Liquefied Natural Gas (LNG) as Propellant Fuels; Storage and Transfer Effects

Background, Testing, Data, & Analysis

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Background

- <u>Project Purpose</u>: Evaluate LNG storage / transfer / operational effects (stratification, weathering, etc.) and mitigations, including Integrated Refrigeration and Storage (IRAS)

- <u>Project Scope</u>: Retrofit an existing 400 liter cryogenic vessel with a commercial off-the-shelf Gifford-McMahon cryocooler to create a lab-scale Integrated Refrigeration and Storage (IRAS) system, internal temperature instrumentation, and sample tubes located at different elevations vertically within the liquid. This system can be used to study the behavior of LNG/methane during storage; most notably weathering (i.e. enrichment of non-methane constituents due to preferential boil-off), and stratification of the bulk liquid. Additionally, in-situ liquefaction of natural gas can be performed, along with zero boil-off (ZBO) control and possible densification. ZBO can be evaluated as a means to reduce or eliminate the weathering process.

- <u>Partners/Funding</u>: $50K – Spaceport Integration & Services (SI); $100K – CMO

- <u>Project Duration</u>: 2017 - 2019

Background Cont.

- <u>Project Timeline</u>
  - June 2017 – Initial funding from SI
  - July 2017 – Cryostat shipped to vendor for retrofit
  - August 2018 – Cryostat received from vendor
  - September 2018 – Additional funding from CMO
  - December 2018 – LN2 boiloff testing on cryostat
  - January – October 2019 – Test setup behind Cryogenics Test Laboratoy
  - October – December 2019 – Weathering test

- <u>Publications</u>
  - Poster—Development of a 400 L Integrated Refrigeration and Storage Cryostat for LNG/LCH4 Research, A. Swanger, and W. Notardonato, 27th International Cryogenic Engineering Conference, Oxford, England, (2018)
  - Integrated Refrigeration and Storage of LNG for Compositional Stability, Rose, L., Swanger, A. M., Notardonato, W. U., Fesmire, J. E., Gleeson, J., and Carro, R., Advances in Cryogenic Engineering, IOP Conf. Series: Materials Science and Engineering 101 (2019)

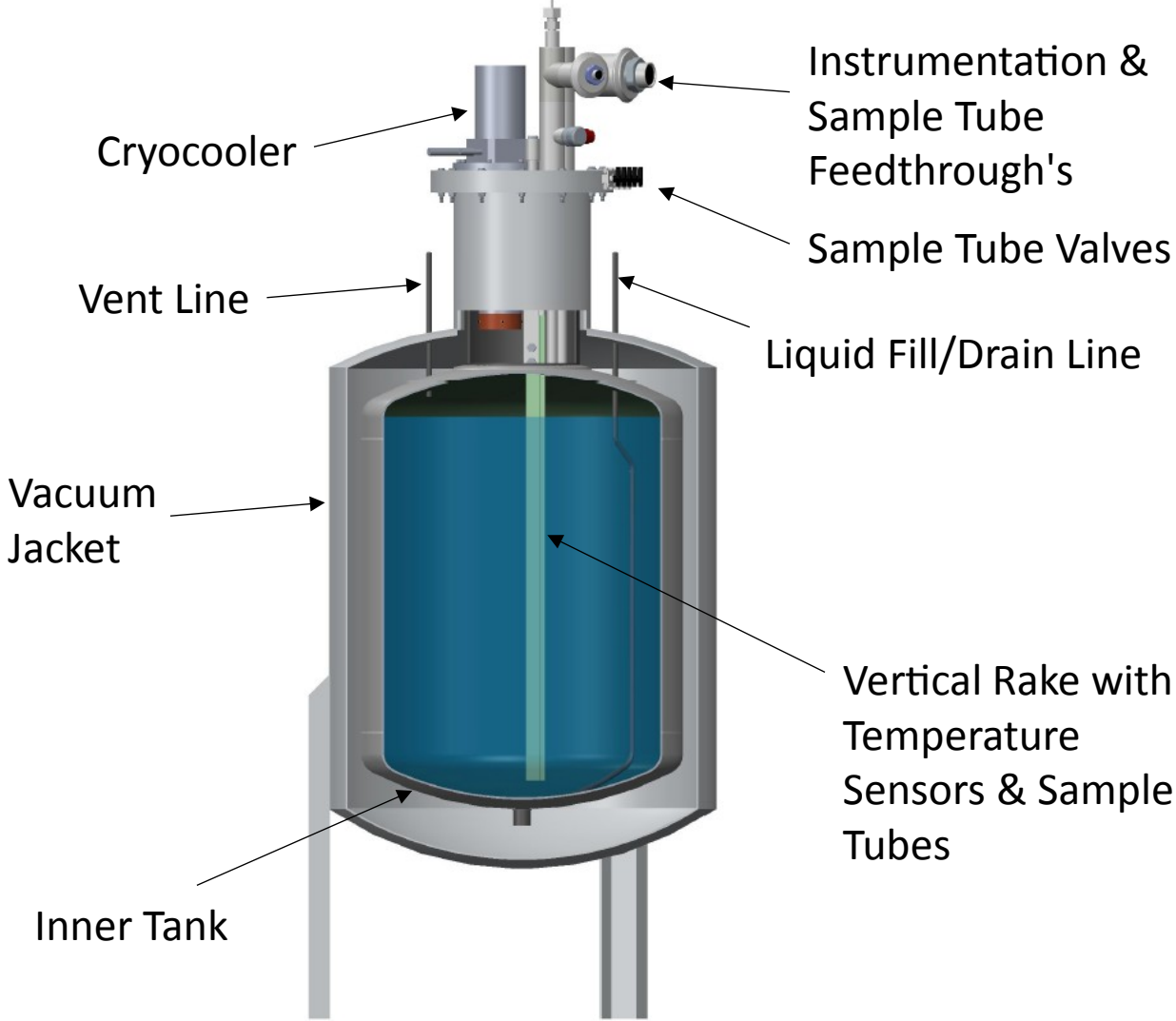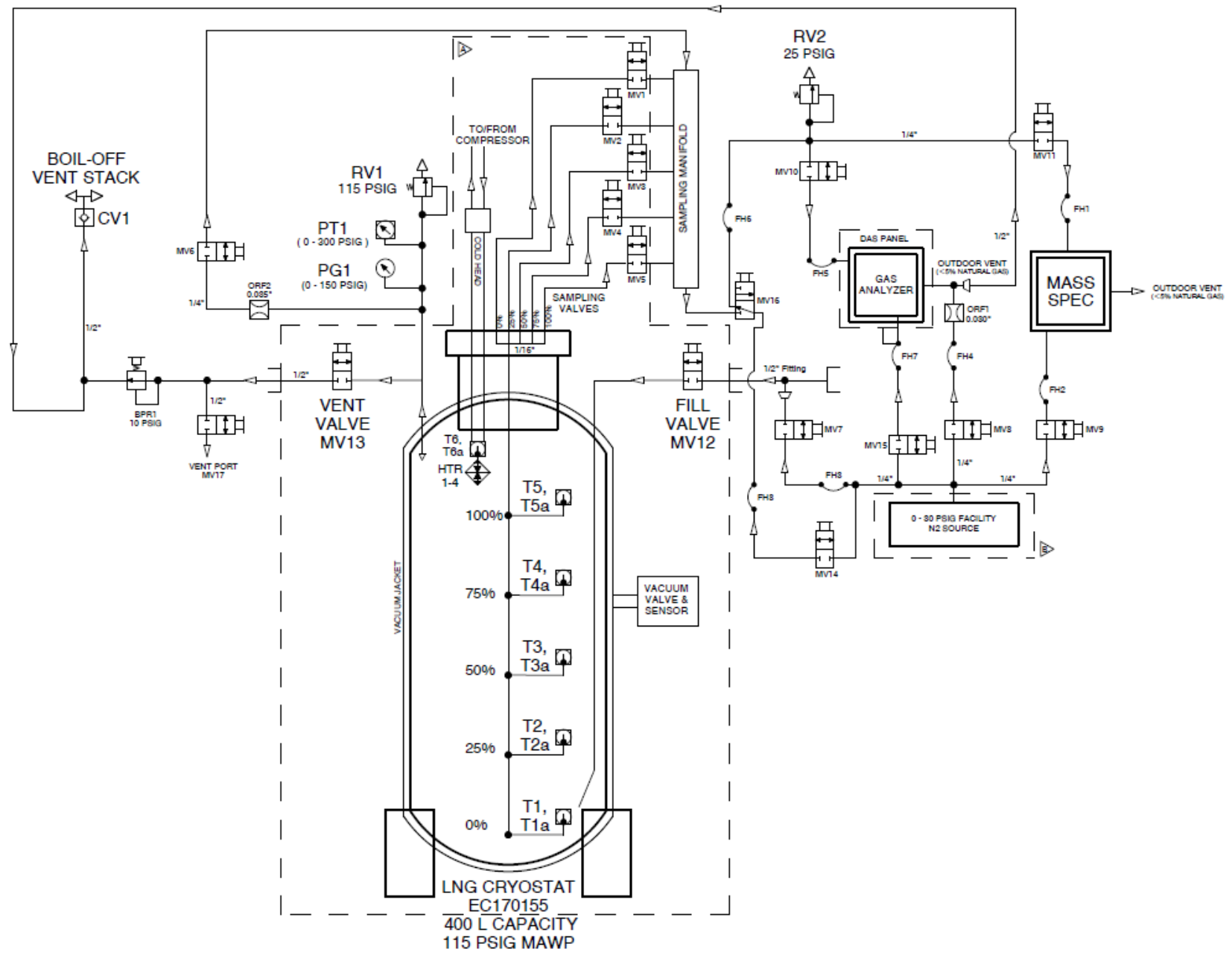# Test Setup—Cryostat

