2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review

Hydrogen Fueling Station Pre-Cooling Analysis

Amgad Elgowainy and Krishna Reddi

Argonne National Laboratory

June 9, 2016

Argonne NATIONAL LABORATORY

PD 107

Overview

Timeline

- Start: FY 2016
- End: Determined by DOE
- % complete (FY16): 60%

Barriers/Challenges

- Lack of hydrogen infrastructure options analysis
- Cost and efficiency of delivery components
- Lack of appropriate models and analytical capability
- Conduct unplanned studies and analyses

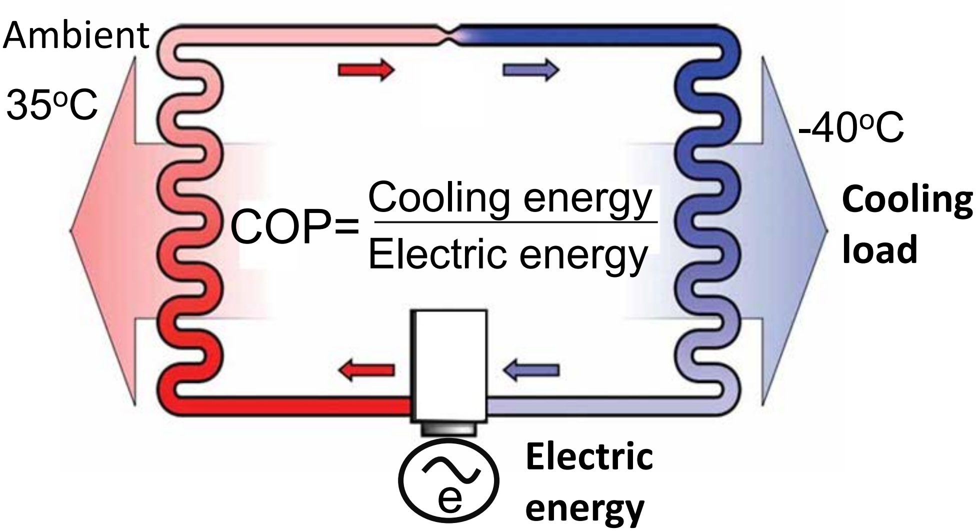
Budget

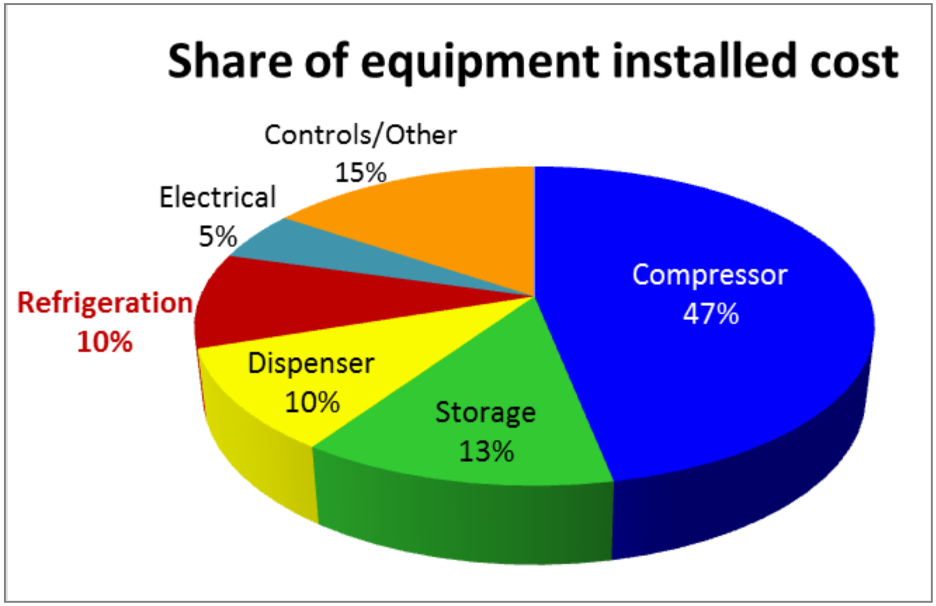
- FY15 Funding: $100K
- FY16 Funding: $100K
- 100% DOE funding

Partners/Collaborators

- NREL, PNNL
- Cal. State Univ. LA
- Boyd Hydrogen
- Honda R&D Americas, Inc.
- Hydrogen station operators

