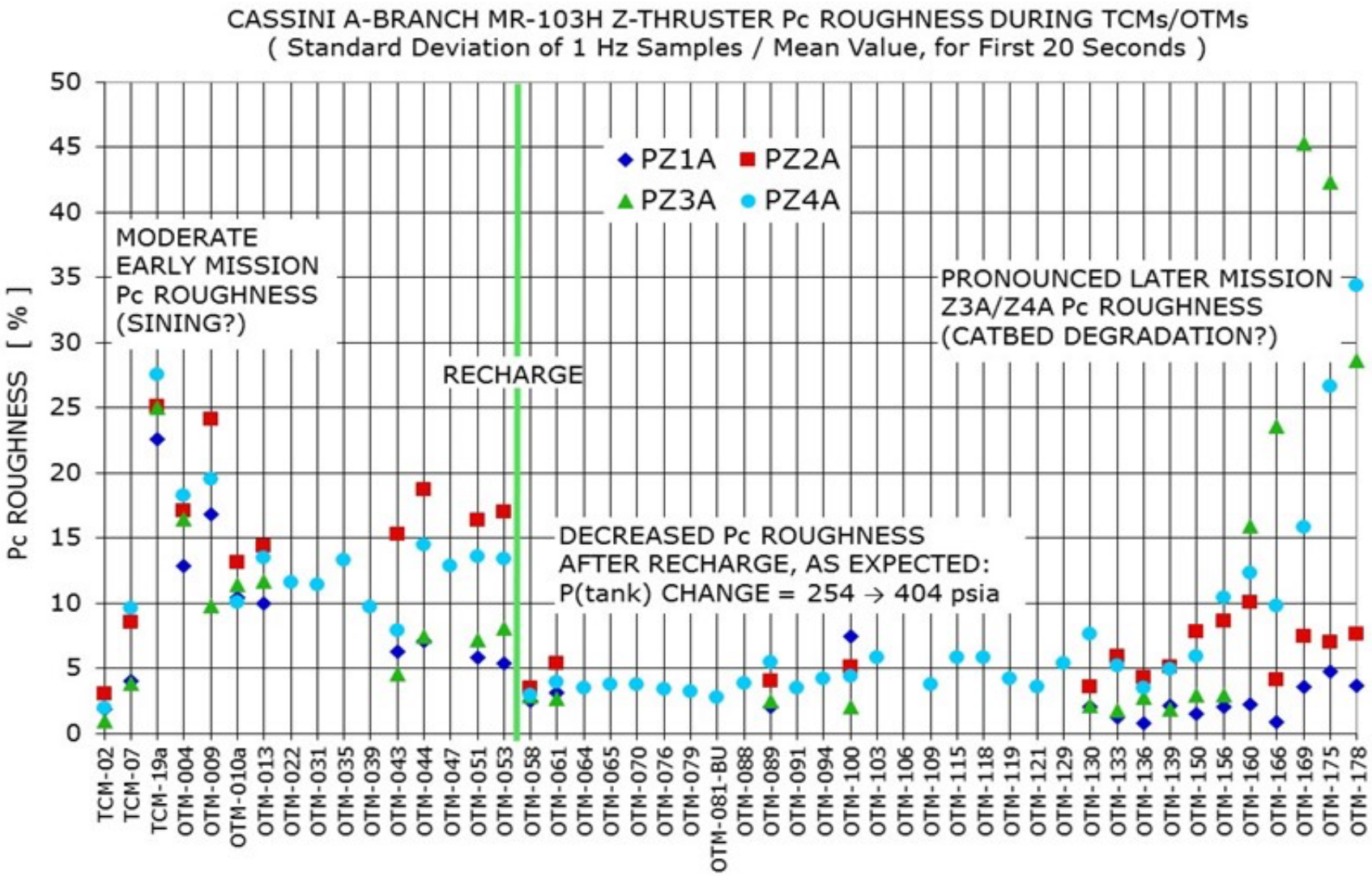
RCS A-Branch TCM/OTM ΔV Error vs. ΔV Magnitude



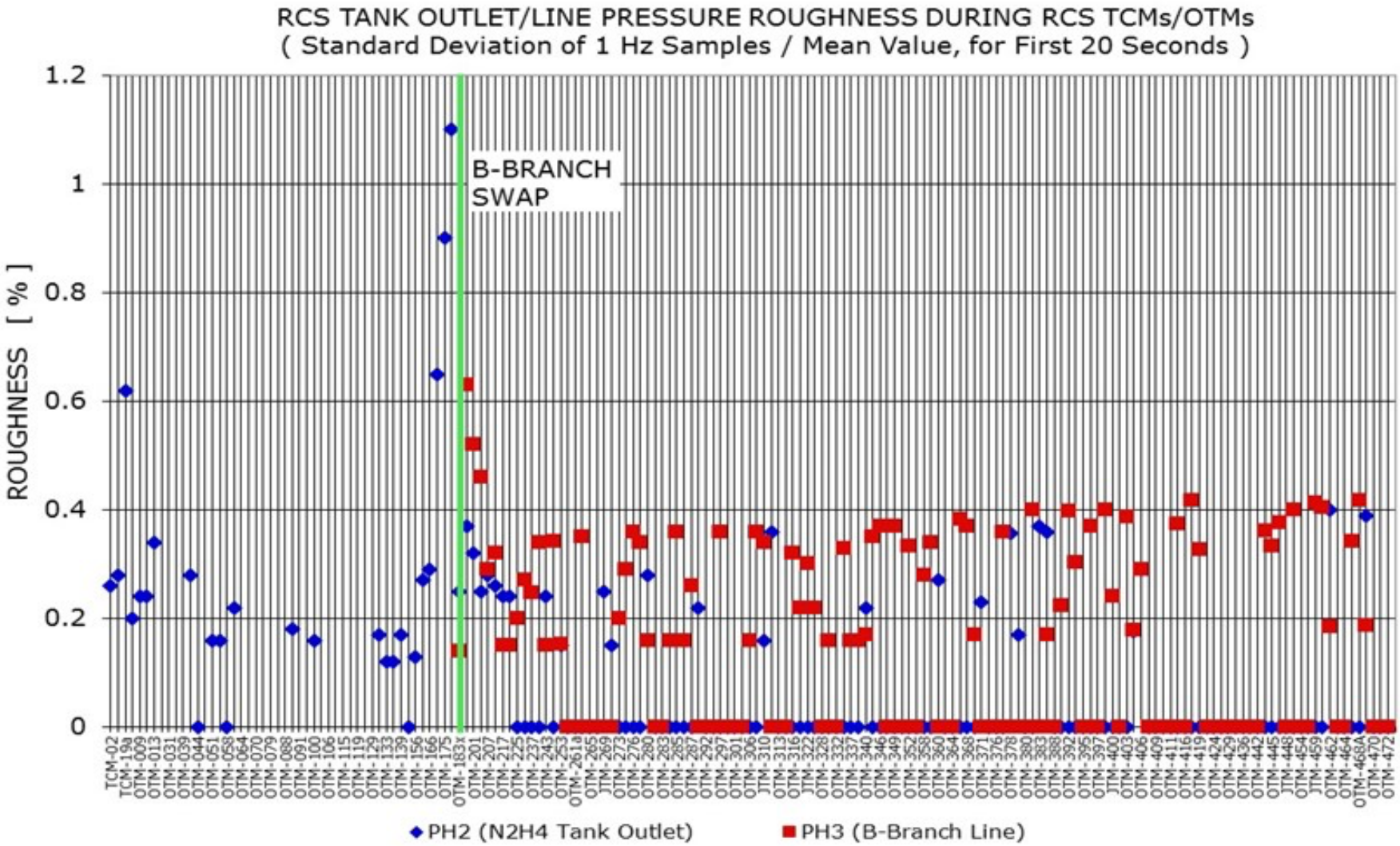
RCS B-Branch OTM ΔV Error vs. ΔV Magnitude



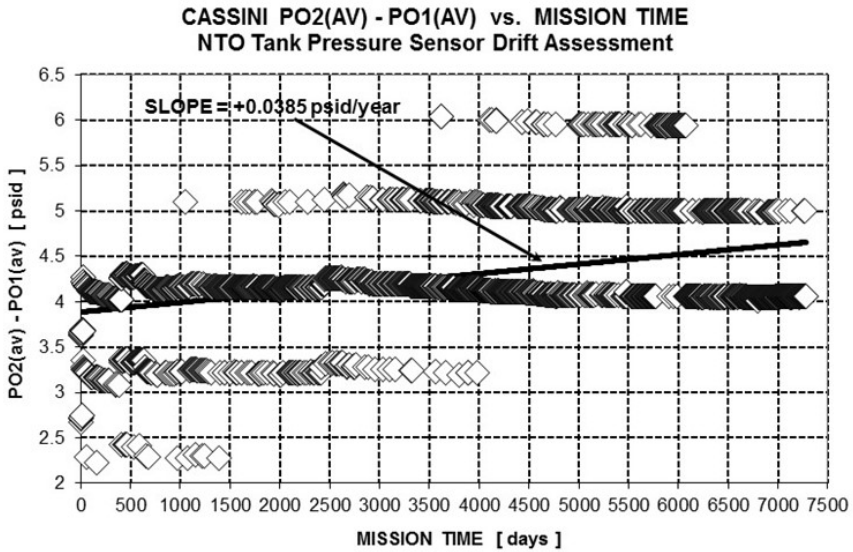
RCS Z1A-Z4A Pc Roughness History During TCMs/OTMs

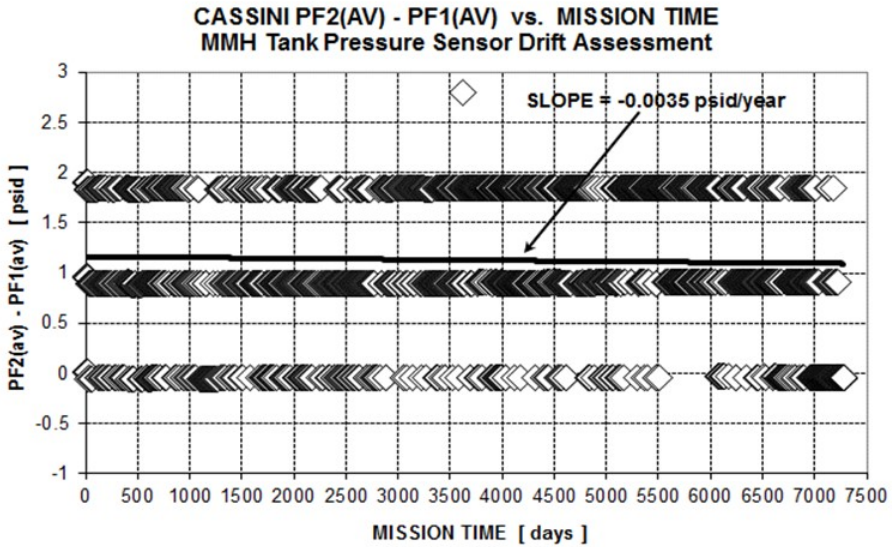


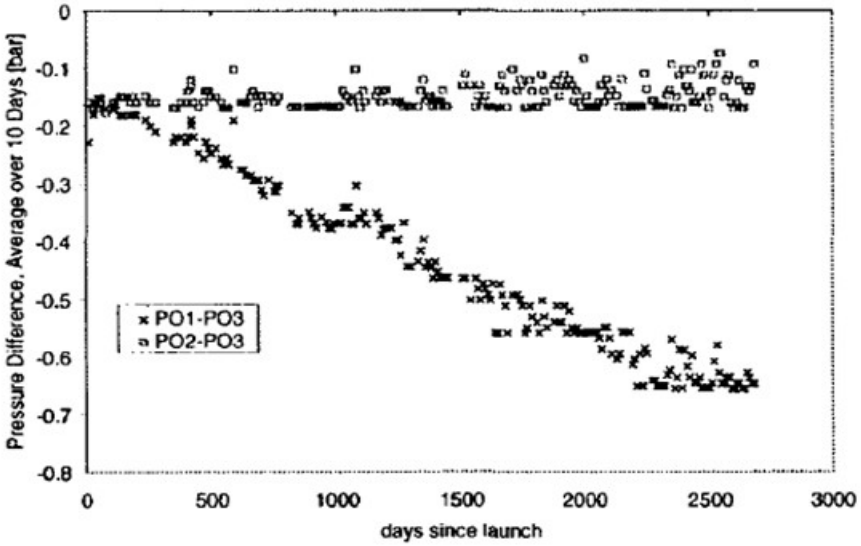
B-Branch Line and N_2H_4 Tank Outlet Pressure Roughness