Cryostat

Vent Stack

Sample Valves

Test Setup—Cryostat

LNG Delivery

Instrumentation & Sample Tube Feedthrough's

Cryocooler

Sample Tube Valves

Vent Line

Liquid Fill/Drain Line

Vacuum Jacket

Vertical Rake with Temperature Sensors & Sample Tubes

Inner Tank

Test Setup—Schematic

Test Setup—Gas Analyzer

mks — Part Number: 1060343-001, Rev. J

USER AND INSTALLATION MANUAL

Precisive® 5 Gas Analyzer

Powered by **Precisive®** mks

Final Span Calibration Verification

Model #: Precisive 5 – 283
Serial #: 110272732
Customer:

Calibrated Concentrations:

|	
Methane:	50 – 100%
Ethane:	0 – 20%
Propane:	0 – 10%
Iso-Butane:	0 – 5%
nC4+nC5+nC6:	0 – 5%
iC5+neo-C5:	0 – 2%
CO2:	0 – 20%

Calibrated Pressure: 0 – 5 psig

Span calibration check:
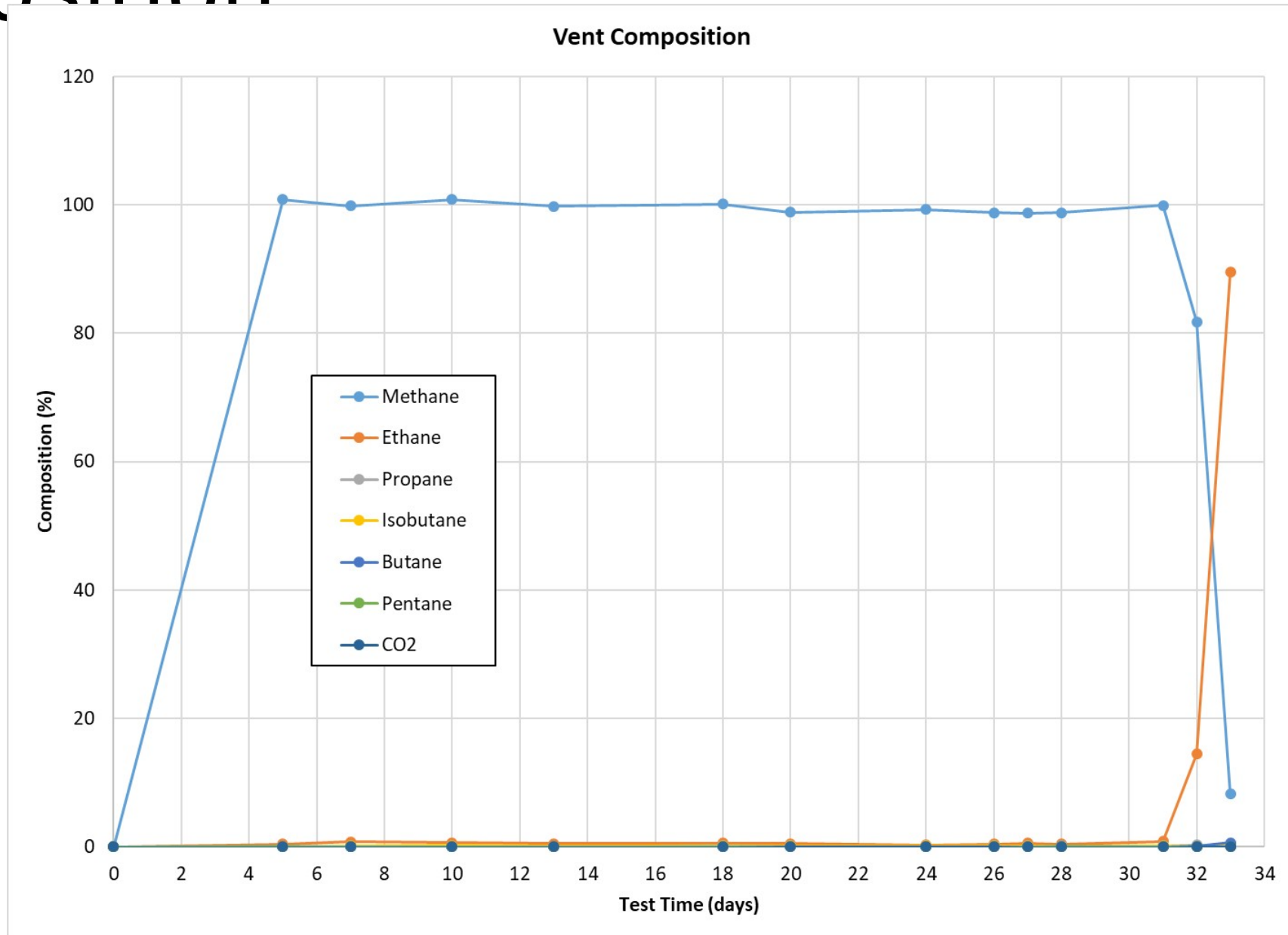Standards used:
- Certified mixture of C1 – C5, CO2 ("Mix B")