Precooling is a major contributor to refueling cost – *Relevance/Motivation*





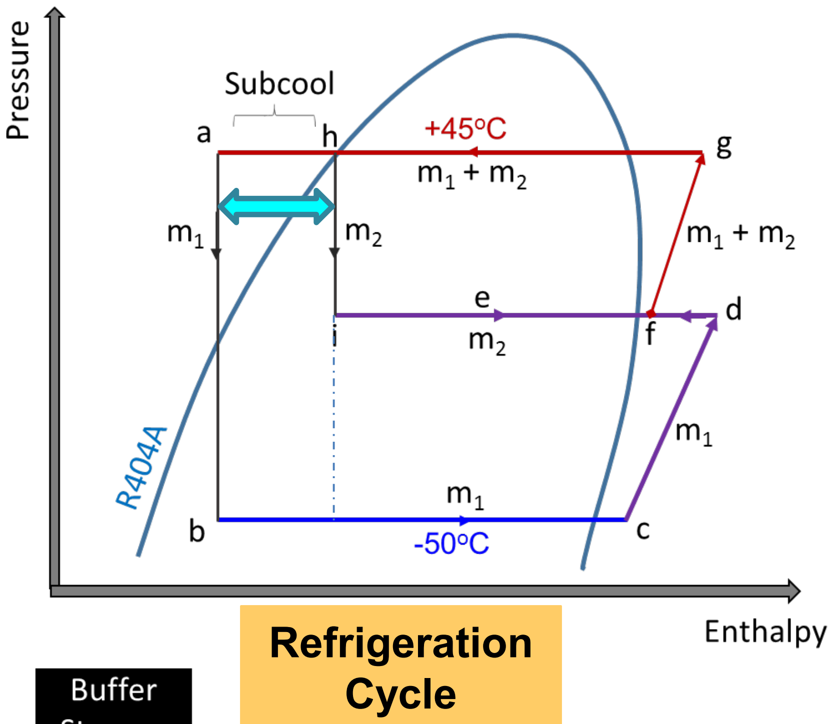
- Equipment cost of refrigeration unit plus heat exchanger (HX) is significant
  - \$100K - \$200K per hose
- Wide range of electric energy for cooling is reported
  - 0.5 – 50 kWh_e/kg_{H2}
- State of the technology is not well understood
  - Emerging system designs and different implementation practices
  - Challenges with meeting sequential back-to-back (BB) fills at HRS

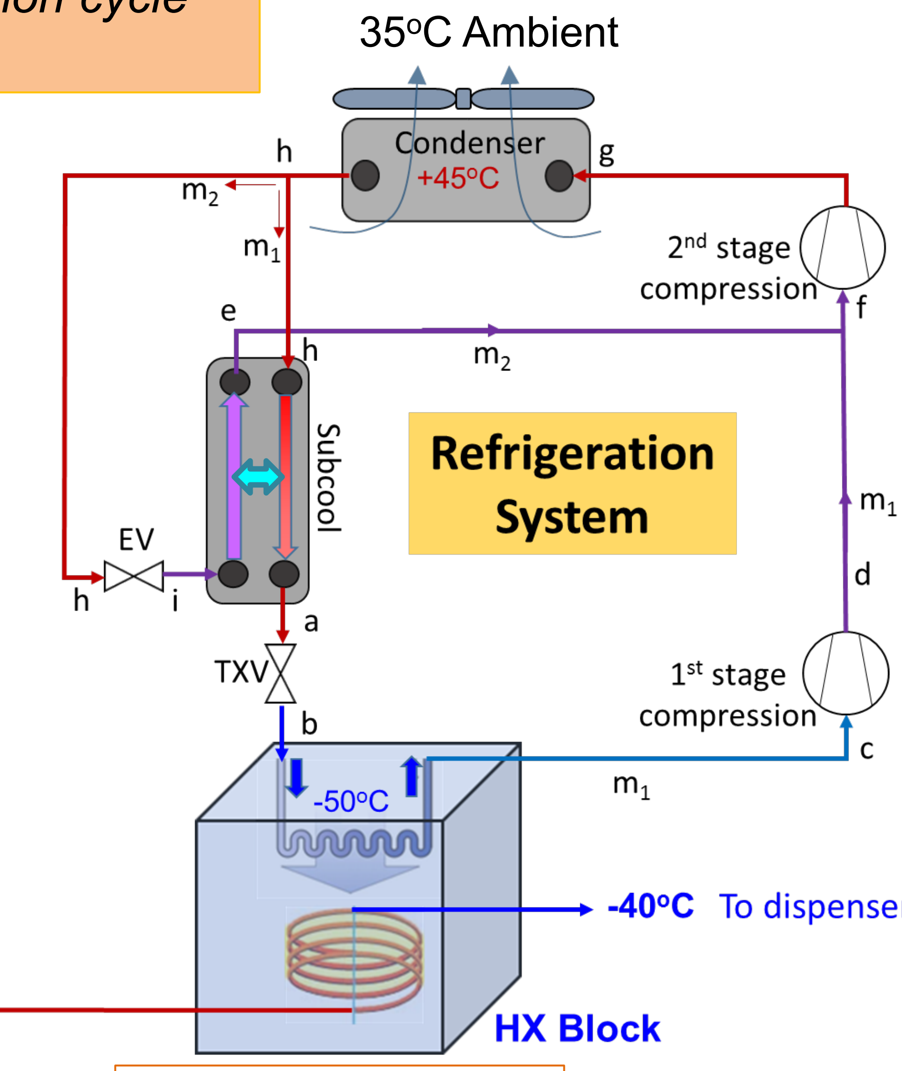
Identify major drivers for precooling capacity/cost and performance – Approach

- **Collaborate** to acquire information on cost and performance of various precooler design configurations
- **Evaluate** current precooling design concepts at hydrogen refueling stations (HRS)
  - Analyze trade-off between various design concepts
- **Identify** major drivers for precooling capacity/cost and performance
  - Impact of number of back-to-back (B2B) fills
  - Impact of J-T expansion on inlet temperature to HX
- **Develop** precooling system optimization algorithm for various component costs and performance specifications (e.g., # of B2B fills)
- **Analyze** trade-off between different design concepts
- **Vet** analysis results and findings
  - Internally via partners
  - Externally, via collaborators, interaction with US DRIVE Tech Teams, and reaching out to experts from industry