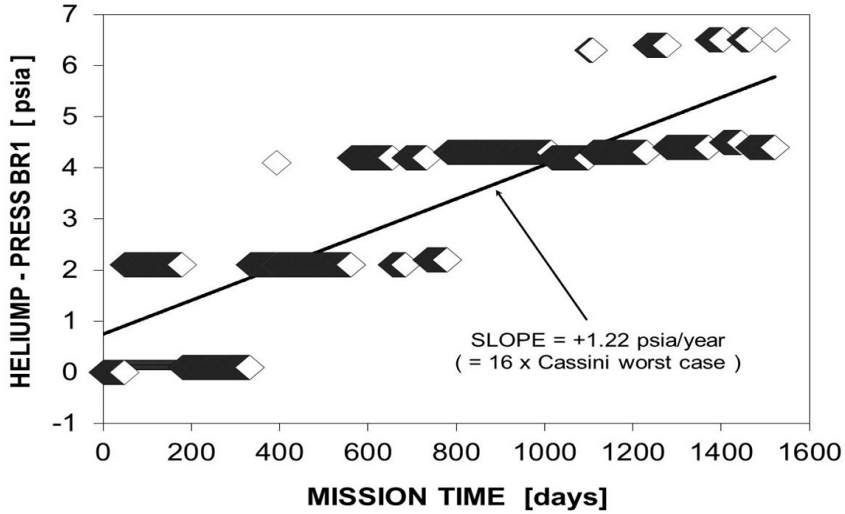
Cassini Tank Pressure Transducer Drift (or lack thereof)