Compound	Modbus Channel	Certified Value	Measured	Error	Specification
Methane	1	85.0	84.91	0.09	+/- 0.3
Ethane	2	5.0	4.95	0.05	+/- 0.2
Propane	3	1.5	1.53	0.03	+/- 0.2
Iso-Butane	4	0.7	0.66	0.04	+/- 0.1
n-Butane	5	0.5	0.48	0.02	+/- 0.2
Pentanes	6	0.3	0.28	0.02	+/- 0.1
CO2	7	4.0	4.12	0.12	+/- 0.2

Test conditions:
Pressure: ~0.1 psig
Flow: ~ 1 L/min
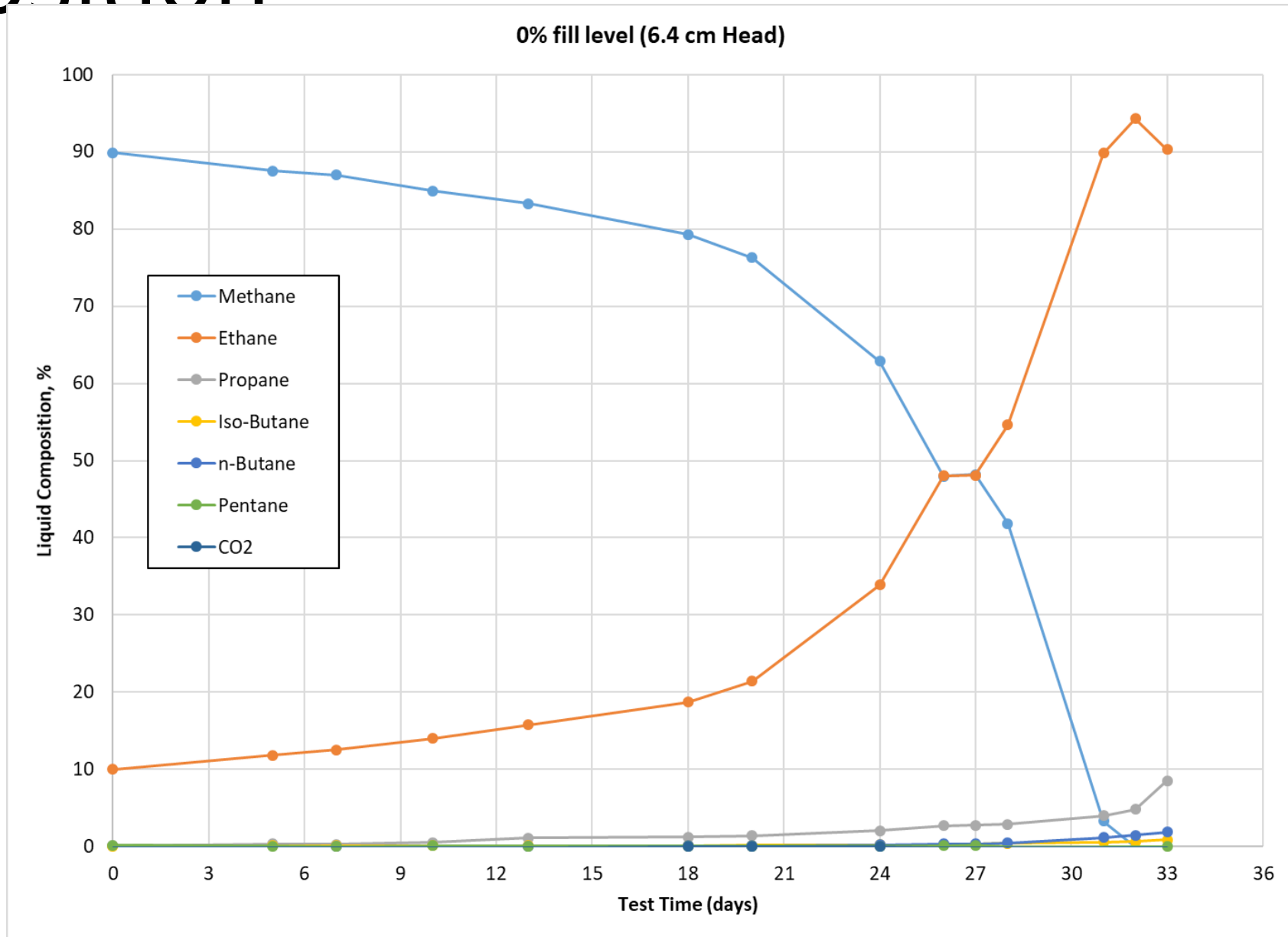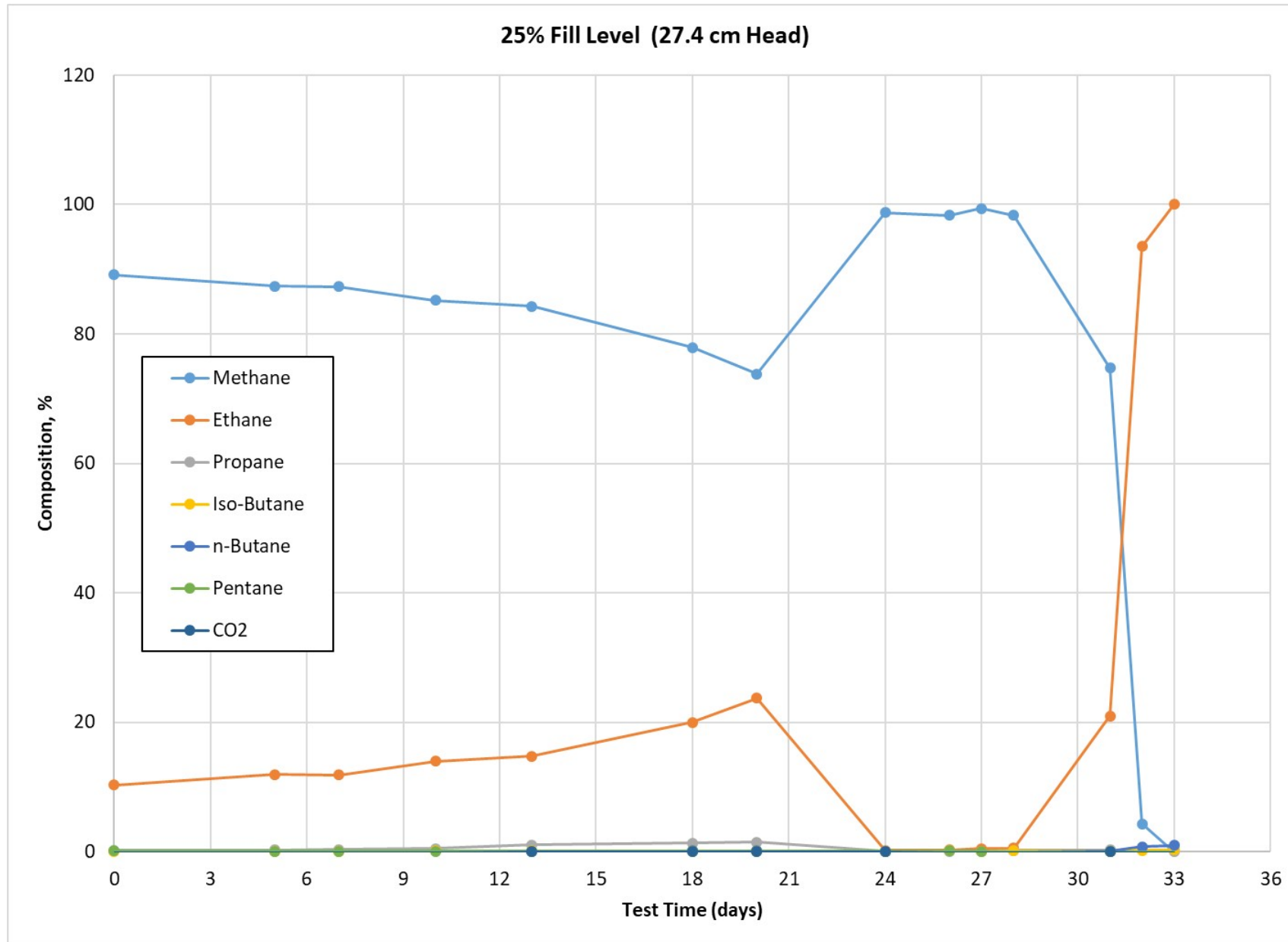Ambient temperature: 24.3 deg C