Acquired information on a typical refrigeration system used in HRS – Approach

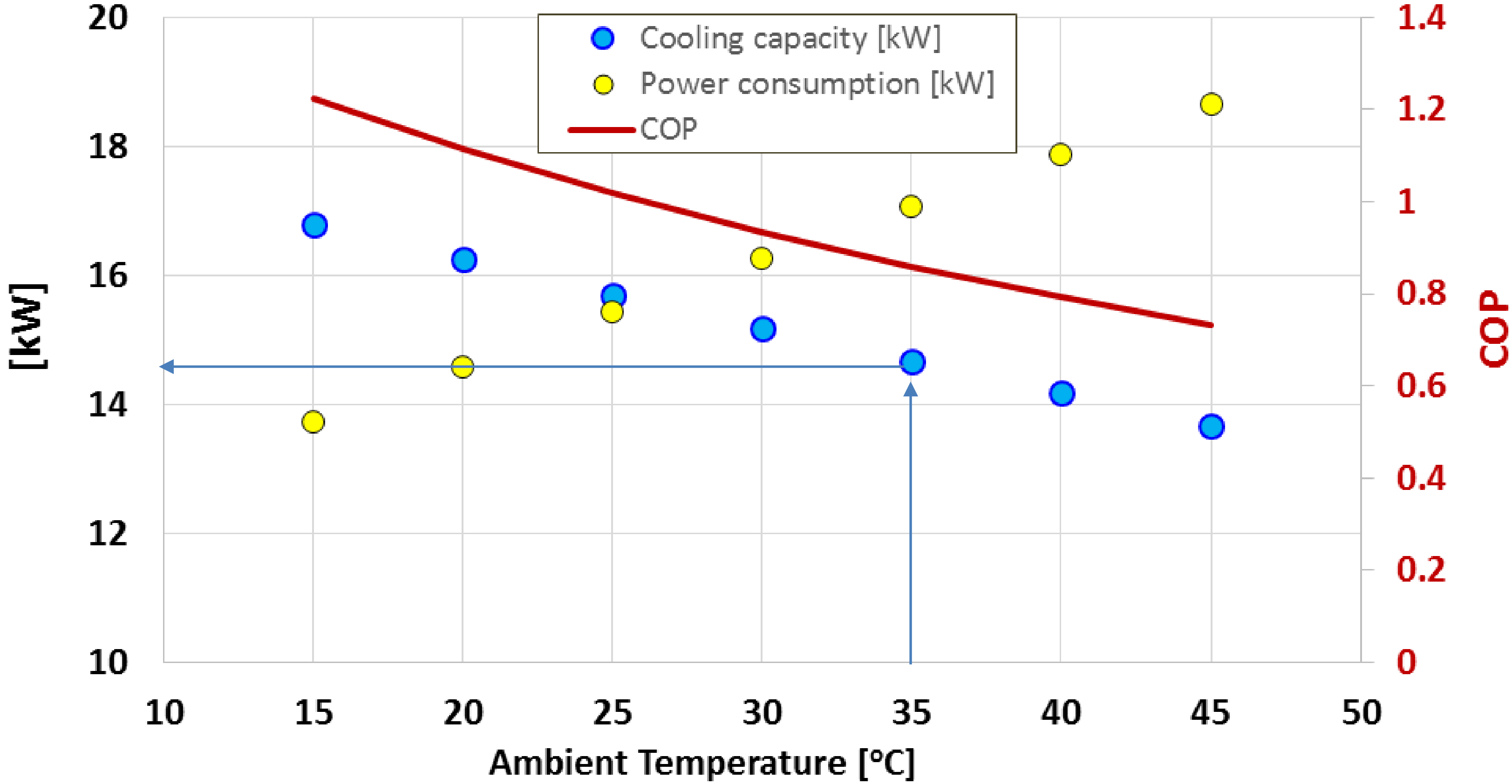
Low temperature (-40°C) precooling requires complex refrigeration cycle and system design