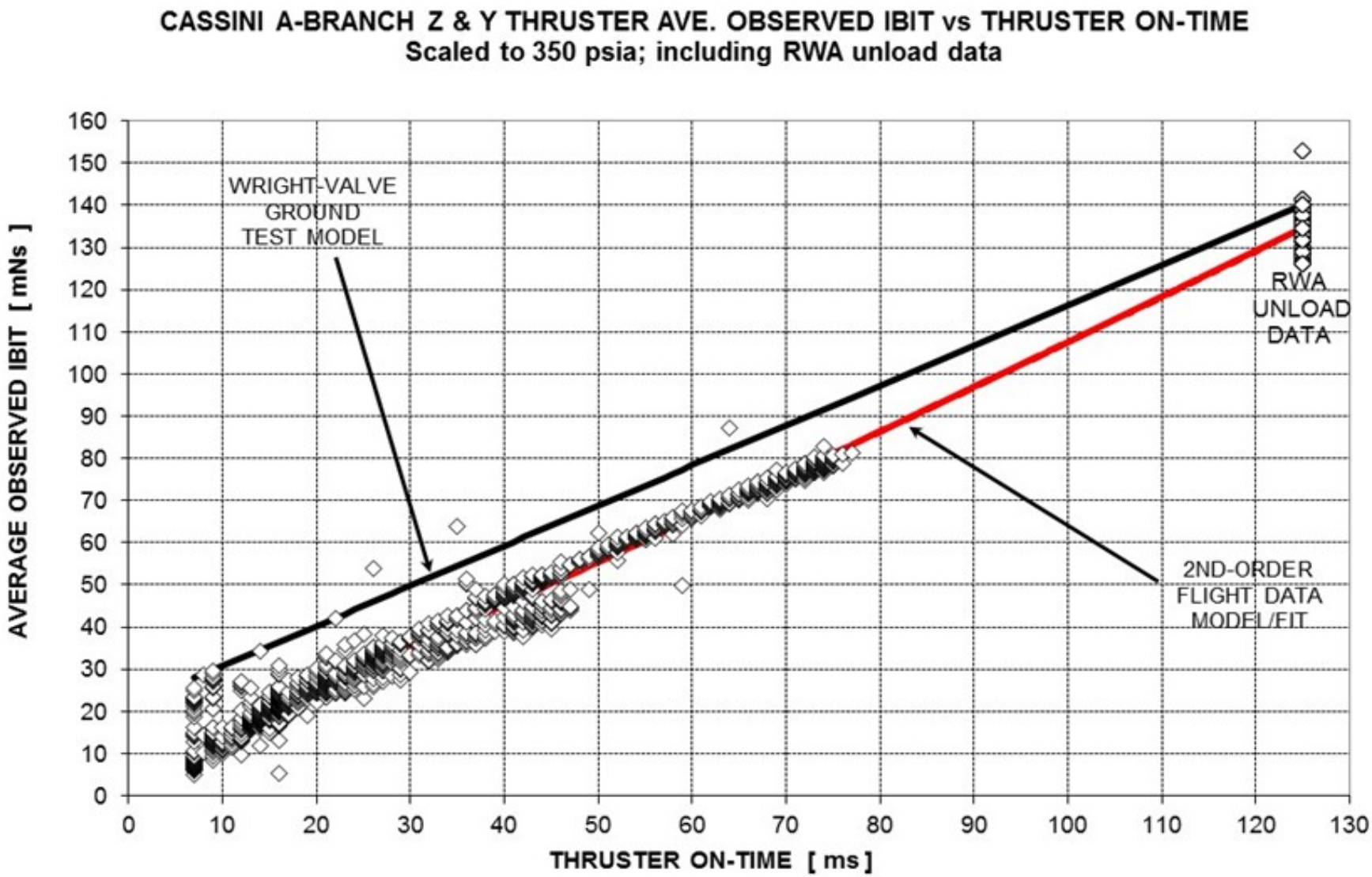


Galileo P-Transducer Drift

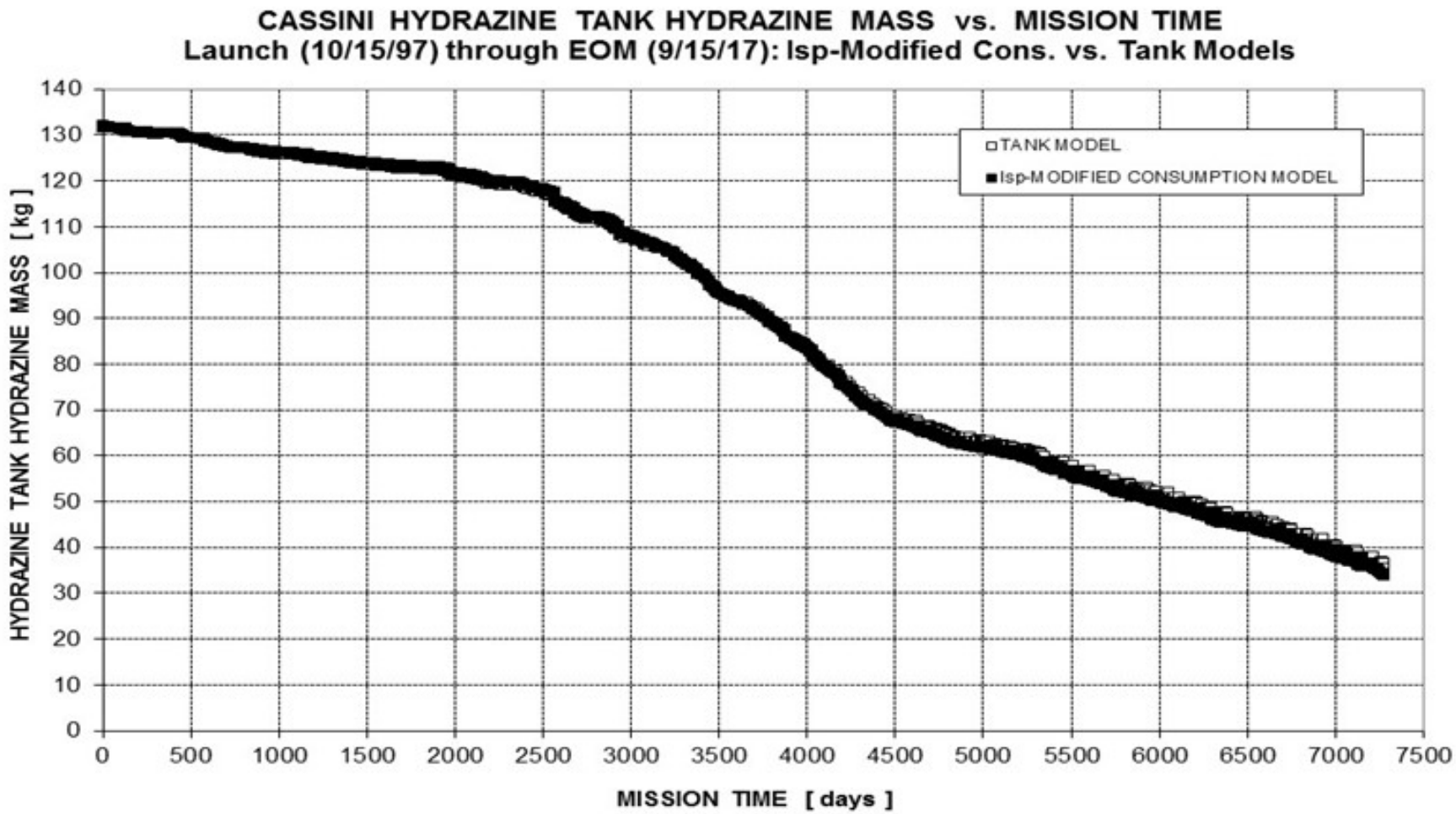


Voyager P-Transducer Drift

Cassini Consumption Model Improvement: IBIT vs. On-Time from Flight Data

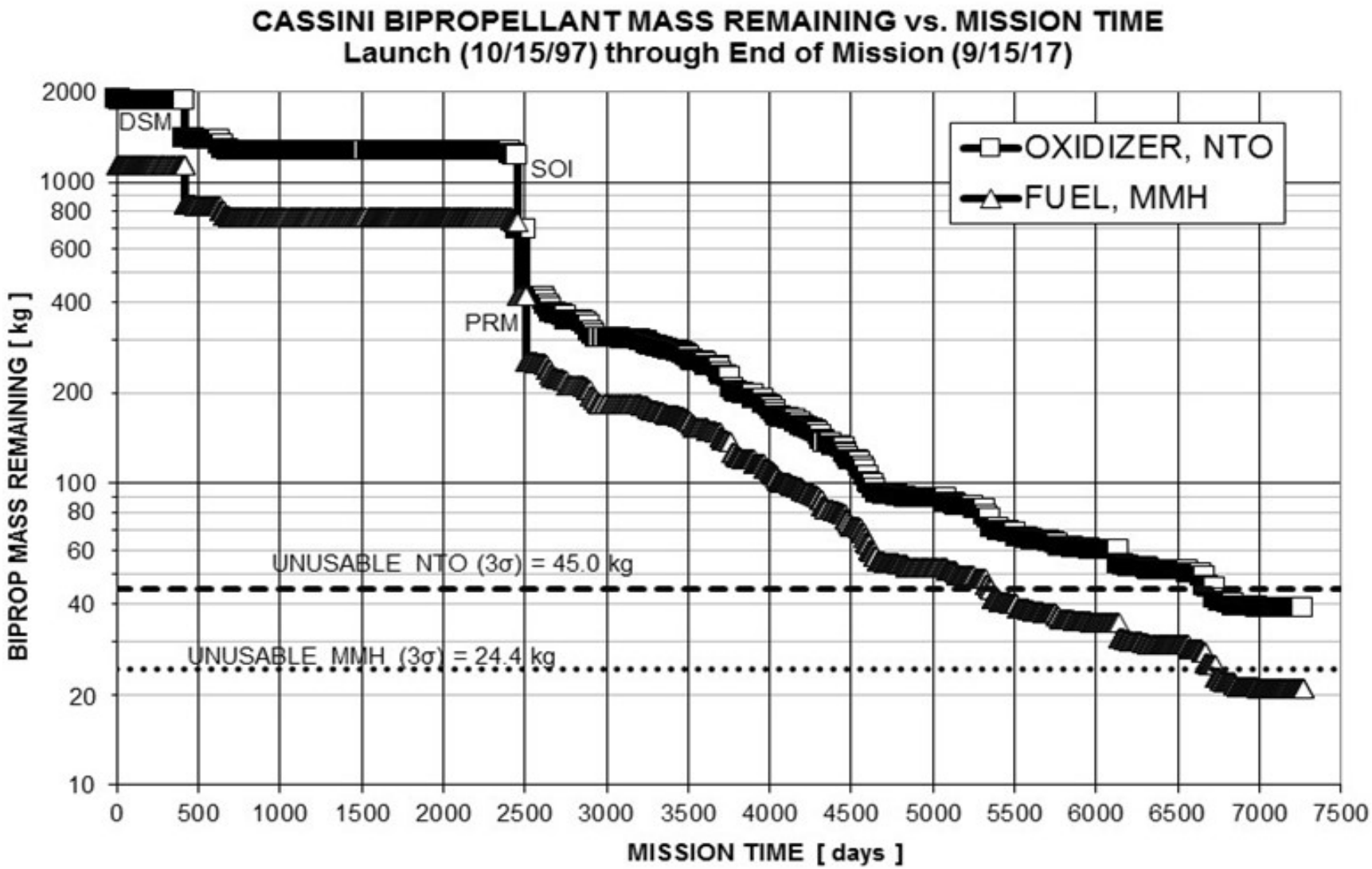


Cassini N_2H_4 Mass vs. Time: Isp-Modified Consumption vs. Tank Model

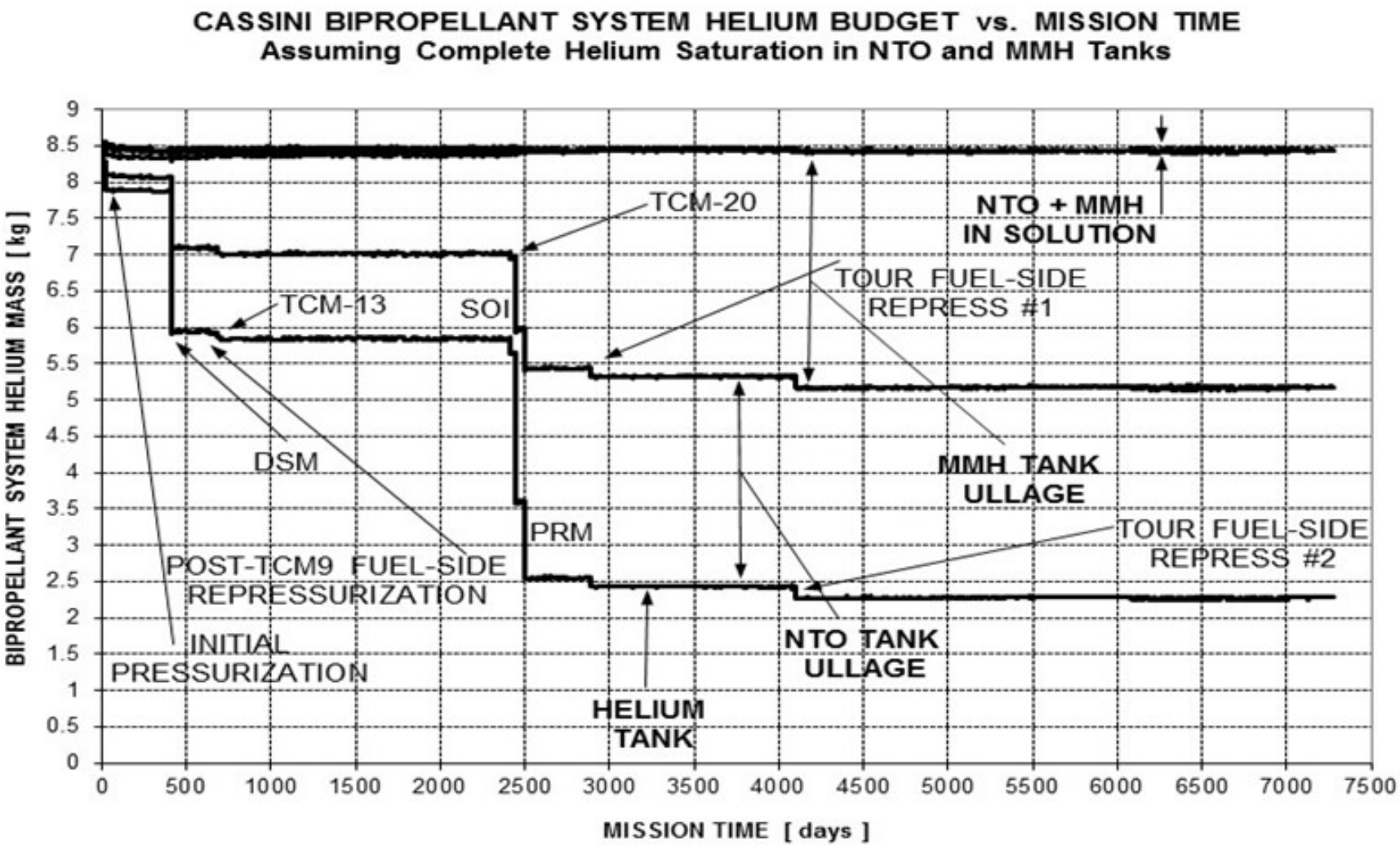


One-time correction around Day 3300: worked well over the next 11 years!

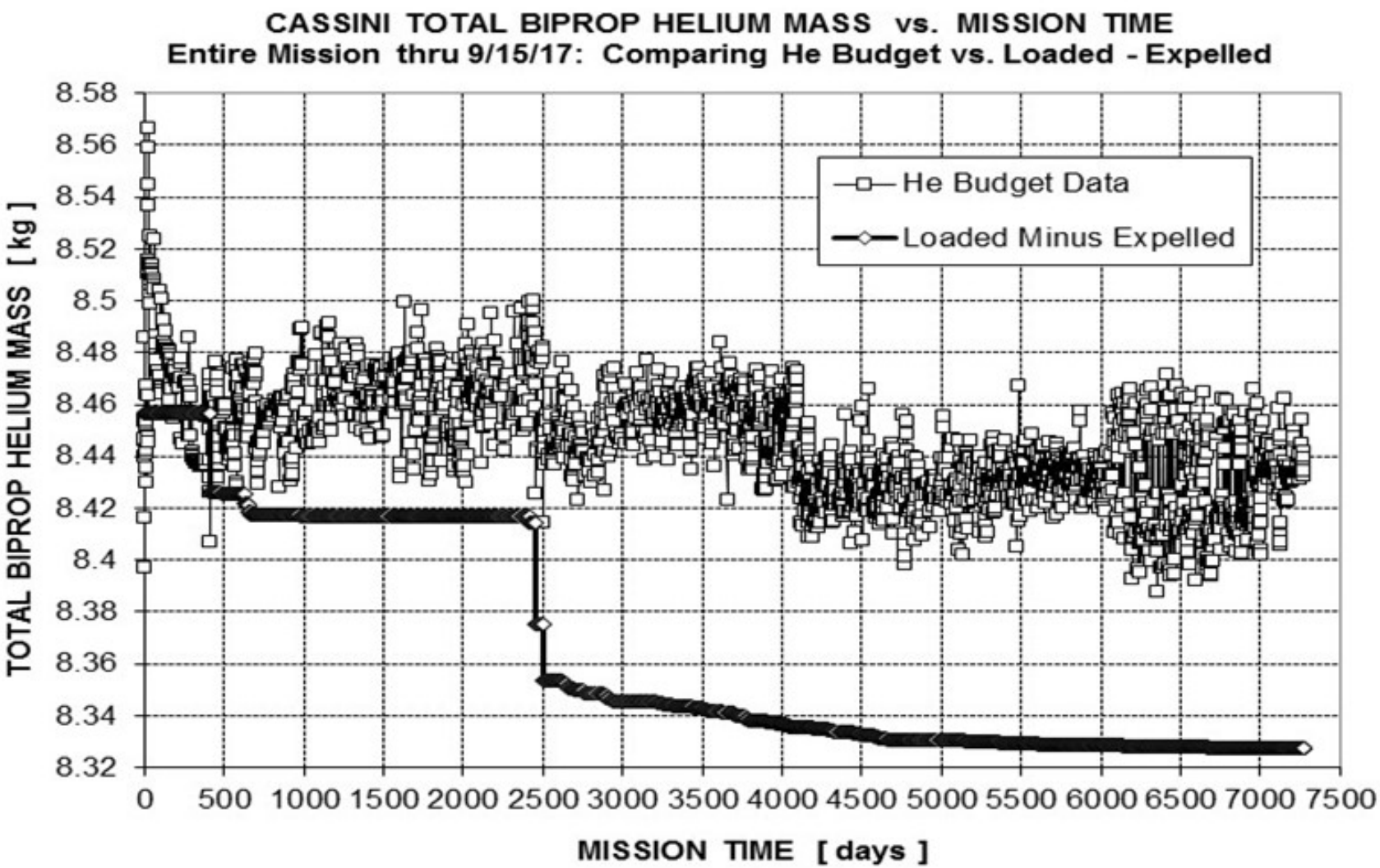
Cassini MMH/NTO Mass Remaining vs. Mission Time



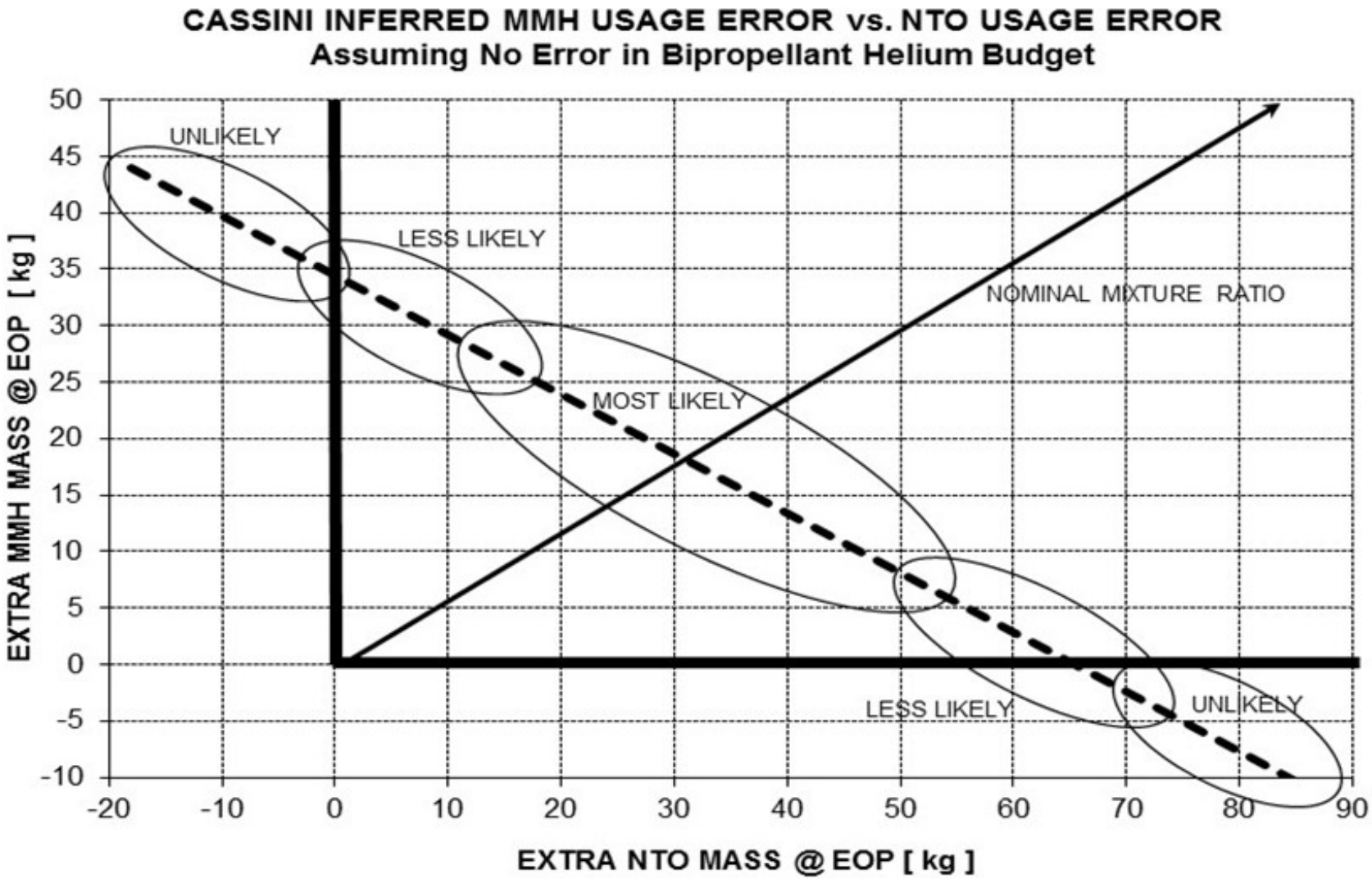
Cassini Bipropellant System "Helium Budget" Results



