Evolvable Cryogenics (eCryo) Project Technology Workshop with Industry

Engineering Development Unit (EDU) Workshop

Mass Gauging Test Results

Greg Zimmerli
Mass Gauging

Mass gauging sensors on the EDU

- DT-670 diode temperature/wet-dry rake
- RF Mass Gauge
- Reduced Gravity CryoTracker (Sierra Lobo)
- Capacitance Probe (American Magnetics)

LH2 Test Objectives met or addressed:

- Ground loading: Mass gauging checkouts & heat load measurement
- Gather data for model validation

LH2 Test Success Criteria met or addressed:

- Load the EDU to 90% full with Liquid Hydrogen
- Conduct mass gauging measurements with RFMG and compare to liquid level information provided by temperature rake
- Measure EDU Boil off for simulated on-orbit heat load
- Data collection from above objectives
- Gauging data was also critical for LAD outflow testing
EDU mass gauging probe

- Al T-bar support structure
- Reduced Gravity CryoTracker
- Capacitance probe

Not shown: RFMG antennas, diode rake
Mass Gauging

Not to Scale

Top View

- DT-670-SD
- G10 Perf Board
- RFMG Antenna @ 50% Fill level
- Diode mounting pin slot
- Cap Probe
- Diode mounting pin
- RFMG Antenna @ 25% Fill level
- Cryo-Tracker
- 3/8” stand off for Cryo-Tracker
Temperature rake (wet-dry sensors) and cap probe data is stored with facility CSV data files.

- RFMG and CryoTracker data were both stored on separate systems.
- RFMG and CryoTracker clocks were synchronized to the facility data computer clock to within a few seconds.

NOTE: The diode tank station values are from the EDU CAD model, not the as-built configuration.
Mass Gauging

Photos of the mass gauging sensors, mounted to aluminum T-bar
The wet-dry rake diodes are mounted above the perf board.

Silicon diodes at 5% location
Mass Gauging

- Reduced Gravity CryoTracker (RGCT) probe; contains 8 sensors mounted on backside of T-bar

- RF Mass Gauge antennas mounted on edges of T-bar, about 20 inches apart

- All mass gauging sensors are attached to the T-bar assembly
Silicon diodes are run “hot” (30 mA) when in wet-dry mode.

- The T reading during wet-dry mode is obviously not accurate. It is based on an DT-670 voltage vs T table (valid for 10 μA) extrapolated to negative temperatures.

- Different offsets in the transition value are due to lead resistance.

- This did not affect the analysis, which was done manually.
To analyze the wet-dry sensor data, CSV data files were used to find the transition times from dry-to-wet, and wet-to-dry. Winplot was used to visually narrow the search.

The data were recorded in an Excel spreadsheet.

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- The T rake was periodically set to wet-dry mode during quiescent conditions, and sometimes left in wet-dry mode continuously during fill/drain.
- 150 transition points have been identified
- The wet-dry sensor data are used as the reference gauging data
- The data are considered accurate to within ±1% of full-scale
Mass Gauging – Wet/dry rake

Wet-dry transition points during EDU LH2 testing:

Discrete wet-dry data points are augmented by the continuous cap-probe data
Capacitance probe:

- American Magnetics, Model 185 controller
- Output was zeroed at LN2 temperature, He gas
- Output was calibrated to “100%” at two different fill levels:
  - An initial cal to “100%” was done with a partially filled tank
  - Wet-dry/RFMG data was used to find the cal-point, which was at 83% fill
- Cap probe output saturates at 100% reading at 163/17:39
- Actual fill level is 83%
- Reported cal fill level was 77% (not consistent with the data)
Cap probe 100% value was re-calibrated on June 20, around 2:17 pm
   - Fill level was between 90%-91%

For a good approximation to the actual %volume fill level, the cap probe data should be multiplied by:
   - 0.83 for times before June 20, 2:17 pm (only good up to 83% fill)
   - 0.90 for times after June 20, 2:17 pm

Note that the cap probe is a level sensor, and there is some error when converting % -level to % -volume. For EDU this is only important at fill levels below ~40%.