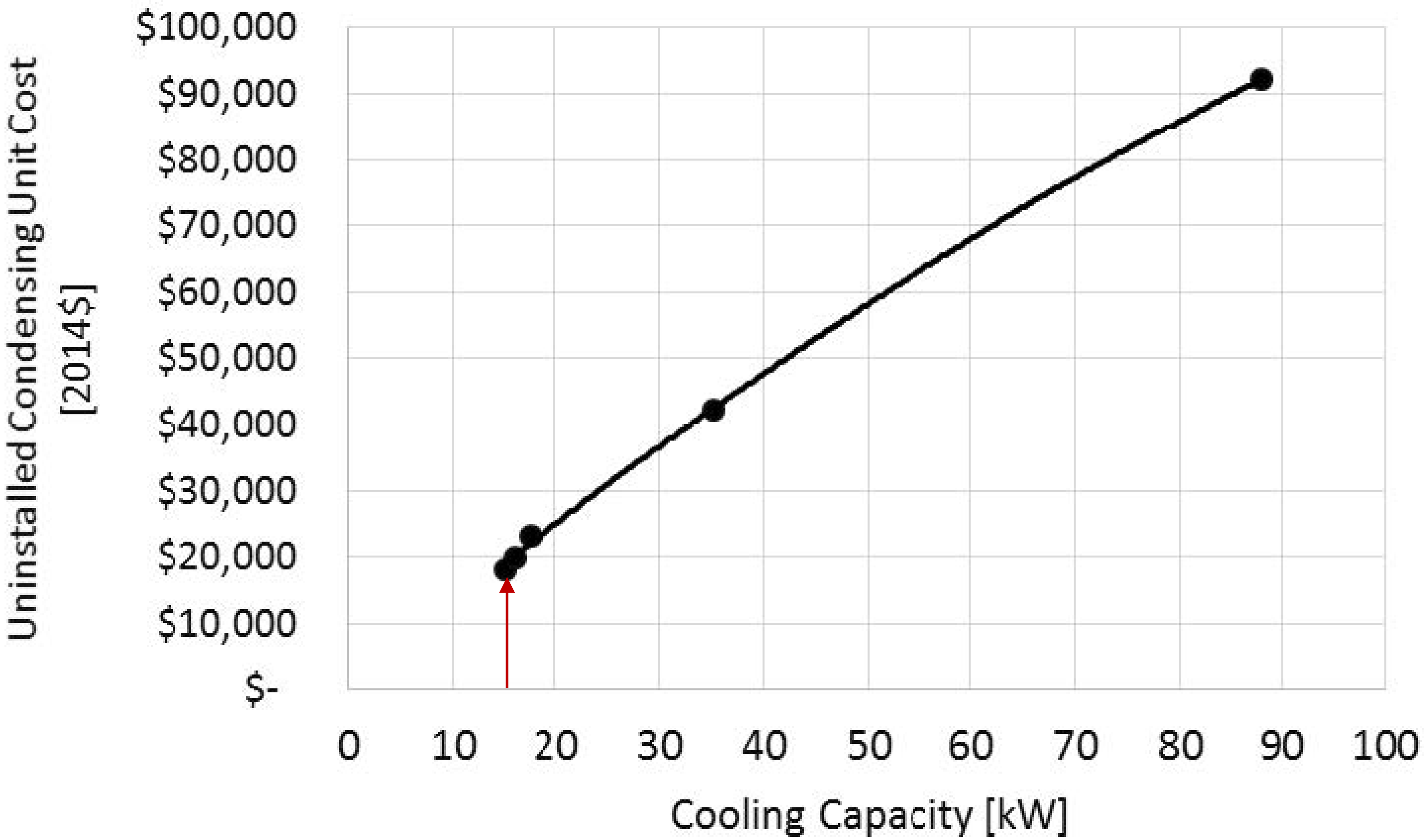
HX capacity = UA $\Delta T_{log\text{-}mean}$

Acquired performance data at different ambient temperatures for a typical HRS precooling system – Accomplishment



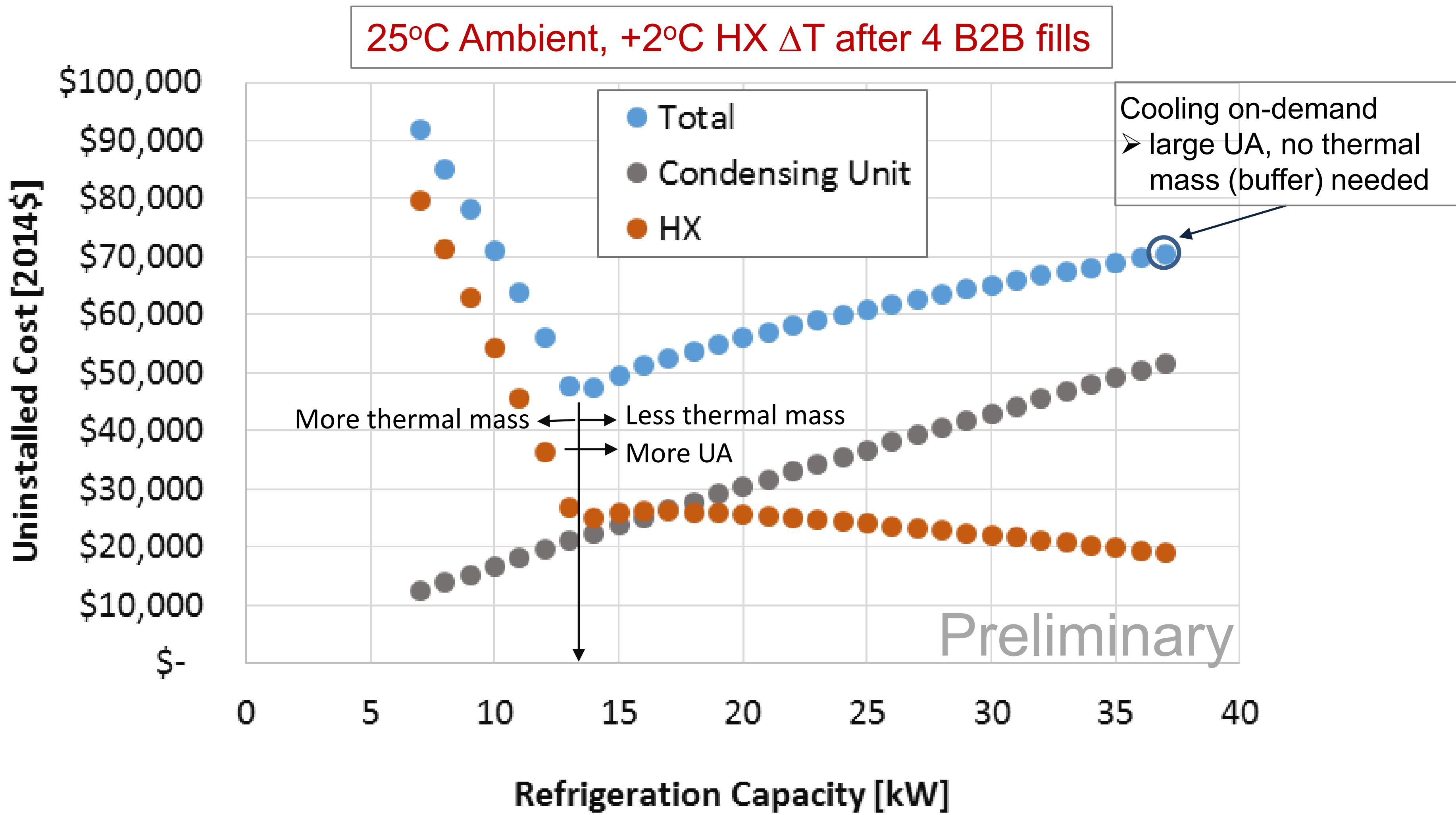
➢ **Strong impact of ambient temperature on precooler performance**