Cassini Bipropellant Total Helium: Loaded – Expelled vs. Helium Budget

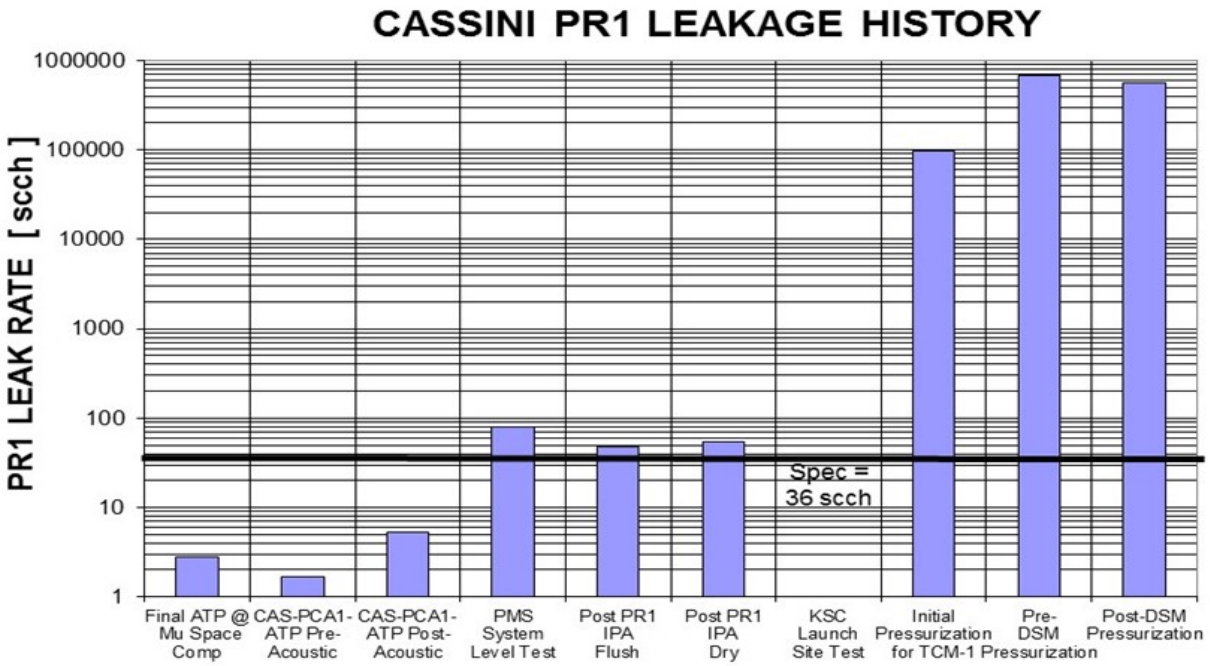


Potential Cassini "Extra" Bipropellant if Helium Budget were Correct

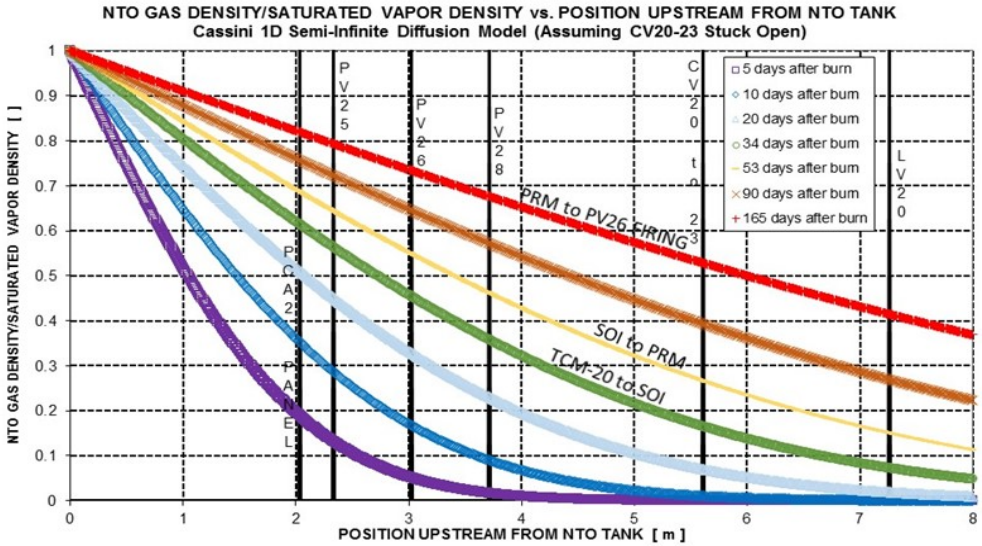


Cassini Prime Regulator (PR1) Leakage History

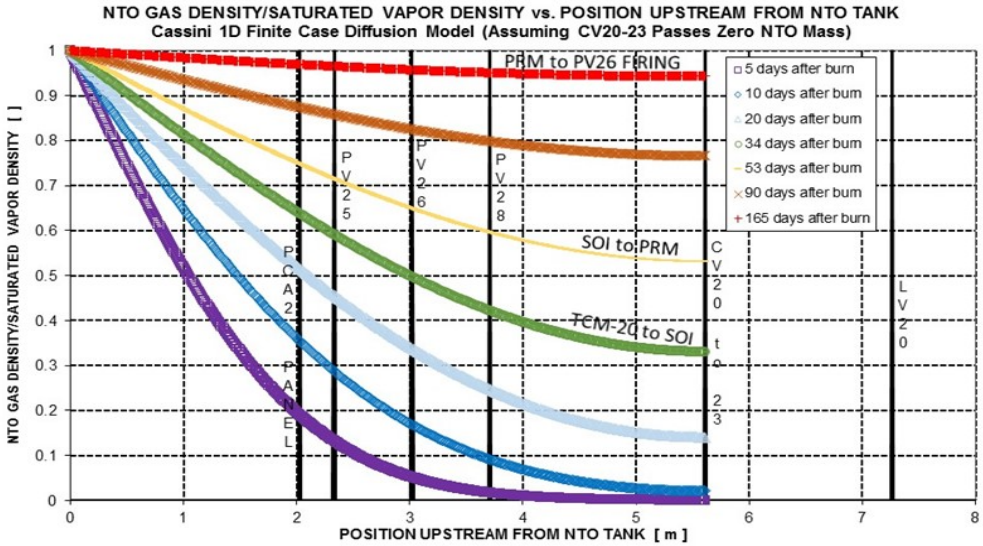
Pressurization Event	Initial Pressurization	Pre-DSM Pressurization	Post-DSM Pressurization
Date [M/D/Y]	11/9/97	12/2/98	12/3/98
Helium Tank Supply Pressure PH1 Δ [psia]	3449 → 3323	3290 → 3231	3231 → 2433
PR1 Leak Rate from P(NTO)/P(MMH) Increase	1636 sccm	11251 sccm	9311 sccm
PR1 Leak Rate from PHE2 Pressure Decrease	1667 sccm	11113 sccm	N/A (LV20/30 closed)
Error between PR1 Leak Calculation Methods	+1.9%	-1.2%	N/A
PR1 Leakage Specification	0.6 sccm	0.6 sccm	0.6 sccm
Observed Leak Rate/Specification Leak Rate	2727x	18752x	15518x
Particle Diameter Consistent w/ Leak Rate [µm]	0.18	1.2	1.3
Maximum Particle Diameter thru Filter [µm]	15	15	15
Particle @ PR1 Hard Seat Could Explain Leak?	Yes	Yes	Yes



NTO Diffusion Modeling: Upstream from NTO Tank

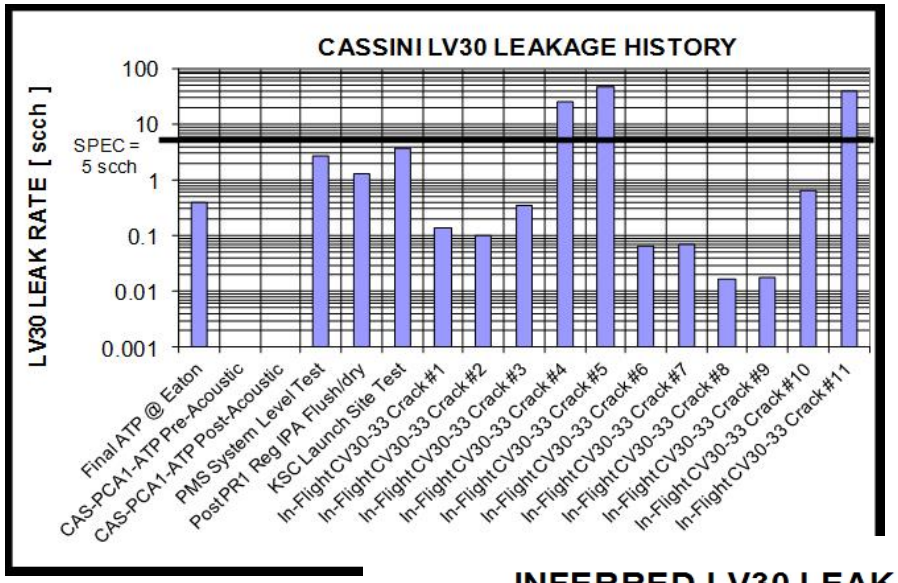


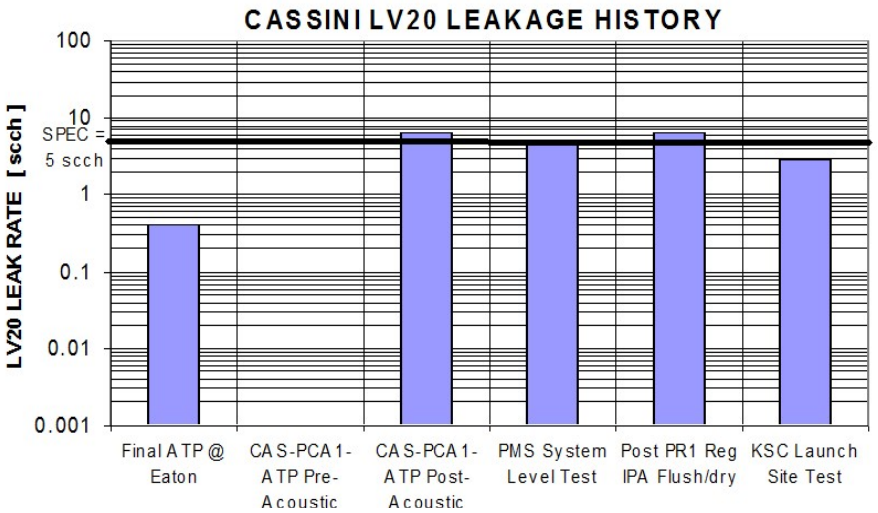
Classic 1D Semi-Infinite Case
Worst-case for diffusion front
Not worst-case for NTO mass
Unrealistic with excellent CVs

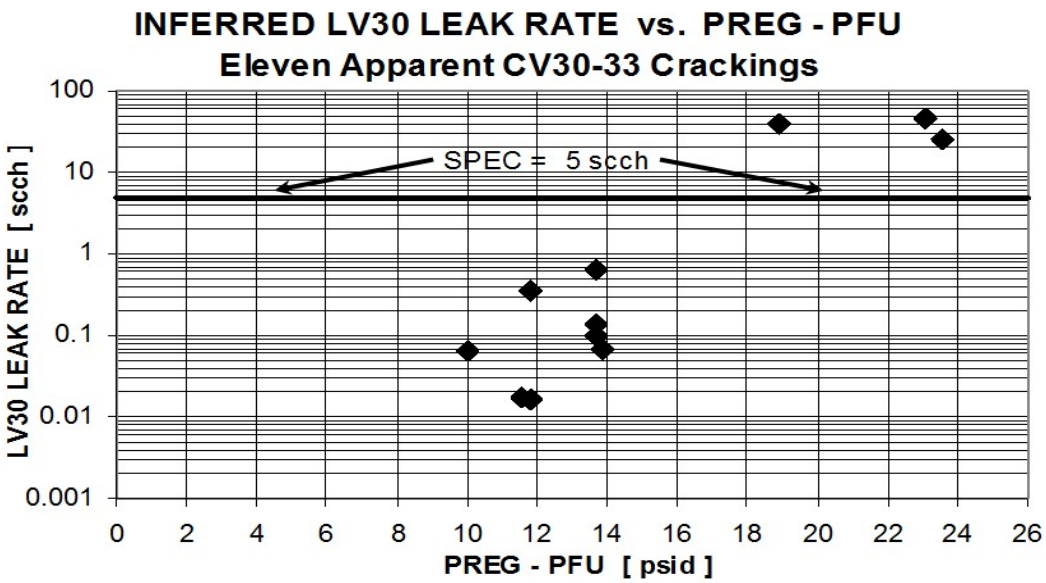


New 1D Finite Location Case
NTO gradient = 0 @ CV20-23
More NTO mass @ CV
Developed for Juno in 2009
Retroactively applied to Cassini