Test Data—LN2 Boiloff
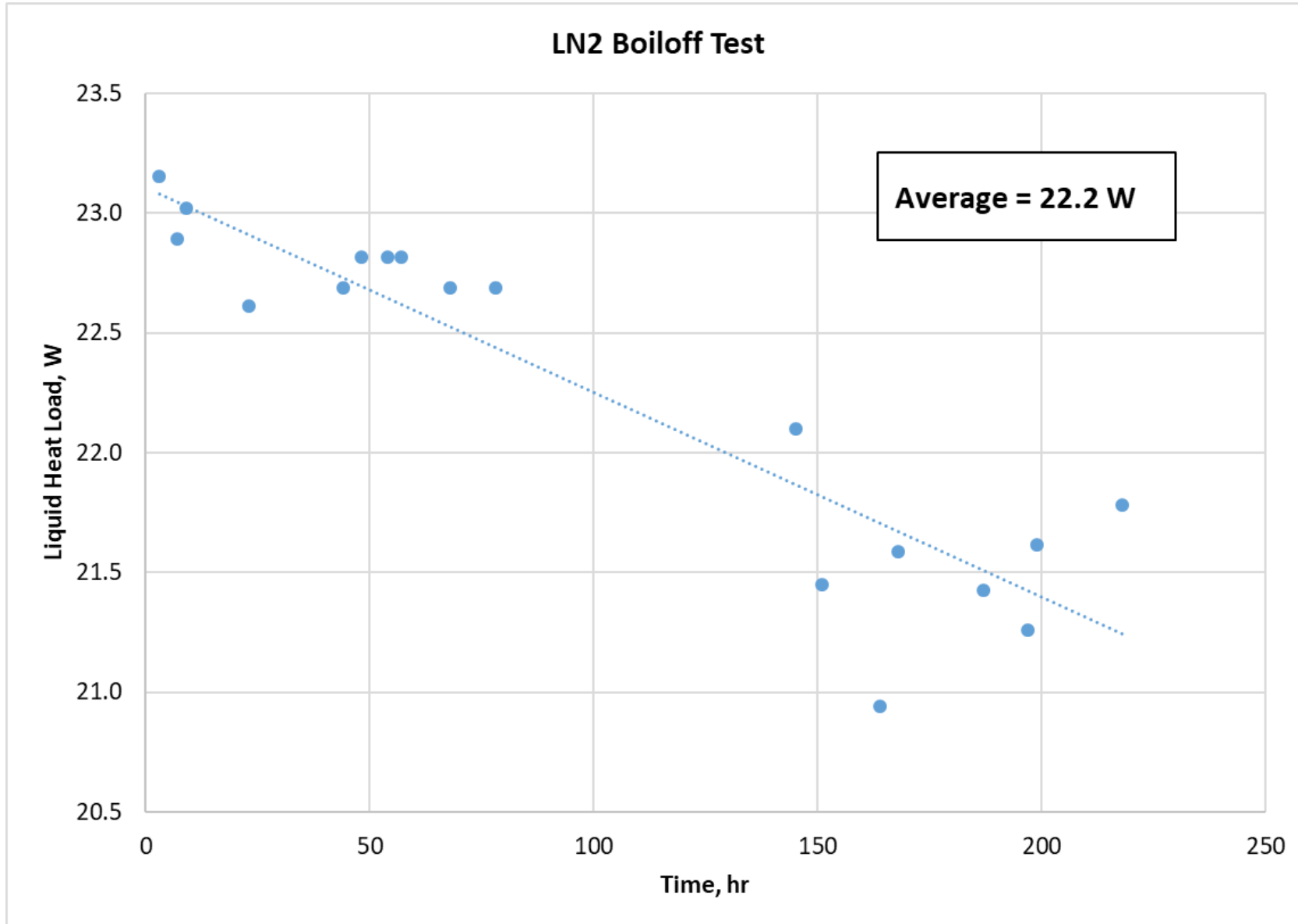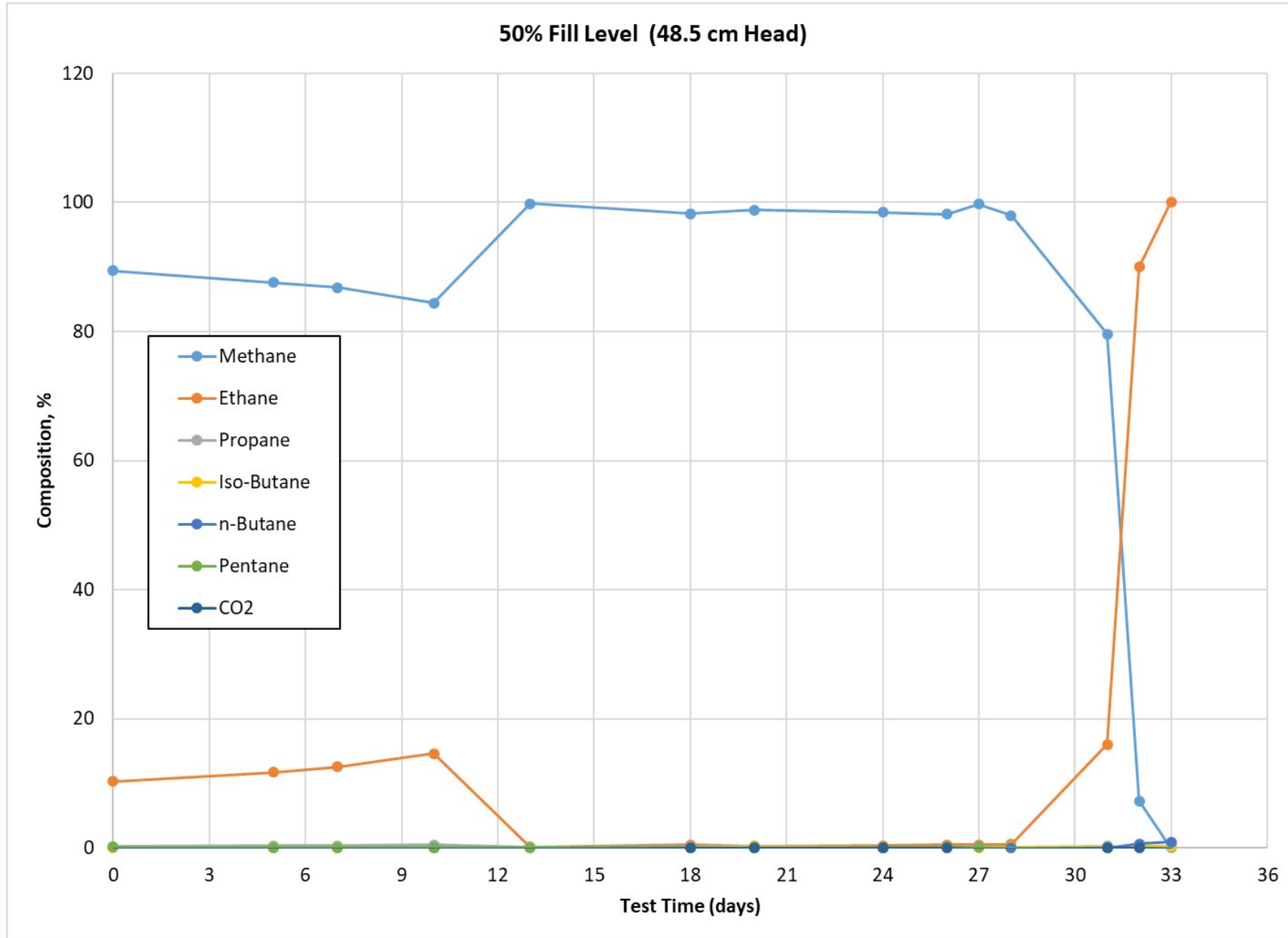
Test Data—Weathering, Vent Gas Composition