Updated precooler cost formula – Accomplishment



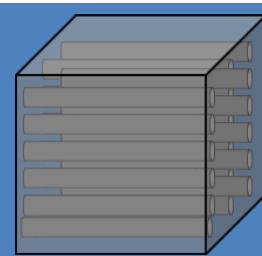
- $20K for 15 kW cooling capacity
- Installation factor = 2 : 2.3

Developed an algorithm to optimize size of precooling equipment and heat exchanger for lowest precooling cost – Accomplishment

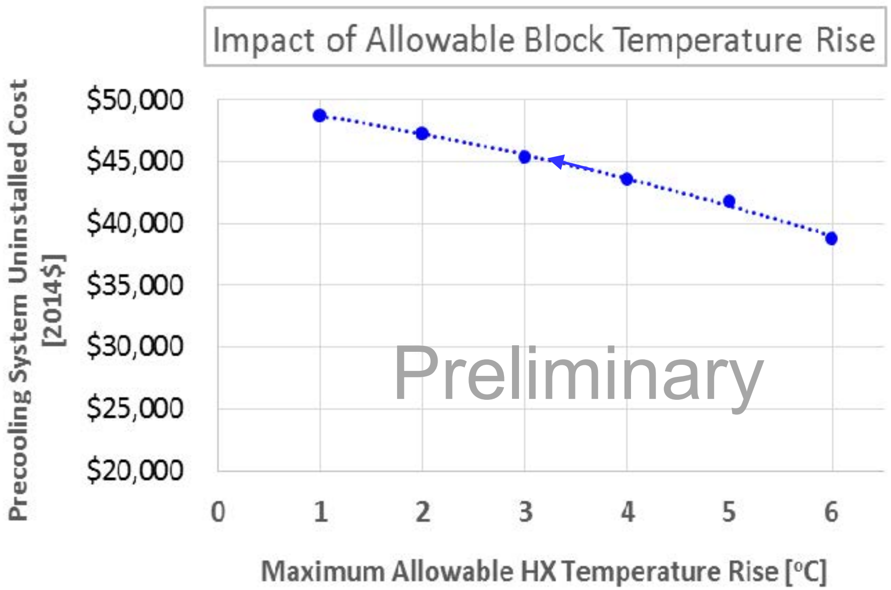


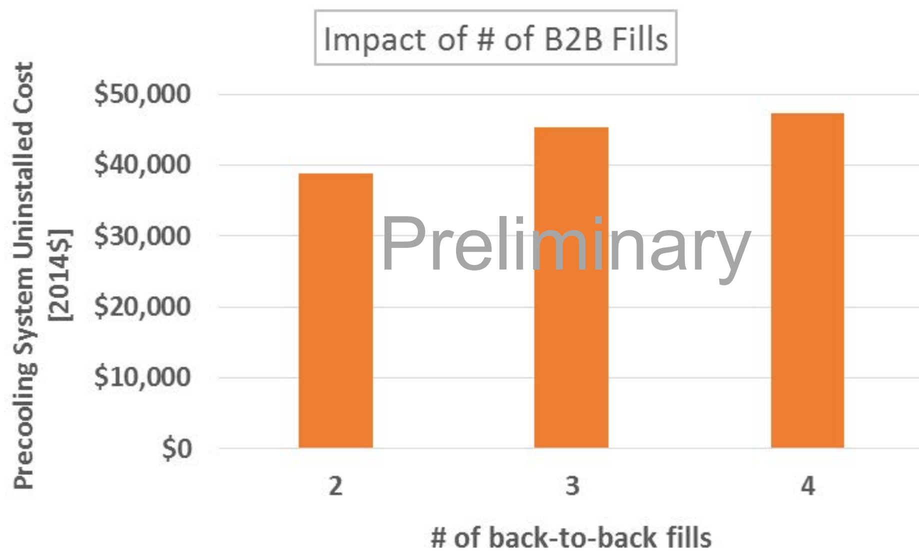
- ➢ Optimizing HX size for desired # of B2B fills can reduce refrigeration capacity requirement
- ➢ Sizing for cooling on-demand is more expensive option
  - ✓ especially if using compact HX for compact packaging

Trade-off between two different HX design concepts

	Large thermal mass HX (cooling block) 	**Compact, high UA, HX** 
Physical Size	Large mass and volume (typical block is ~1 ton, 27 ft^3)	Very small mass and volume (Very high H.T. area/volume ratio)
Cooling power	Relatively small power requirement	Relatively large power requirement
Sensitivity to ambient	System cooling capacity is less sensitive to ambient temperature	System cooling capacity is more sensitive to ambient temperature
Cooling energy overhead	Large cooling overhead (large thermal mass)	Small cooling overhead (very small thermal mass)
B2B Fill Capability	HX size increases with # of B2B fills	Virtually infinite
Packaging/ footprint	Large footprint	Small, can fit inside dispenser cabinet
Cost	- Purchase cost is low - Shipping and installation cost is high	- Purchase cost is high - Shipping and installation cost is low