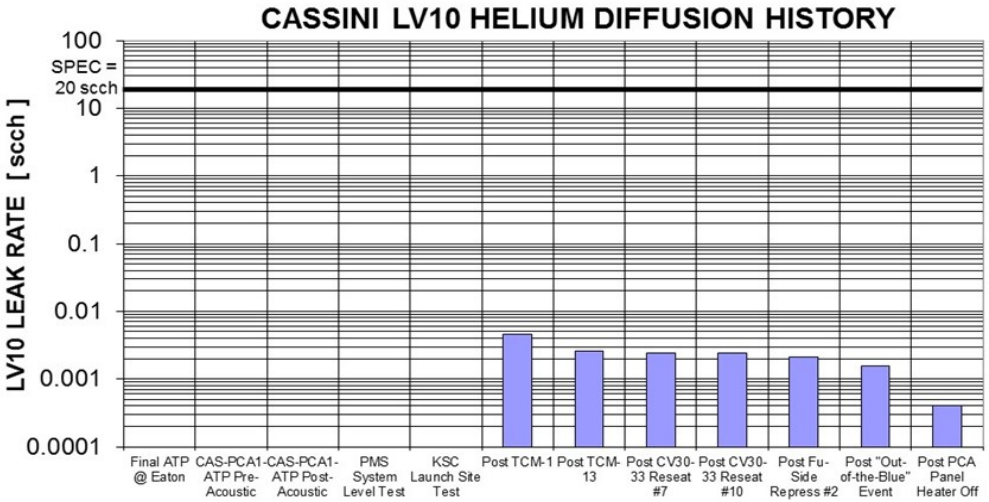
Cassini LV20 & LV30 Leakage History (only pre-launch data for LV20)



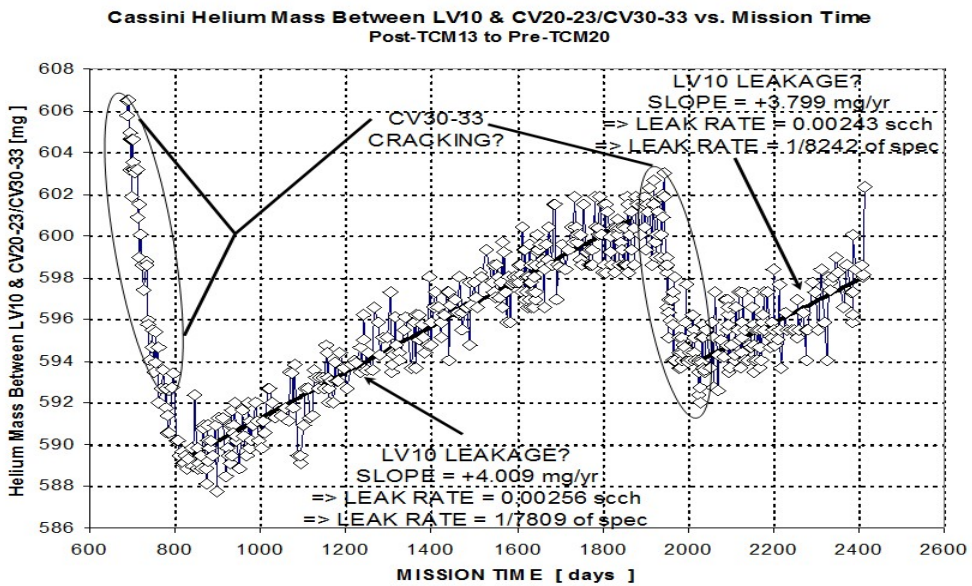




Cassini LV10 Leakage History: Diffusion-Limited Performance!



PREG went up ~1 DN/year
Re and Kn numbers near 1 → Helium diffusion through LV10



PREG increase 2000-2003
CV30-33 cracking/reseat 2003
Diffusion seen @ same rate
LV10 crucial for Cassini success

Unusable NTO/MMH Assessment

Deterministically Unusable Bipropellant	NTO [kg]	MMH [kg]	NTO%	MMH%
Trapped Liquid in Propellant Lines	0.7	0.4	0.04	0.04
Trapped Vapor in Propellant Tank @ Depletion	5.9	0.2	0.32	0.02
Trapped Due to 99.5% Tank Expulsion Efficiency	9.3	5.7	0.50	0.50
Total Deterministic	15.9	6.3	0.85	0.56
Statistically Unusable Bipropellant (3σ)	**NTO [kg]**	**MMH [kg]**	**NTO%**	**MMH%**
Bipropellant Loading Uncertainty	3.4	2.2	0.18	0.19
Tank Pressure Uncertainty	27.0	17.2	1.44	1.52
Line Pressure Drop Uncertainty	7.7	3.3	0.41	0.29
Tank Temperature Uncertainty	1.6	0.4	0.09	0.04
Main-Engine Burn Time Uncertainty	0.6	0.3	0.03	0.03
Delivered Mixture Ratio Uncertainty	6.6	4.0	0.35	0.35
Total Statistical (3σ, RSS)	29.1	18.1	1.56	1.60
TOTAL UNUSABLE PROPELLANT	45.0	24.4	2.41	2.16

Unusable N_2H_4 Assessment

Deterministically Unusable Monopropellant	**N_2H_4 [kg]**	**N_2H_4 [%]**
Trapped Liquid in Propellant Lines	0.608	0.461
Trapped Vapor in Propellant Tank @ Depletion	0.004	0.003
Trapped Due to Diaphragm Permeation, Diffusion, & Condensation	0.939	0.711
Trapped Due to Assumed 99.5% Tank Expulsion Efficiency	0.660	0.500
Unmodeled Usage due to STV Tank Temp Sensor Offset (reserve)	0.650	0.492
Unmodeled Usage due to Tank/Line Pressure Sensor Offset (reserve)	0.787	0.596
Total Deterministic	3.648	2.764
Statistically Unusable Monopropellant (3σ) in Reserves	**N_2H_4 [kg]**	**N_2H_4 [%]**
Hydrazine Loading Uncertainty	0.911	0.690
Tank Pressure Uncertainty @ Depletion (w/o Transducer Drift)	5.367	4.066
Tank Pressure Uncertainty @ Depletion due to Pressure Sensor Drift	5.824	4.412
Tank Temperature Uncertainty @ Depletion	0.531	0.402
Monopropellant System Helium Mass Uncertainty @ Depletion	0.869	0.658
Total Statistical (3σ, RSS) in Reserves	8.037	6.089
TOTAL UNUSABLE N_2H_4 (HOLD-UP) & RESERVES (3σ)	11.685	8.852

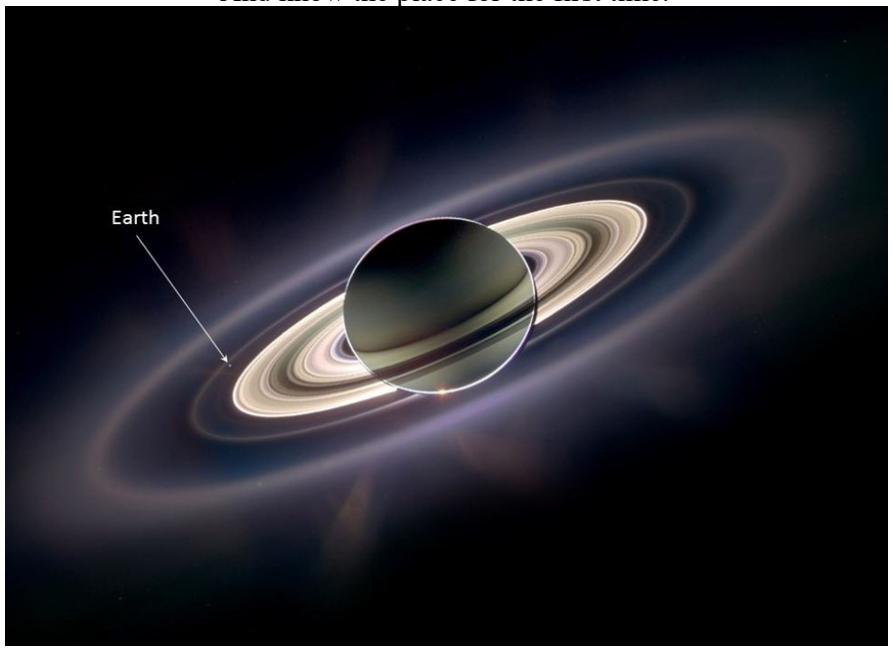
Conclusions/Favorite Image

Everything worked beautifully over two decades

(minor mission issues = PR1 leakage, A-branch thruster degradation, etc.)

During thirteen years in Saturn orbit, the spacecraft twice had the opportunity to image Saturn while the ringed planet eclipsed the sun. Both times this "Kodak moment" happened, a single pale-blue pixel was readily visible within the ghostly lit background. Gazing upon our precious and precarious Earth from 900 million miles away reminded the author of the famous quote from T. S. Eliot's "Little Gidding":

"We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time."