Test Data—Weathering, Liquid Composition

0% fill level (6.4 cm Head)

Test Data—Weathering

Test Data—Weathering

50% Fill Level (48.5 cm Head)

Test Data—Weathering

75% Fill Level (69.6 cm Head)
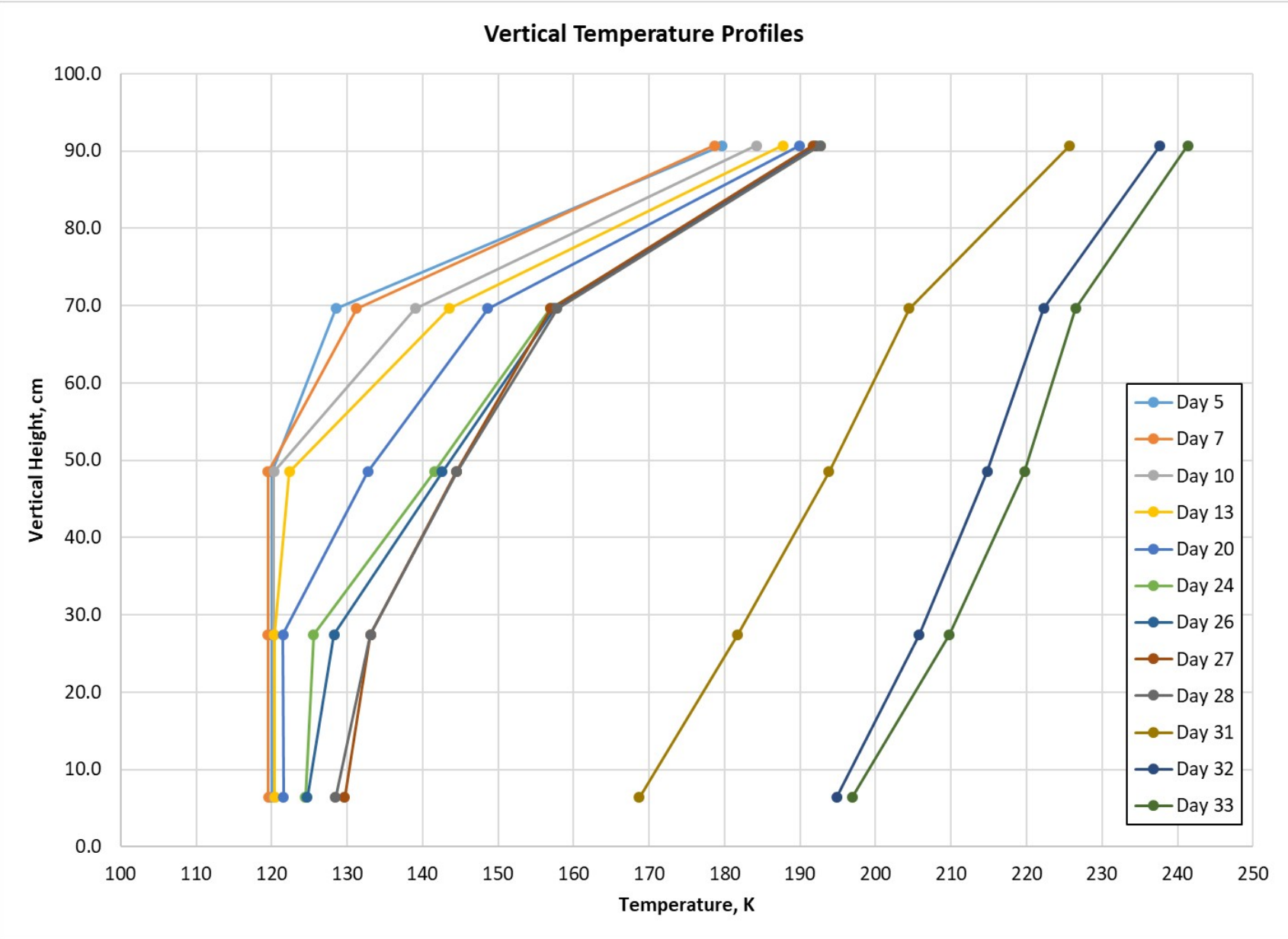
Test Data—Weathering