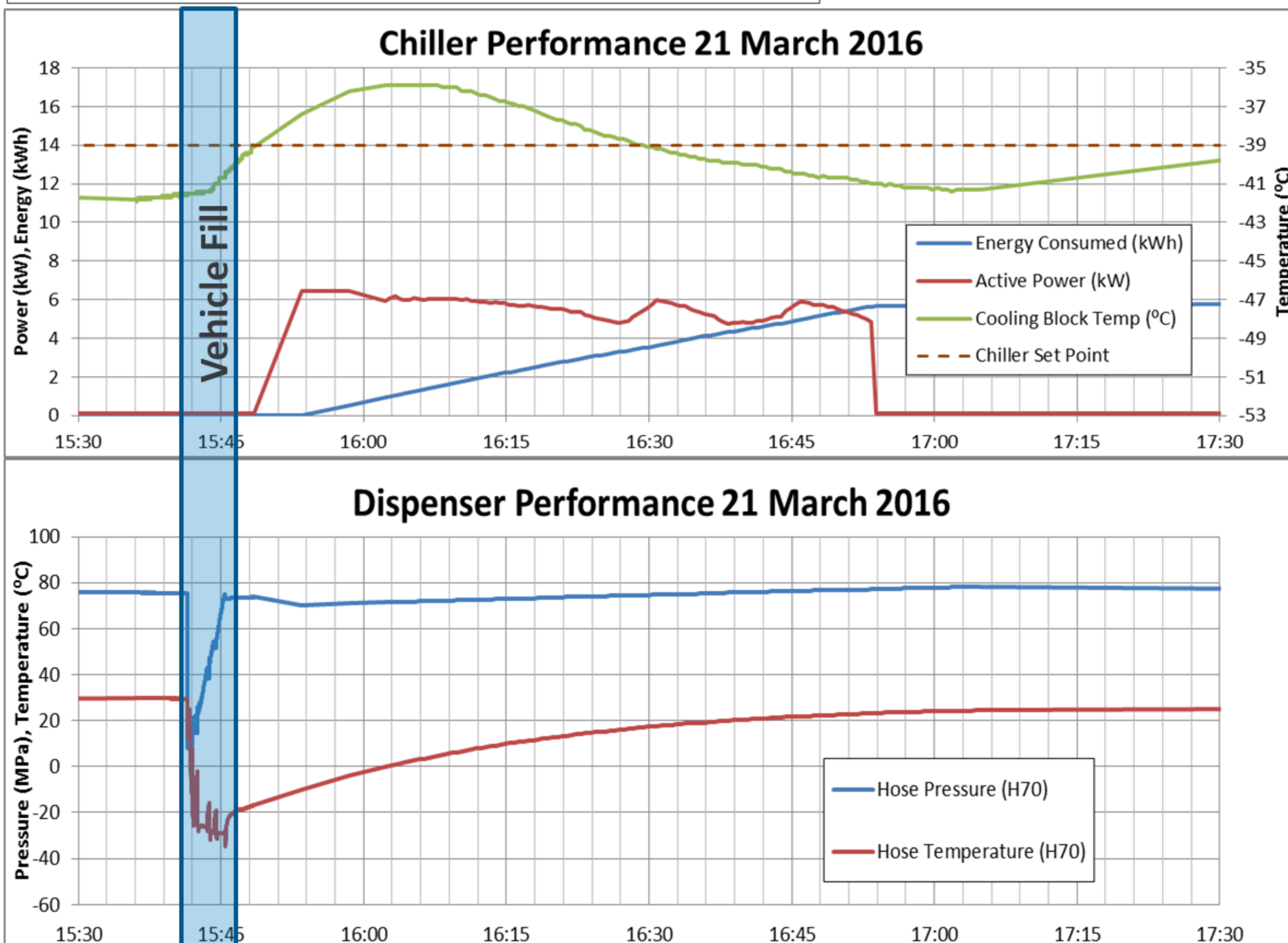
More stringent requirement on B2B fills or allowable block temperature rise increases precooling system capacity and cost – Accomplishment





Improper sizing of refrigeration system can jeopardize HRS ability to perform B2B fills