Back-Up Charts

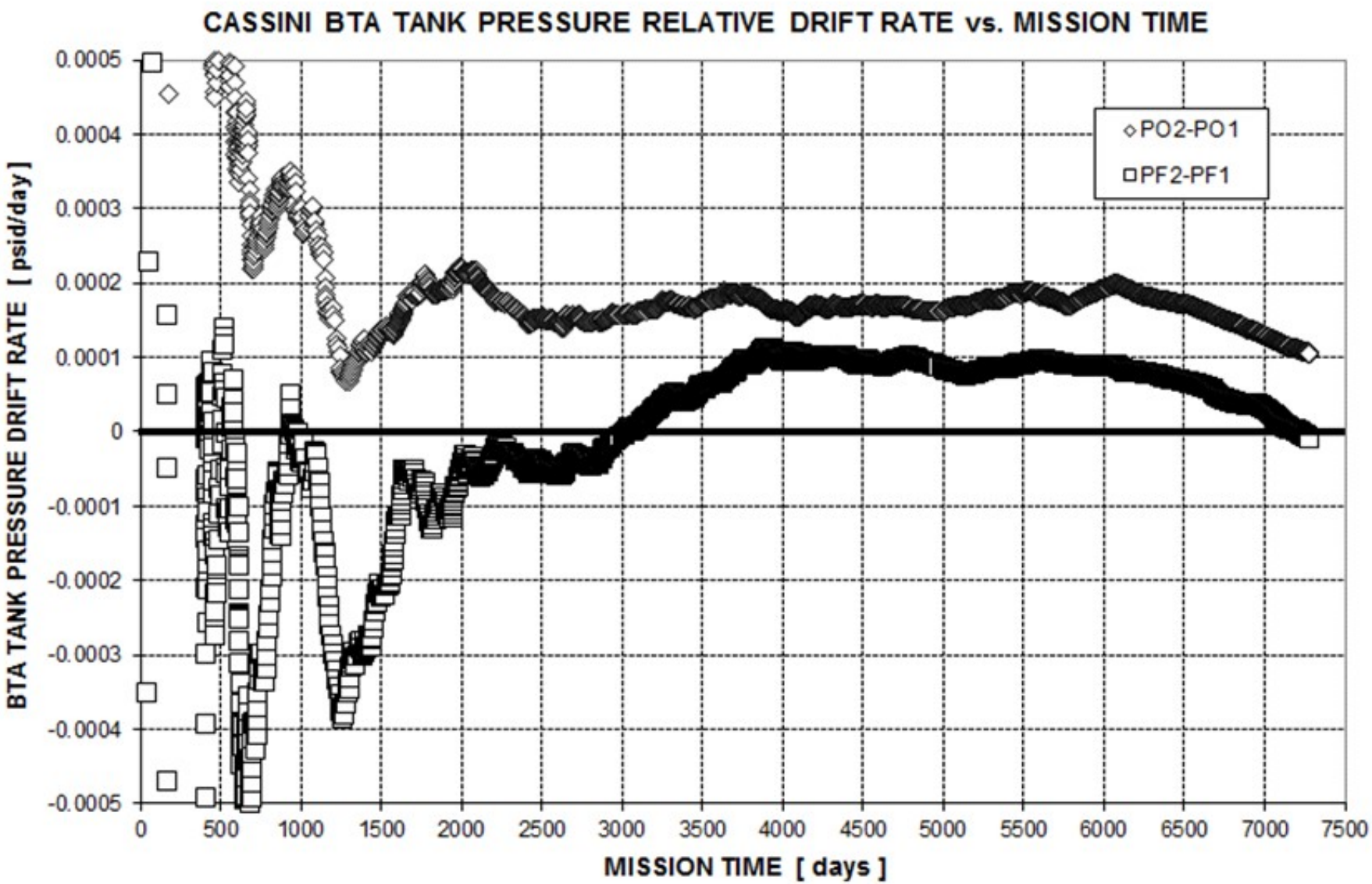
Final CPMS Consumable Values

CPMS Consumable	Used thru End of Mission	Lifetime Limit	% Used
NTO (Biprop Oxidizer) Mass [kg]	1833.4	1869.0	**98.1%**
MMH (Biprop Fuel) Mass [kg]	1116.1	1131.0	**98.7%**
N_2H_4 (Monoprop) Mass [kg]	98.1	132.0	74.3%
Z1A Thruster Valve Cycles [ ]	121205	273000	44.4%
Z2A Thruster Valve Cycles [ ]	106846	273000	39.1%
Z3A Thruster Valve Cycles [ ]	99874	273000	36.6%
Z4A Thruster Valve Cycles [ ]	117930	273000	43.2%
Y1A/Y3A Thruster Valve Cycles [ ]	48839	273000	17.9%
Y2A/Y4A Thruster Valve Cycles [ ]	49874	273000	18.3%
Z1A Thruster Throughput [kg]	10.43	25.0	41.7%
Z2A Thruster Throughput [kg]	8.79	25.0	35.2%
Z3A Thruster Throughput [kg]	8.94	25.0	35.8%
Z4A Thruster Throughput [kg]	10.29	25.0	41.2%
Y1A/Y3A Thruster Throughput [kg]	3.54	25.0	14.2%
Y2A/Y4A Thruster Throughput [kg]	4.49	25.0	18.0%
Z1B Thruster Valve Cycles [ ]	77728	273000	28.5%
Z2B Thruster Valve Cycles [ ]	61994	273000	22.7%
Z3B Thruster Valve Cycles [ ]	58283	273000	21.3%
Z4B Thruster Valve Cycles [ ]	76470	273000	28.0%
Y1B/Y3B Thruster Valve Cycles [ ]	52894	273000	19.4%
Y2B/Y4B Thruster Valve Cycles [ ]	58994	273000	21.6%
Z1B Thruster Throughput [kg]	8.14	25.0	32.6%
Z2B Thruster Throughput [kg]	6.39	25.0	25.6%
Z3B Thruster Throughput [kg]	5.97	25.0	23.9%
Z4B Thruster Throughput [kg]	7.73	25.0	30.9%
Y1B/Y3B Thruster Throughput [kg]	3.56	25.0	14.2%
Y1B/Y3B Thruster Throughput [kg]	3.56	25.0	14.2%
Latch Valve LV10 Cycles [ ]	10	5000	0.2%
Latch Valve LV11 Cycles [ ]	0	5000	0.0%
Latch Valve LV20 Cycles [ ]	5	5000	0.1%
Latch Valve LV21 Cycles [ ]	183	5000	3.7%
Latch Valve LV22 Cycles [ ]	2	5000	<0.1%
Latch Valve LV30 Cycles [ ]	10	5000	0.2%
Latch Valve LV31 Cycles [ ]	183	5000	3.7%
Latch Valve LV32 Cycles [ ]	2	5000	<0.1%
Latch Valve LV40 Cycles [ ]	2	5000	<0.1%
Latch Valve LV41 Cycles [ ]	1	5000	<0.1%
REA-A Cycles [ ]	183	200	**91.5%**
REA-B Cycles [ ]	0	200	0.0%

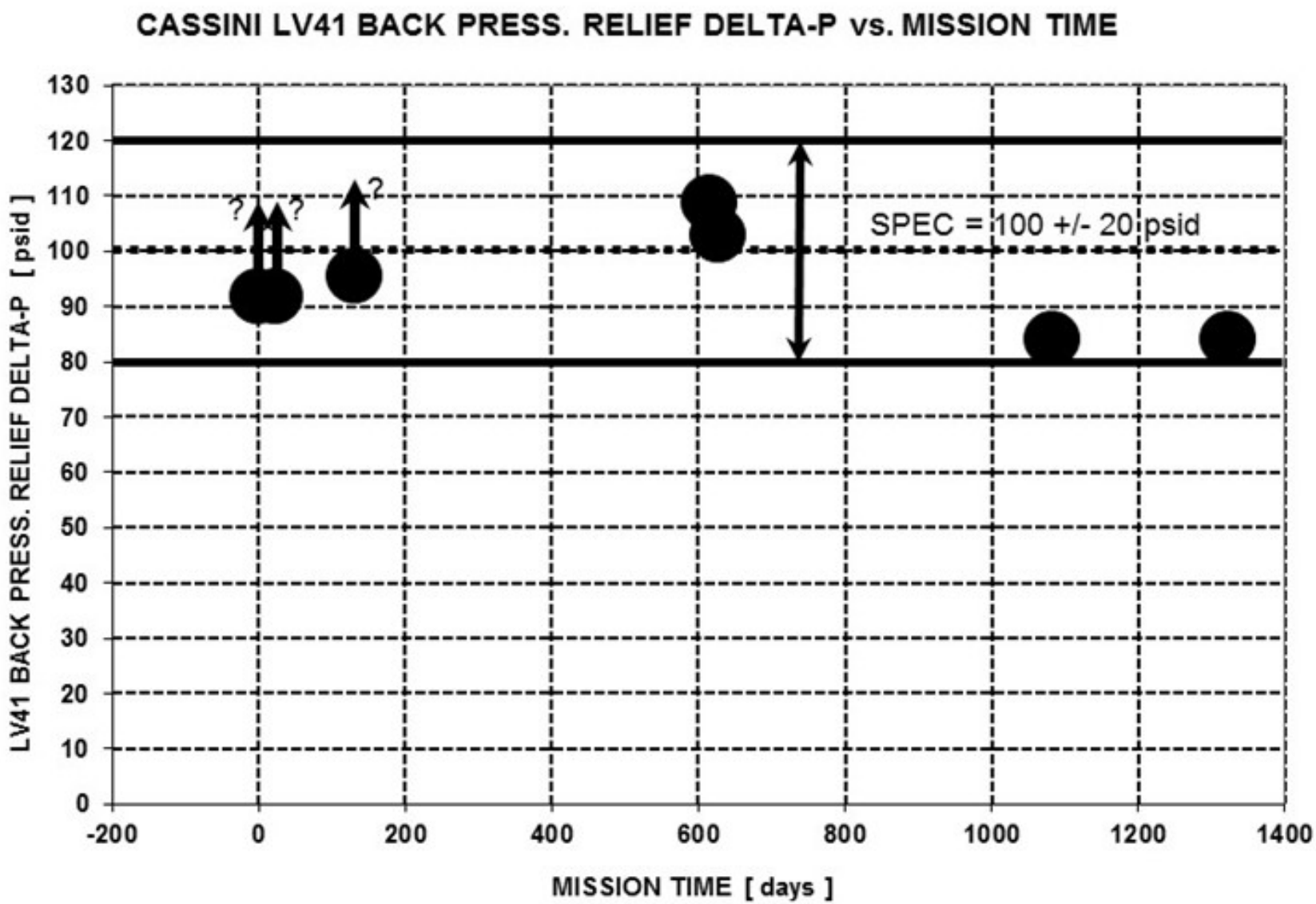
Summary of Cassini's Five Regulated ME Burns

Parameter	DSM (TCM-5)	TCM-13	TCM-20	SOI	PRM (OTM-2)
Date [D/M/Y]	12/3/98	8/31/99	5/27/04	7/1/04	8/23/04
ΔV [m/s]	450.0	6.685	34.71	626.17	393.05
t(burn) [s]	5254.884	72.100	361.896	5780.250	3067.840
LV10 Opening Time	T – 78 s	T – 168 s	T – 108 s	T – 78 s	T – 78 s
LV10 Closing Time	7STOP + 2400 s	7STOP + 14 s	7STOP + 29 s	7STOP + 31 s	7STOP + 1897 s
P(NTO, MMH) [psia]	239, 237	229, 238	238, 238	240, 238	240, 238
PREG [psia]	255	255	254	256	255
Pc(av) [psia]	98	96	98	98	98
Thrust(av) [N]	439.9	427.3	437.2	442.9	441.8
Isp(av) [s]	304.4	296.3	305.6	308.0	306.6
Mixture Ratio [ ]	1.654	1.585	1.640	1.658	1.664
∂M(NTO)/∂t [g/s]	91.82	90.15	90.63	91.45	91.76
∂M(MMH)/∂t [g/s]	55.53	56.87	55.26	55.17	55.15
∂M(prop)/∂t [g/s]	147.35	147.02	145.89	146.62	146.91
ΔM(NTO) [kg]	482.5	6.5	32.8	528.6	281.5
ΔM(MMH) [kg]	291.8	4.1	20.0	318.9	169.2
ΔM(Prop) [kg]	774.3	10.6	52.8	847.5	450.7
Impulse(tot) [Ns]	2.311e7	3.081e4	1.582e5	2.560e7	1.355e7

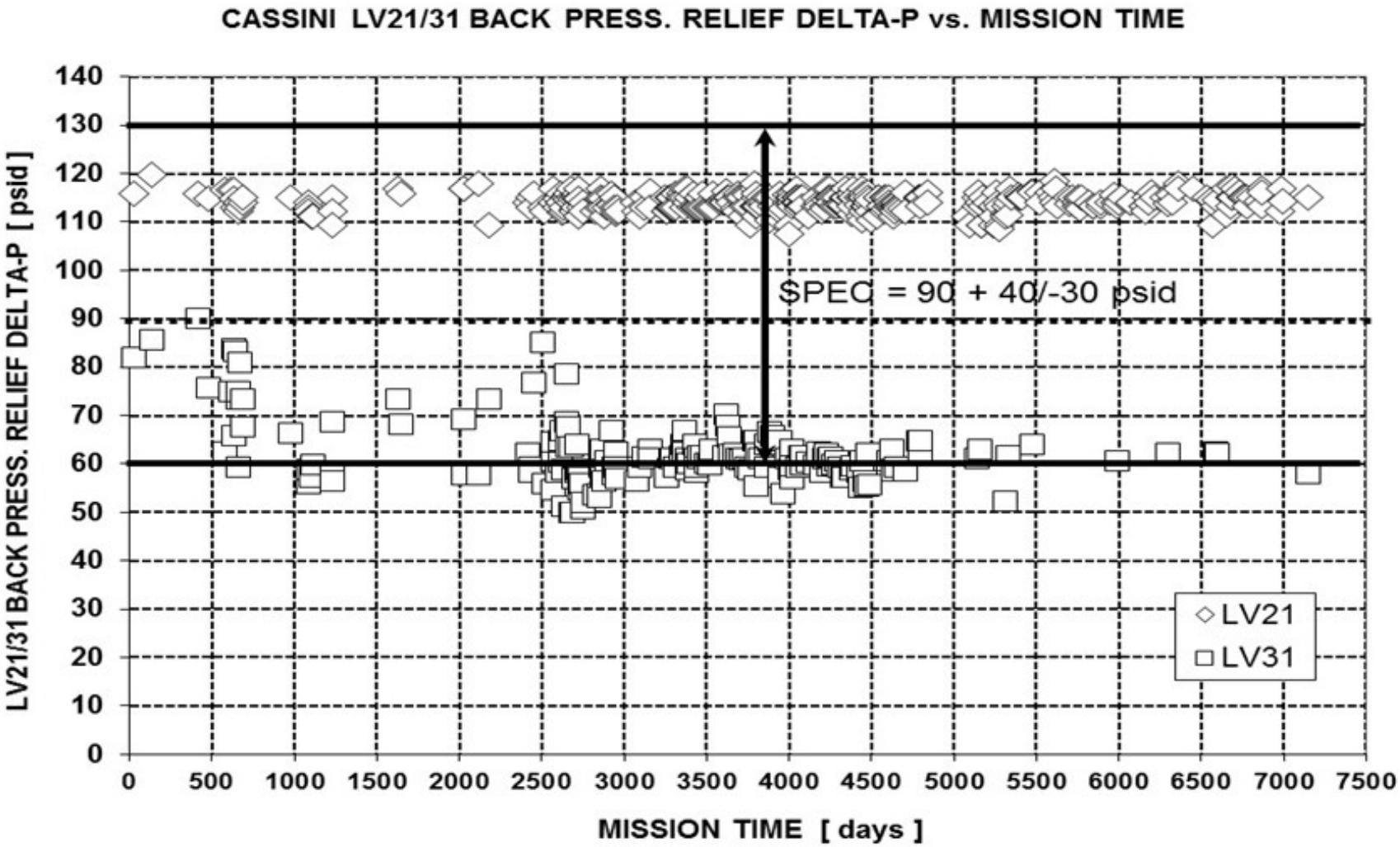
Cassini NTO/MMH Tank Pressure Drift Rate vs. Mission Time