Test Data—Weathering

Methane & Ethane Comparison
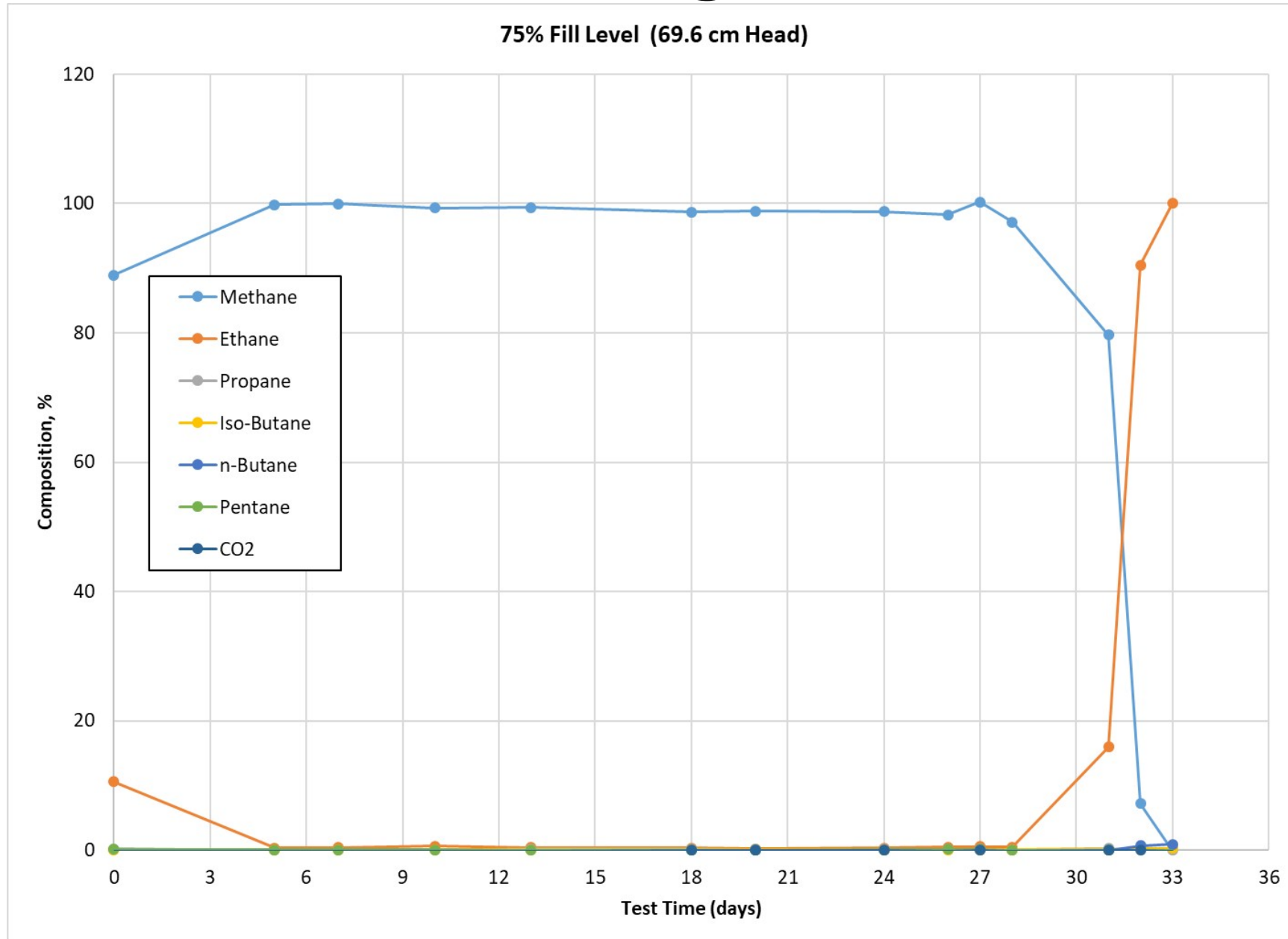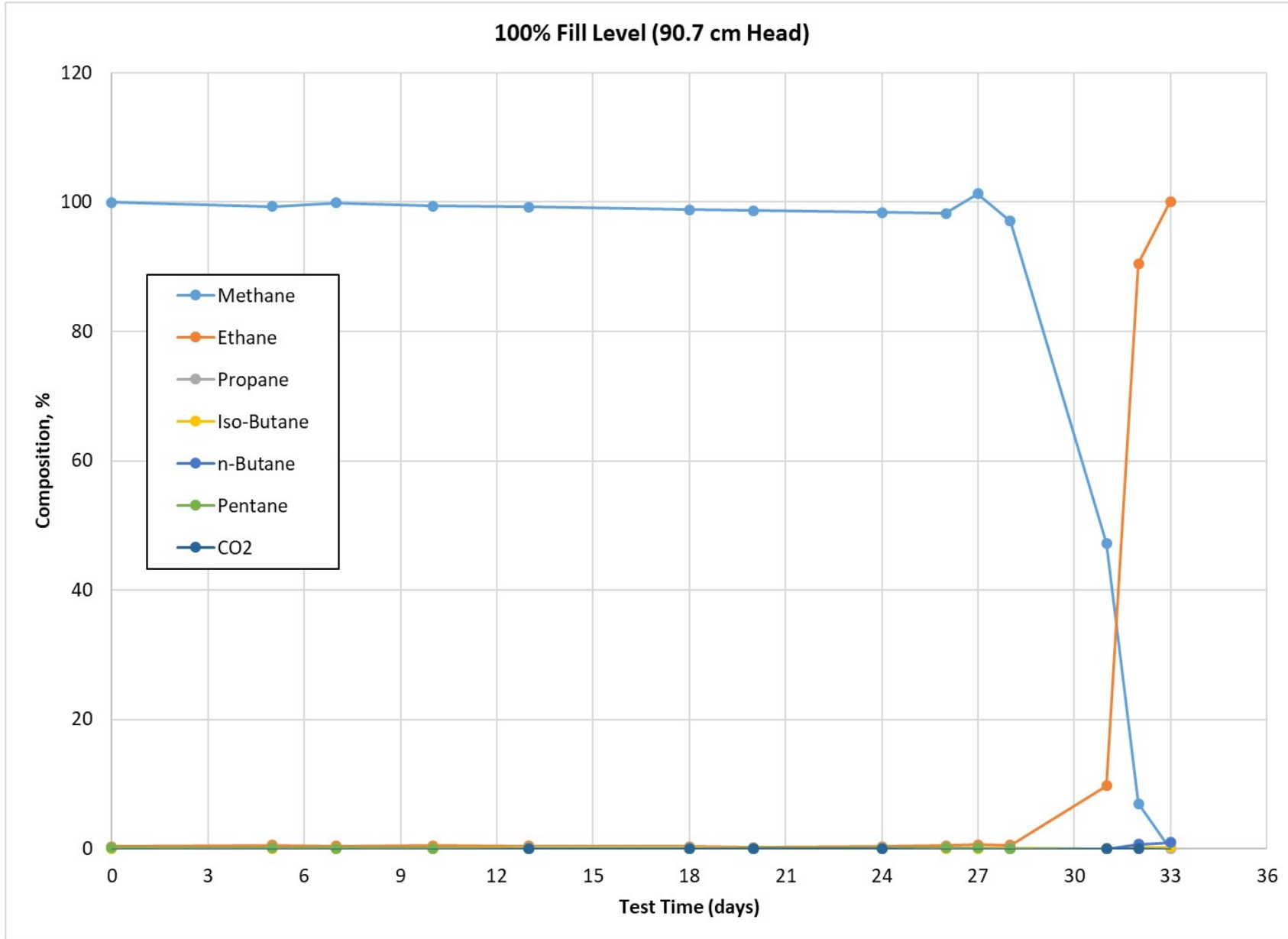
Test Data—Thermal Stratification