A model of the cap probe and tank was used to refine the cap probe data
   - The correction is only significant below 30%
Refined cap probe output model

\[ h_{\text{liq}} = h_0 + (h_{100} - h_0) \times \text{Cap\%} \]

\[ \%\text{-Volume} = f(h_{\text{liq}}) \]

7 inches

- COMSOL RF tank model was used to convert liquid height to \%Vol
Actual value of $h_0$ is 7 inches. Using 10 inches provides an additional offset that provides better agreement, especially below 40% fill during final drain.
Mass Gauging – Capacitance probe

Cap probe correlation with wet-dry data

Detail during LAD testing

% fill

- \( h_0 = 7 \)
- \( h_0 = 10 \)
- wet/dry

time
Comparison of adjusted cap-probe data ($h_0 = 10''$) with wet-dry rake

Mean difference: -0.3%
STDEV = 1.3%
RFMG: Principle of operation

• Metal tank has natural RF modes
  \[ f \sim \frac{c}{L} \]

• RF network analyzer measures the tank spectrum (< 1 mW RF power)

• RFMG software finds the peaks, compares the frequencies to a database of simulations, and returns the best match %fill-level information

• Gauging operation takes 1 - 10 s, depending on number of frequency points (4k – 40k)

• The tank RF spectrum changes with fill level, since the dielectric fluid slows the speed of light

• The basis of the RFMG is that these changes can be accurately predicted
COMSOL – RF Module was used to calculate the tank mode frequencies

Model includes: 3 LAD arms, LAD crossover TVS tube, top diffuser, bottom diffuser, axial jet nozzle, mass gauging T-bar, horizontal ullage T rake
Computed RF modes for EDU tank

- 100 simulation files – 1% resolution
- Specified dielectric constant for liquid and vapor phases in the model

5 modes used for gauging
Plot of RFMG raw data from June 24/03:41:51

The RFMG software finds the frequencies of these peaks, compares it to the database of 5 modes, and returns a % fill level.
RFMG data

- Typically collected RFMG data once every 15 minutes during boil-off tests
  - Once every 10-20 seconds during fill/drain
- 12,900 files were collected, zipped, and sent to GRC

- Bad connection somewhere along Antenna 2 line before start of test. Signal came back during fill.

- A couple re-boots of the ZVL network analyzer were required during testing

- RFMG software initially set to use 3 measured modes
  - This led to poor results around 38% fill level, and several % discrepancy with wet-dry data near 90% fill
  - June 26: Updated software to use 5 measured modes, and updated the mode calibration factors
  - The 6/12 – 6/26 data reported here has been re-processed using the June 26 software update
Comparison of RFMG result with wet-dry data:

- No correction has been applied to convert wet-dry %-fill by volume to %-fill by mass (small effect)
Mass Gauging – RF Mass Gauge

6/12/14 EDU initial fill detail

Detail of initial fill and 6/25 top-off

- RFMG
- Wet-dry rake

6/25 top-off detail

- RFMG
- Wet-dry rake
Excellent agreement between RFMG and wet-dry rake data
Comparison of RFMG output with wet-dry rake:

Mean difference: -0.6%
STDEV = 2.6%
Reduced Gravity CryoTracker probes:

- CryoTracker instrument was controlled via laptop in instrument area
- Control room “mass gauge” computer running Remote Desktop was used to control and monitor the instrument
- CryoTracker software was used to manually switch the probe between T mode and mass gauging mode
- Data was recorded once every 10 s
- Unresolved software bug: CryoTracker software had to be restarted many times throughout testing
Reduced Gravity CryoTracker

- Data is similar to wet-dry rake
- Wet-dry transition points were found manually
- 72 wet-dry transition points were identified

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Comparison of CryoTracker with cap probe and T rake: June 30

- Capacitance $h_0 = 10''$
- Temperature Rake
- Cryotracker
Comparison of CryoTracker with cap probe and T rake: July 1

A few points appear off by 2-3%
Comparison of RGCT output with cap-probe data:

Mean difference: -1.4%
STDEV = 2.2%
Mass Gauging – Comparison of all probes

Initial fill:

- RF Mass Gauge
- Capacitance Gauge
- Temperature Rake
- Cryotracker

% fill

06/12.5 to 6/13.0
Mass Gauging – Comparison of all probes

LAD outflow testing

- RF Mass Gauge
- Capacitance Gauge
- Temperature Rake
- Cryotracker
Conclusions:

- Very good correlation among mass gauging %-fill readings once corrections are made to cap probe data.
- Wet-dry diode rake provided benchmark data for other probes, with an output resolution of ~ 4%.
- Cap probe data using $h_0 = 10$ inches produces an excellent match with wet-dry data (mean difference = -0.3%, STDEV = 1.3%), continuous output resolution.
- Wet-dry/Cap probe data is regarded as accurate to within ±1%.
- RFMG data agrees well with wet-dry sensors, using 6/26 software update (mean difference = 0.6%, STDEV = 2.6%). Output was quasi-continuous, 1% resolution.
- CryoTracker data shows good agreement with wet-dry/cap probe data at the transition points (mean difference = -1.4%, STDEV = 2.2%). Eight sensors provided course gauging between 30% and 90% fill, 8% resolution.