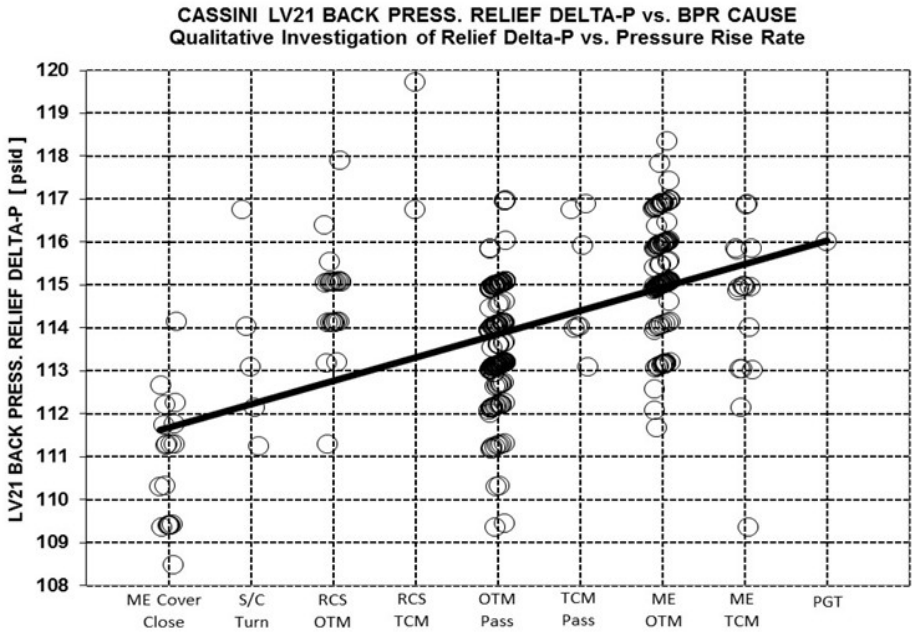
Cassini LV41 Back-Pressure Relief Performance