➢ With respect to # of B2B fill capability



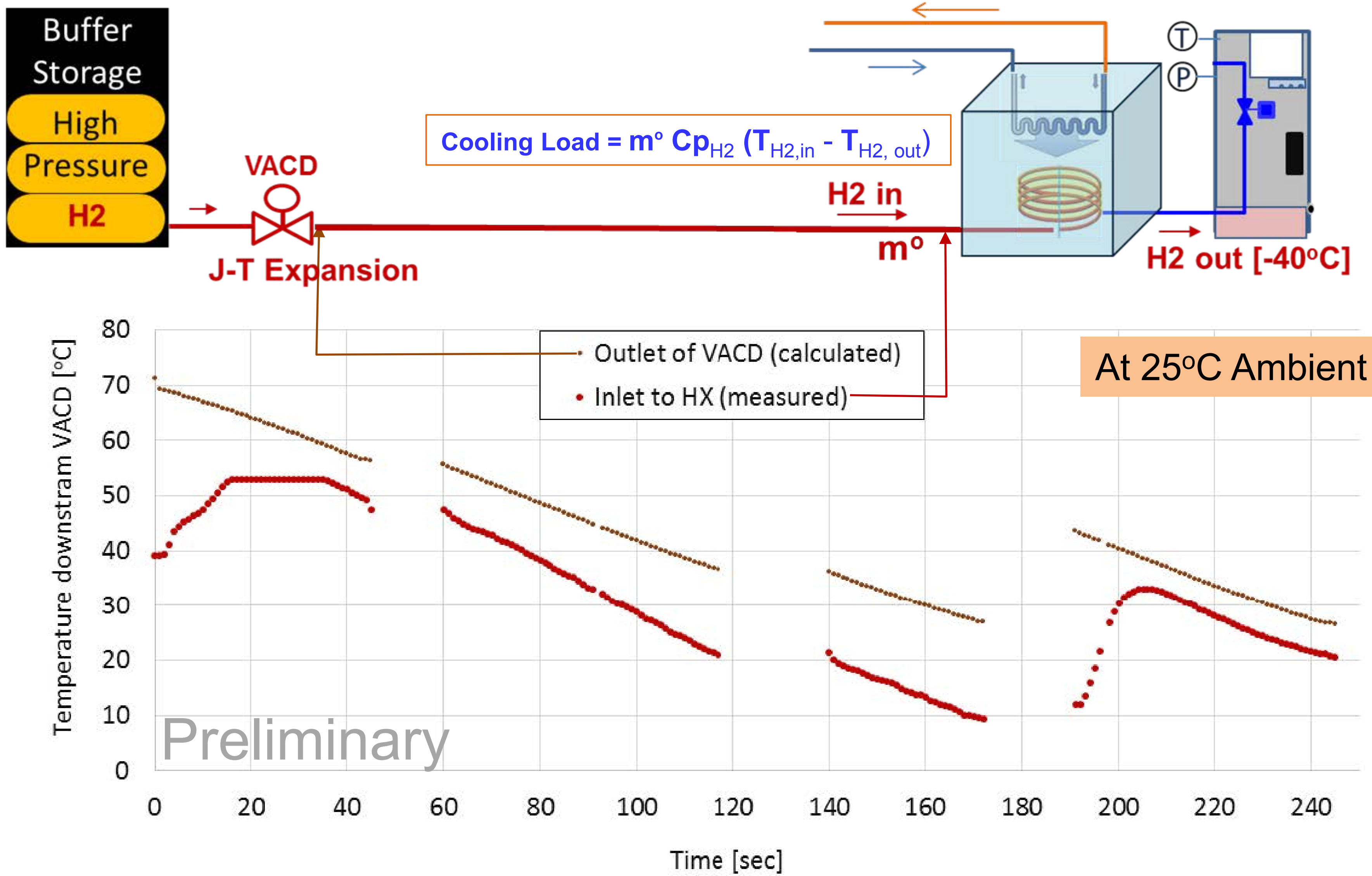
Full Recovery
5.9 kWh
58.9 min
6.46 kW_{max}