Test Data—LNG Composition Report from Vendor

PMS=Scenario 4 | PMS Ready ○   **RAMAN GAS ANALYZER**

| Report	Truck Loading ONLINE 10 / 22 / 2019 17:47:22		Report	LNG Into Tank ONLINE 10 / 22 / 2019 17:45:11		Report	LNG Out of Tank BUSY 10 / 22 / 2019 17:43:0	
Methane:	96.480		Methane:	96.528		Methane:	96.278	
Ethane:	3.109		Ethane:	2.745		Ethane:	3.275	
Propane:	0.167		Propane:	0.154		Propane:	0.174	
Isobutane:	0.020		Isobutane:	0.034		Isobutane:	0.029	
Butane:	0.013		Butane:	0.019		Butane:	0.016	
Isopentane.	0.000		Isopentane	0.000		Isopentane	0.000	
Pentane:	0.003		Pentane:	0.000		Pentane:	0.019	
Neopentane:	0.000		Neopentane:	0.000		Neopentane:	0.000	
Nitrogen:	0.194		Nitrogen:	0.517		Nitrogen:	0.210	
Oxygen:	0.014		Oxygen:	0.004		Oxygen:	0.000	
Carbon Dioxide	0.000		Carbon Dioxide	0.039		Carbon Dioxide	0.000	
Ideal BTU Dry:	1035		Ideal BTU Dry:	1037		Ideal BTU Dry:	1037	
Real BTU Dry:	1037		Real BTU Dry:	1031		Real BTU Dry:	1039	
Specific Gravity:	0.572		Specific Gravity:	0.572		Specific Gravity:	0.573	
Wobbe Index:	1368		Wobbe Index:	1361		Wobbe Index:	1369	

Analysis—Density Variation

- Density determined via REFPROP Version 10 using a mass-based mixture of constituents, with percentages from measured values during testing

- Liquid density is of a saturated liquid mixture at the test pressure

- Vapor density is taken to be the mixture at the 100% fill level (90.7 cm elevation), with an average temperature between the lower- and upper-most sensors.


Liquid and Vapor Density Changes
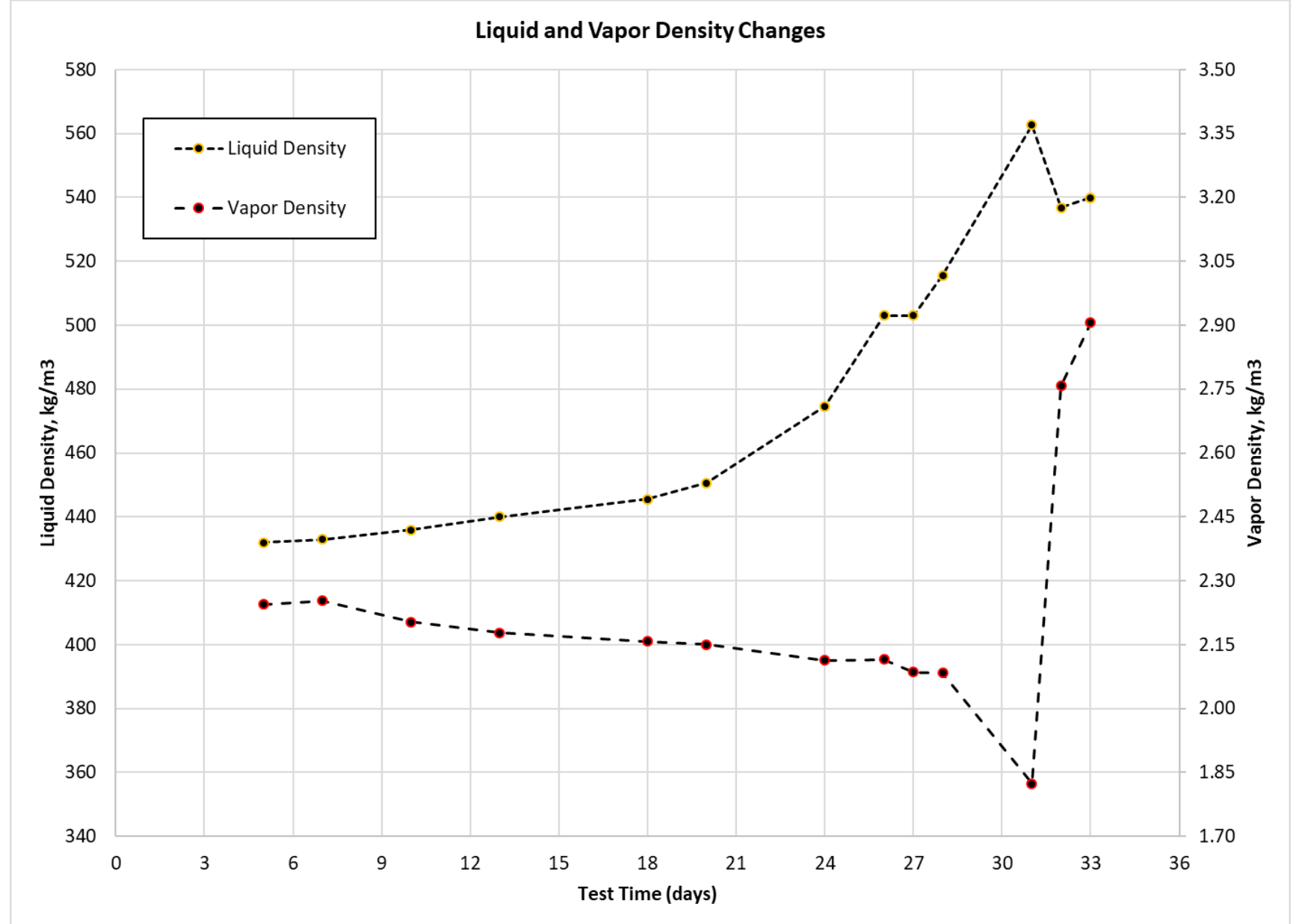
Analysis—Heating Value Variation

- Heating values determined via REFPROP Version 10 using a mass-based mixture of constituents, with percentages from measured values during testing

- Liquid volume basis values calculated by multiplying the HHV or LHV by the saturated liquid density at the test pressure.