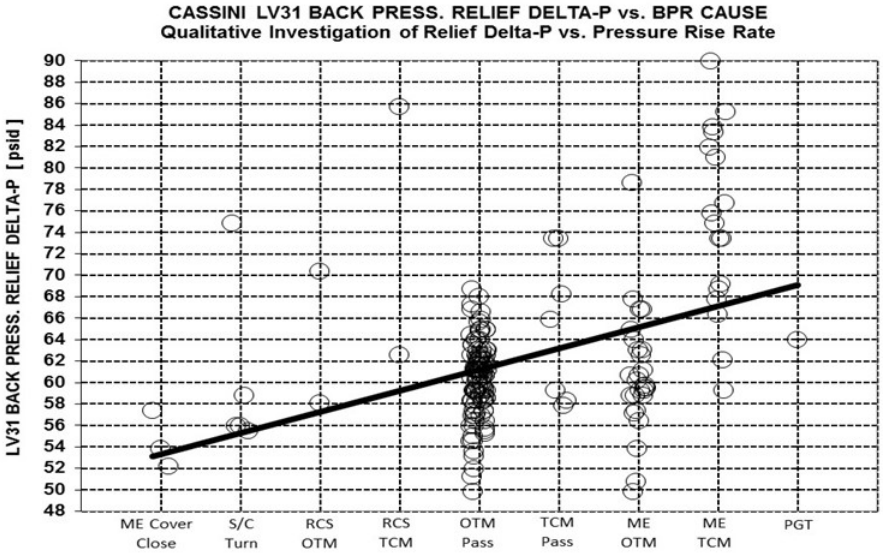


Cassini LV21/LV31 Back-Pressure Relief Performance

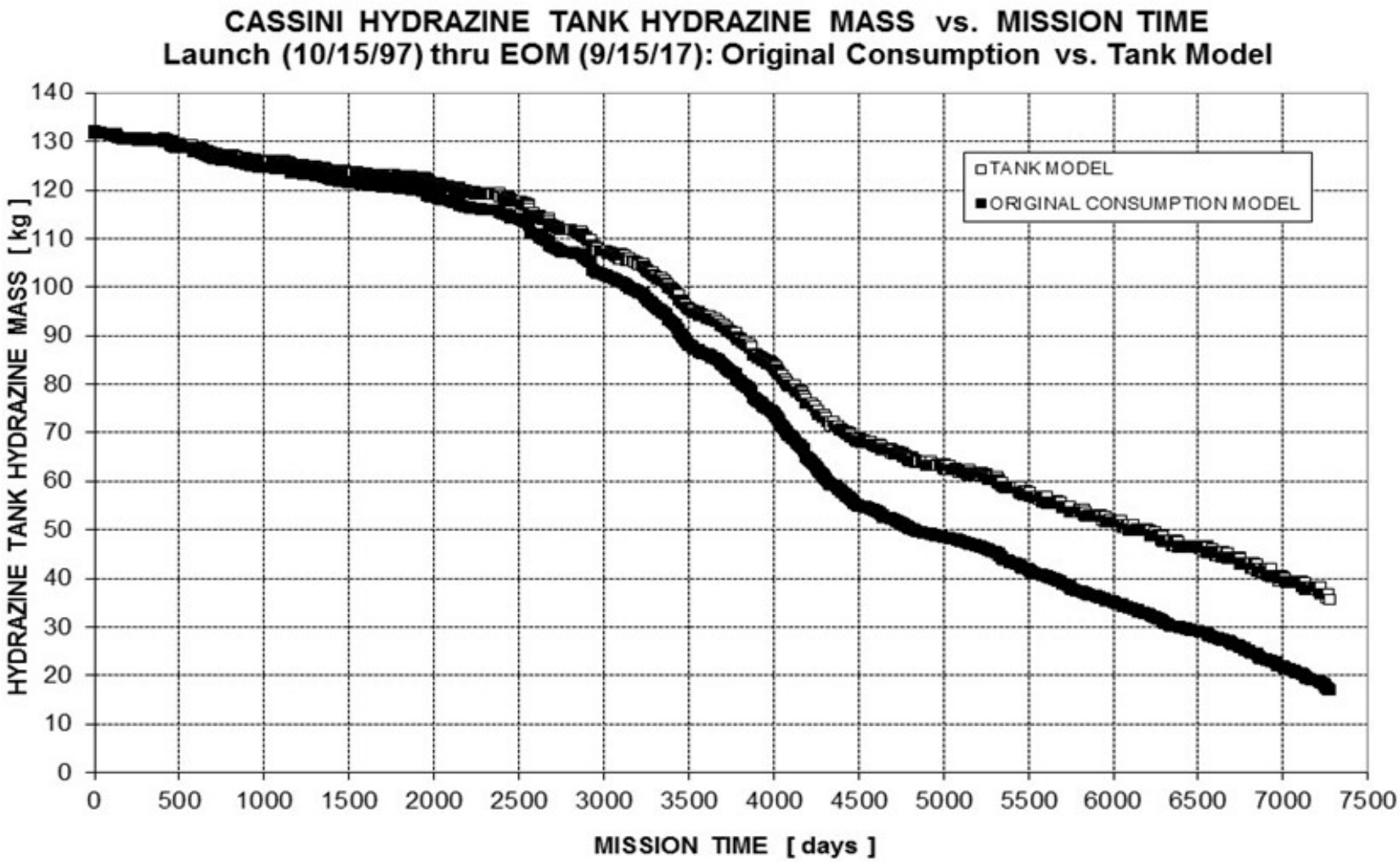


Cassini LV21/LV31 Back-Pressure Relief: Effect of Pressure Rise Rate

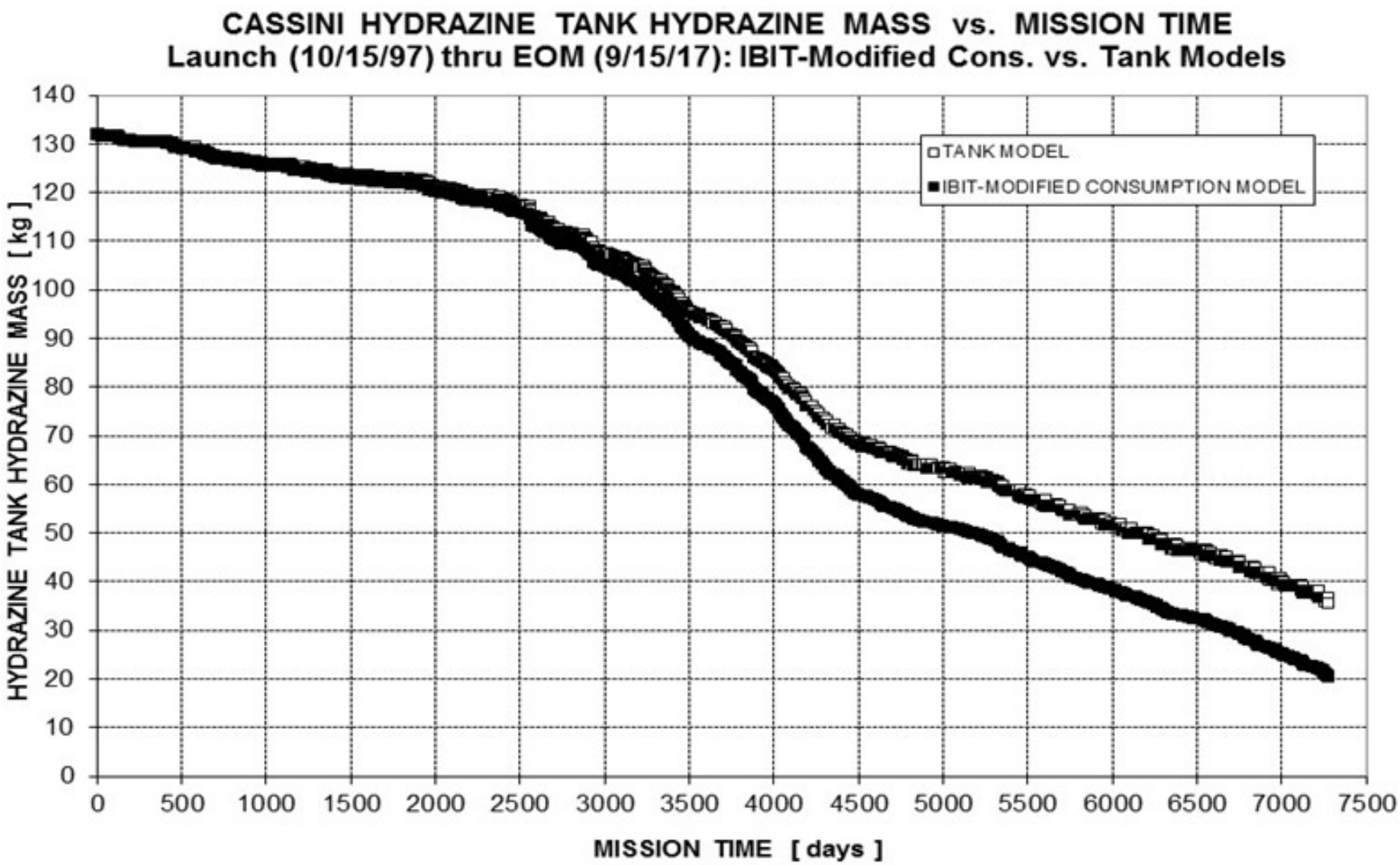




Cassini N_2H_4 Mass vs. Time: Original Consumption vs. Tank Model



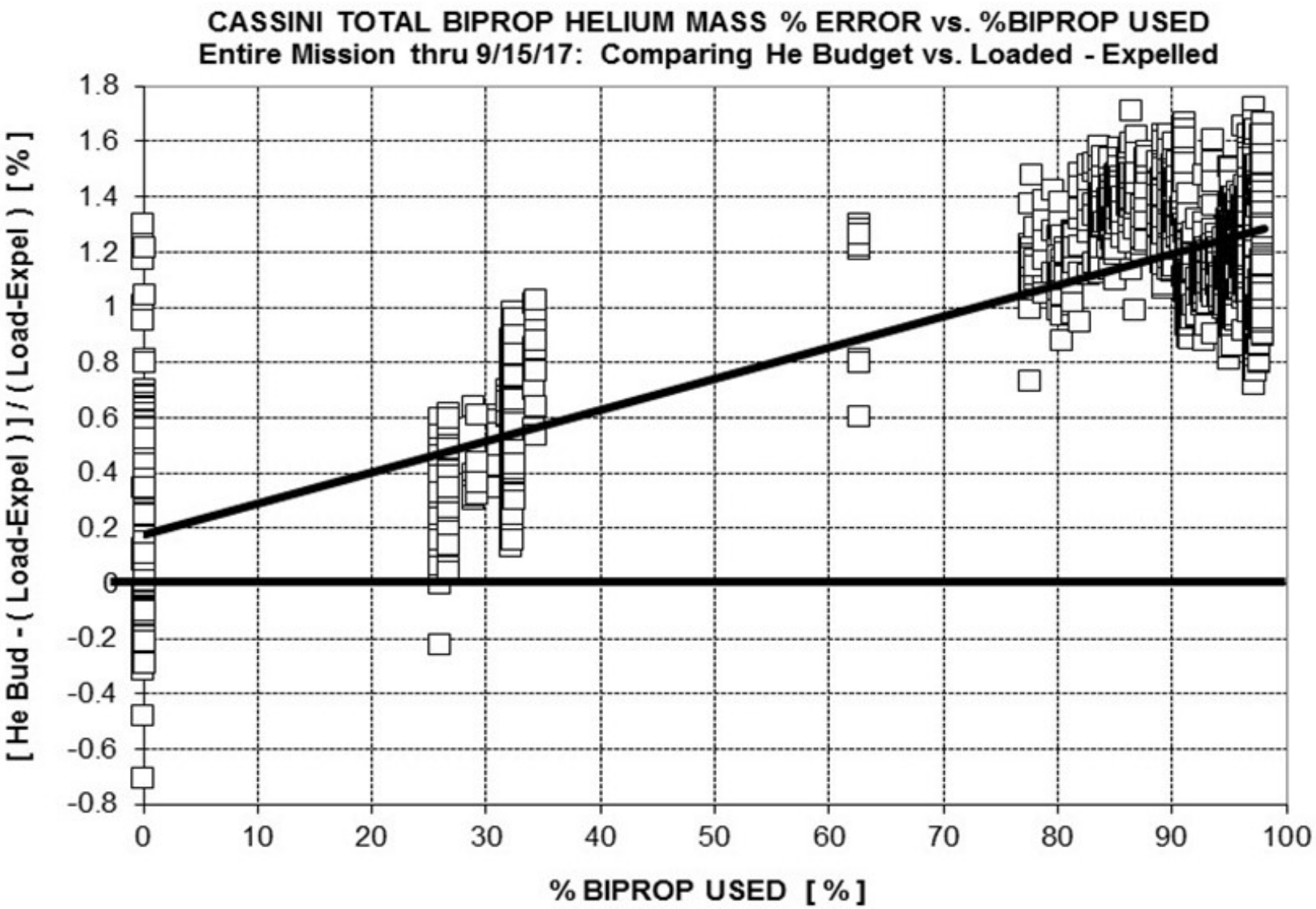
Cassini N_2H_4 Mass vs. Time: IBIT-Modified Consumption vs. Tank Model



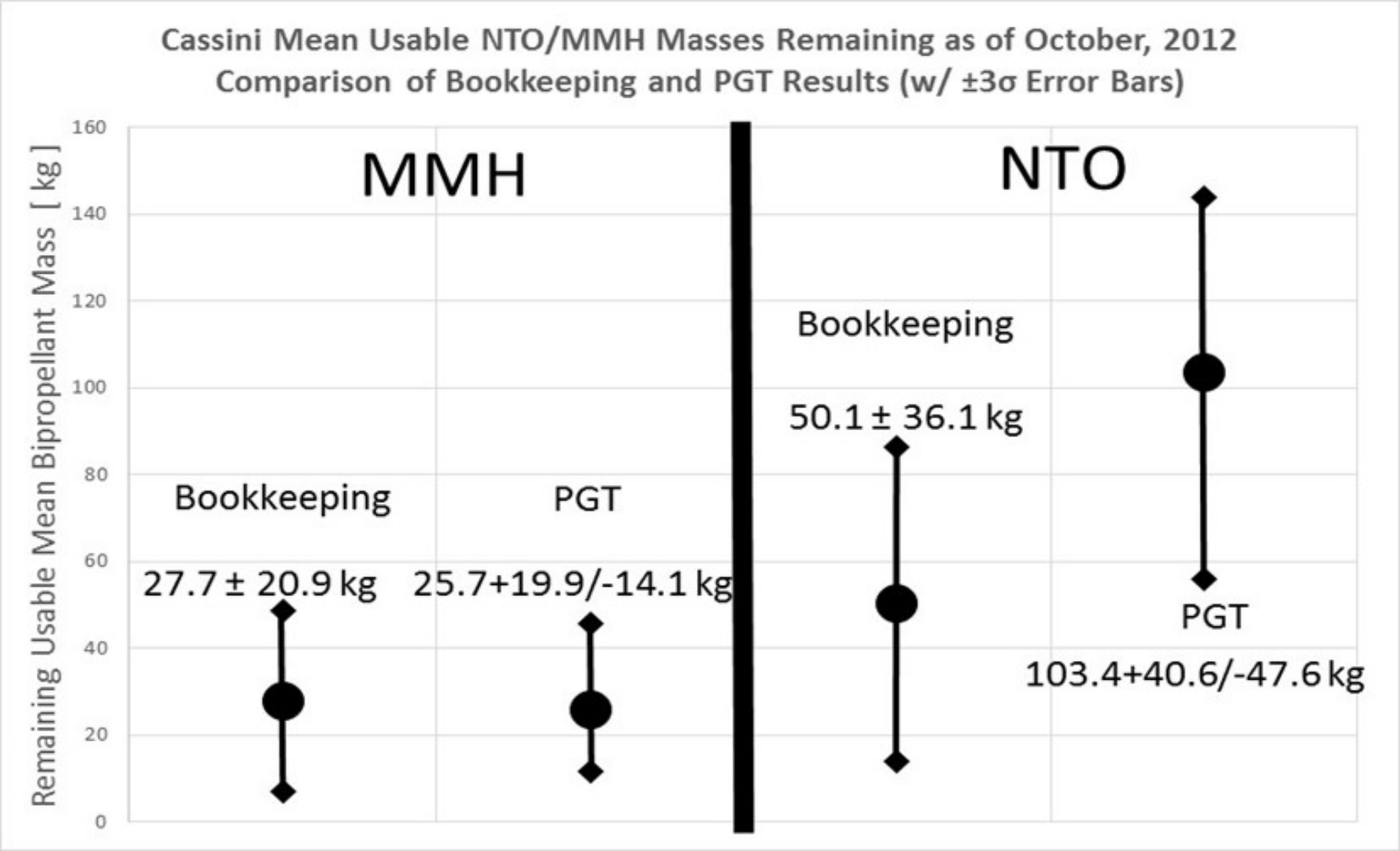
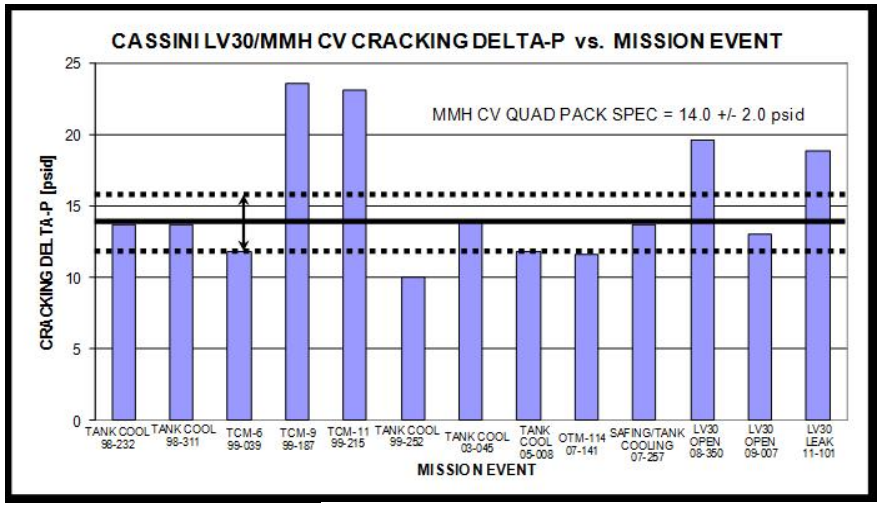
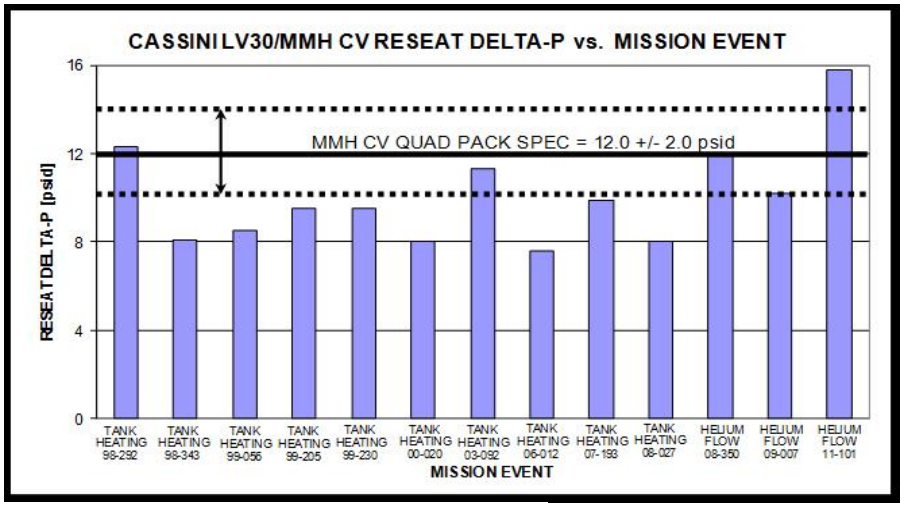
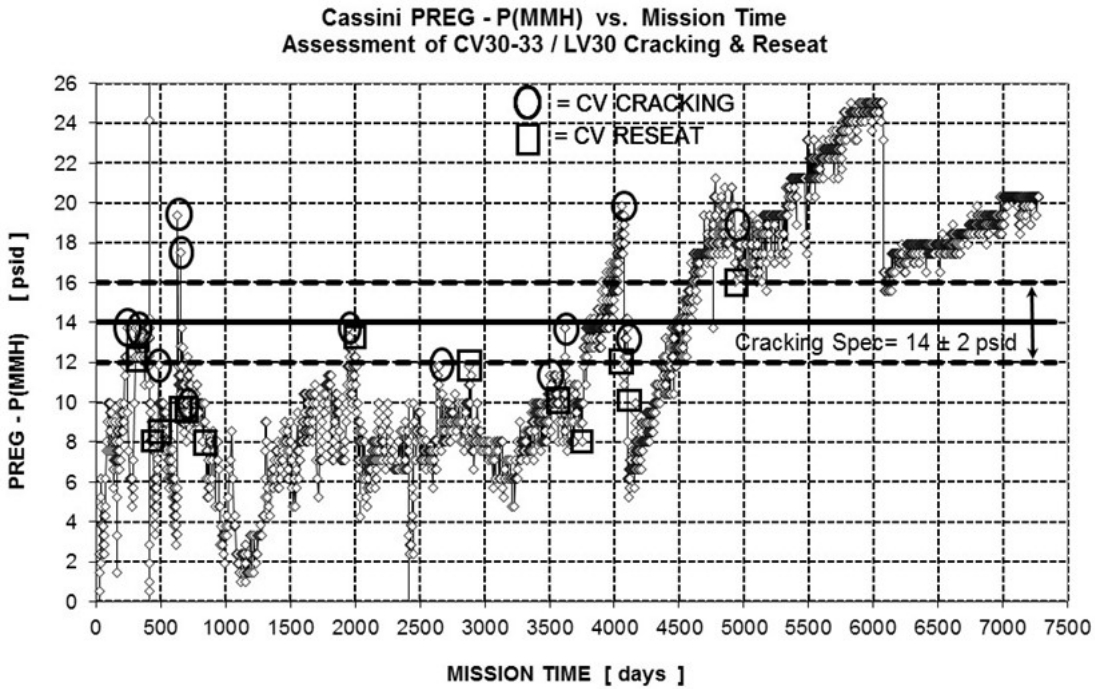
Cassini Biprop System: Conservation of Helium during Pressurization Events?

Pressurization Event	Date [M/D/Y]	NTO ΔHe MASS [kg]	MMH ΔHe MASS [kg]	BTA ΔHe MASS [kg]	HTA ΔHe MASS [kg]	BTA/HTA ERROR [%]
Initial Press.	11/9/97	0.139	0.181	0.320	-0.309	-3.4
DSM	12/3/98	0.916	0.948	1.864	-1.831	-1.8
Post-TCM9	7/13/99	0	0.352	0.352	-0.385	+9.4
TCM-13	9/1/99	0	0.731	0.731	-0.769	+5.2
TCM-20	5/27/04	0.145	0.078	0.223	-0.204	-8.5
SOI	7/1/04	1.055	1.004	2.054	-2.036	-0.9
PRM	8/23/04	0.514	0.540	1.054	-1.055	+0.1
Fu Repress #1	9/12/05	0	0.133	0.133	-0.118	-11.3
Fu Repress #2	1/8/09	0	0.137	0.137	-0.158	+15.3

Cassini Bipropellant Total Helium Mass % Error vs. % Biprop Used



Cassini Propellant Gauging Test (PGT) Results: Not Exactly Reassuring!



Cassini CV30-33 Cracking and Reseat History in Flight (with LV30 leaky)