Analysis—Methane Loss

Methane Loss (% lost per day, per Watt of heat load on the liquid)
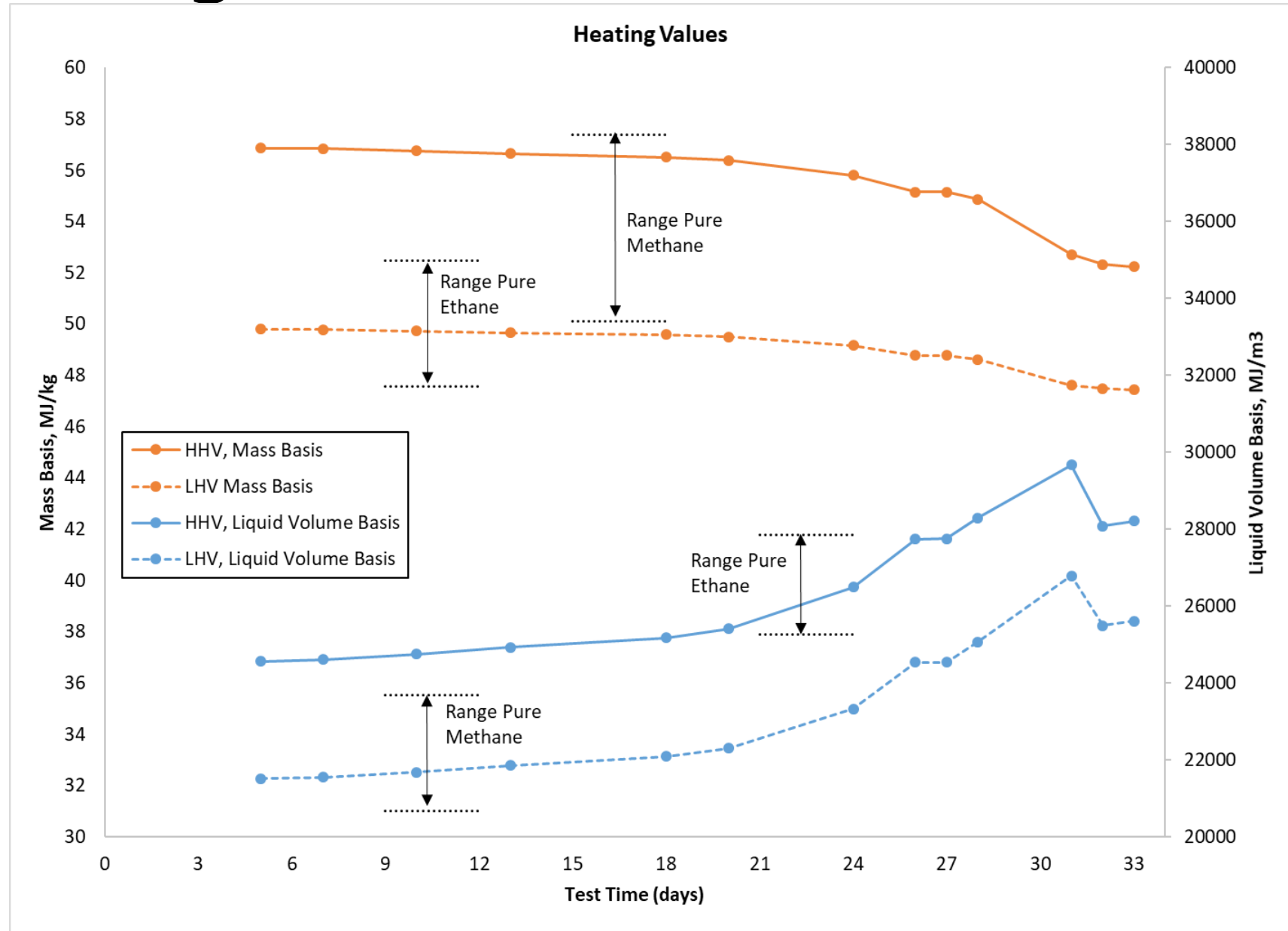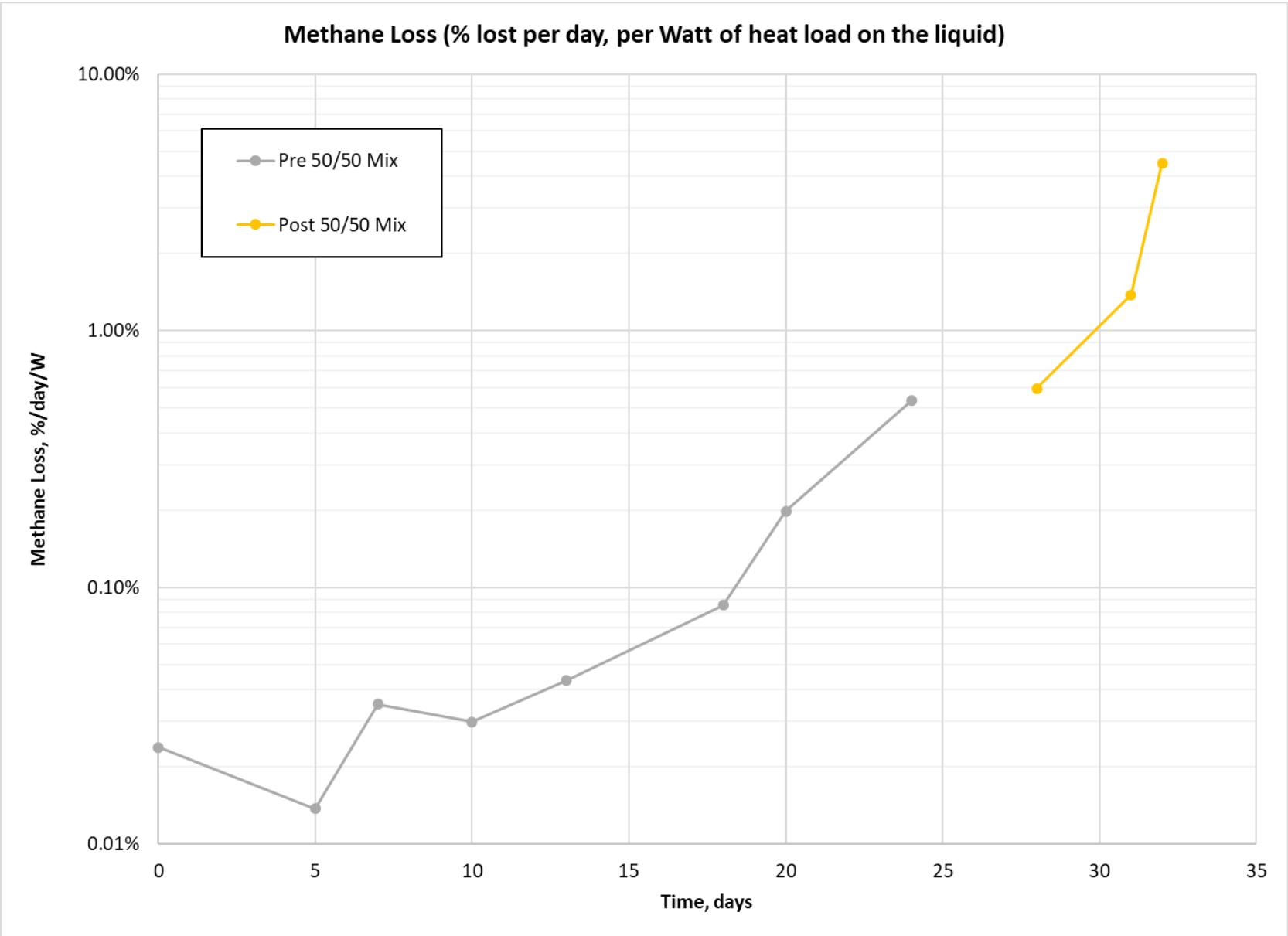
Existing Publications/Presentations

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