B2B Recovery
3.7 kWh
45 min
6.46 kW_{max}

Fill Data
4.36 kg
3.8 min
20 g/s_{avg}

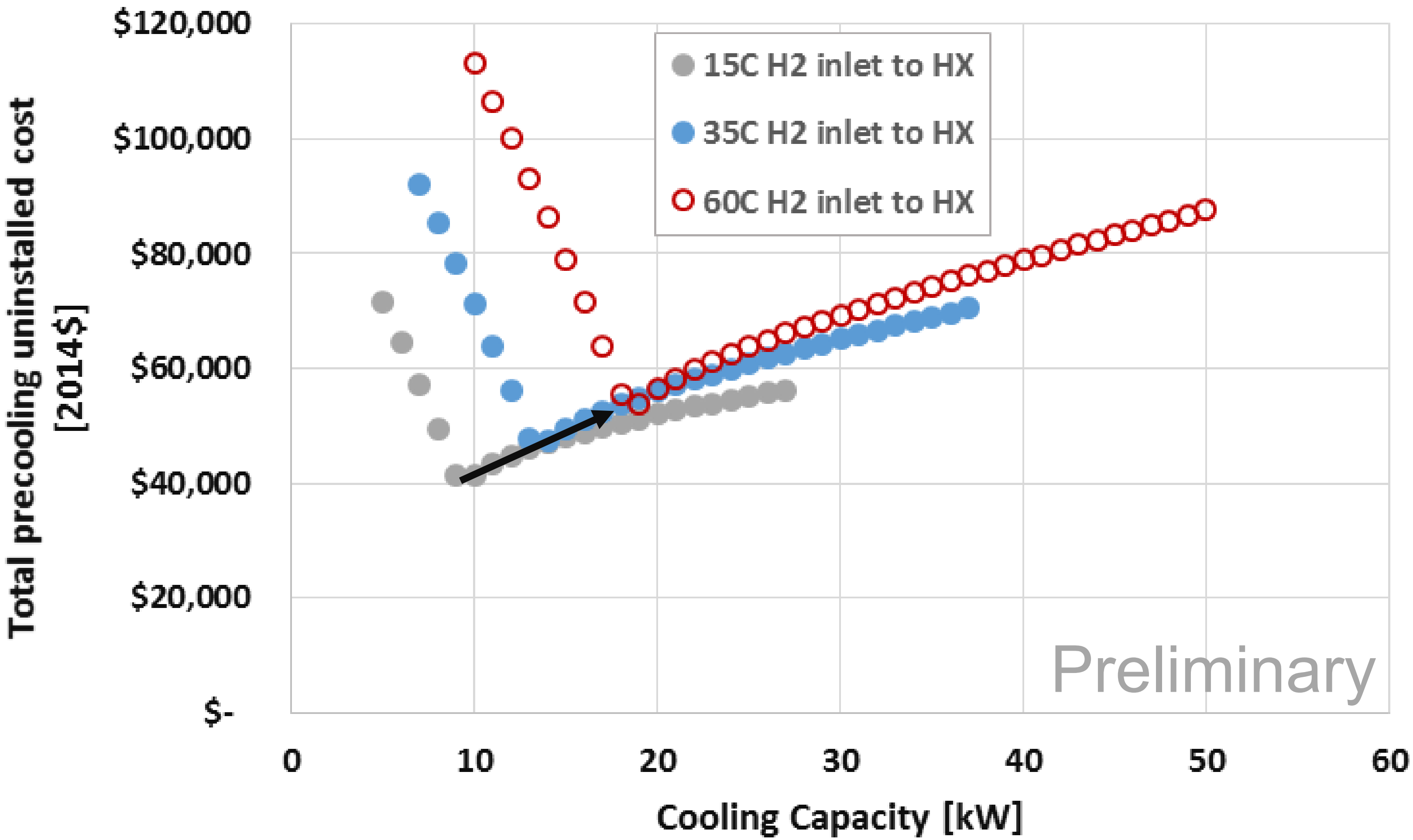
Credit: Danny Terlip, NREL

H_2 inlet temperature to HX and mass flow rate define cooling load and HX size



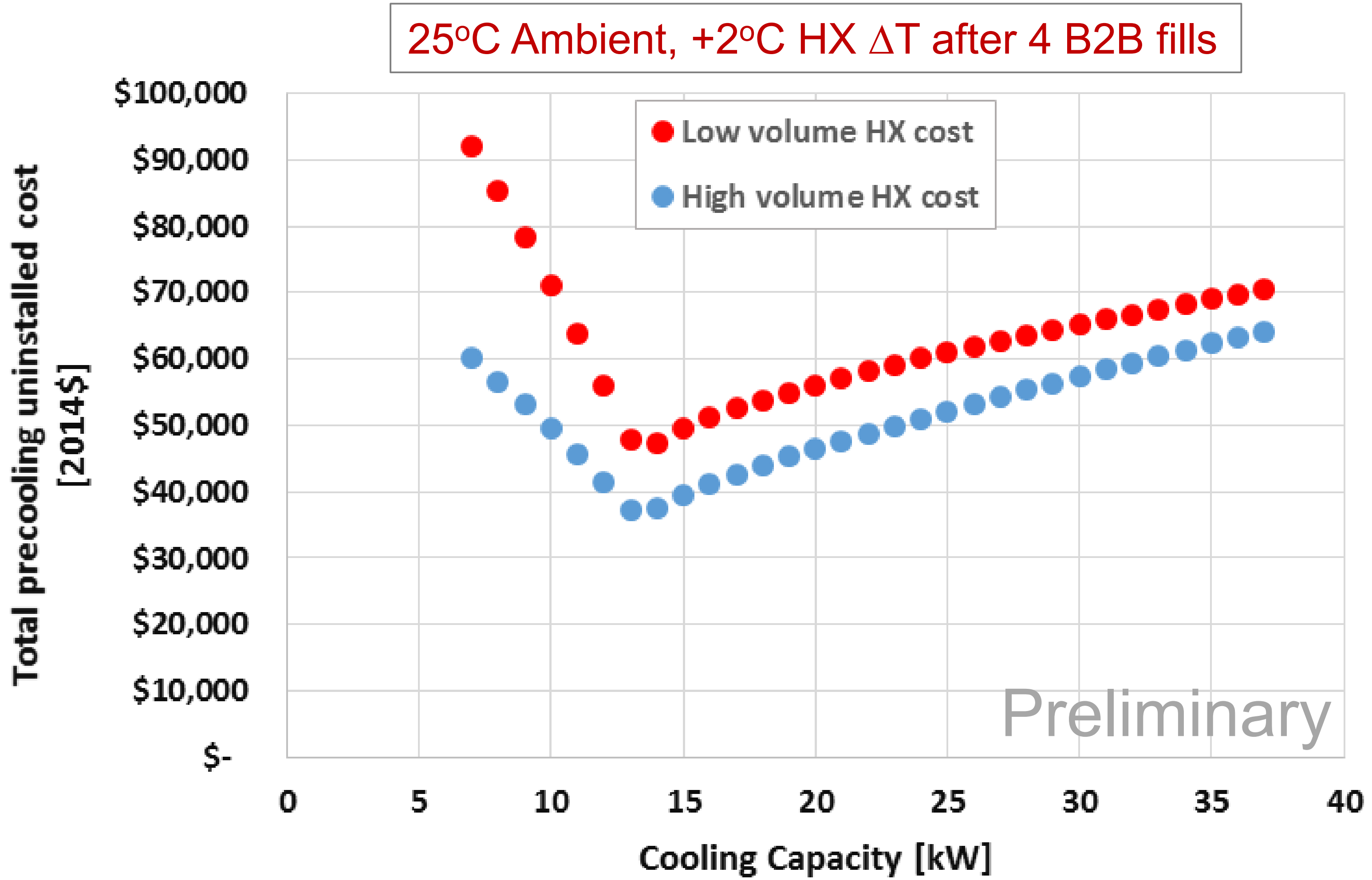
- Several HRS operators reported significant increase in heat exchanger temperature during initial period of fill

Temperature increase due to J-T expansion increases precooler system capacity and cost – Accomplishment



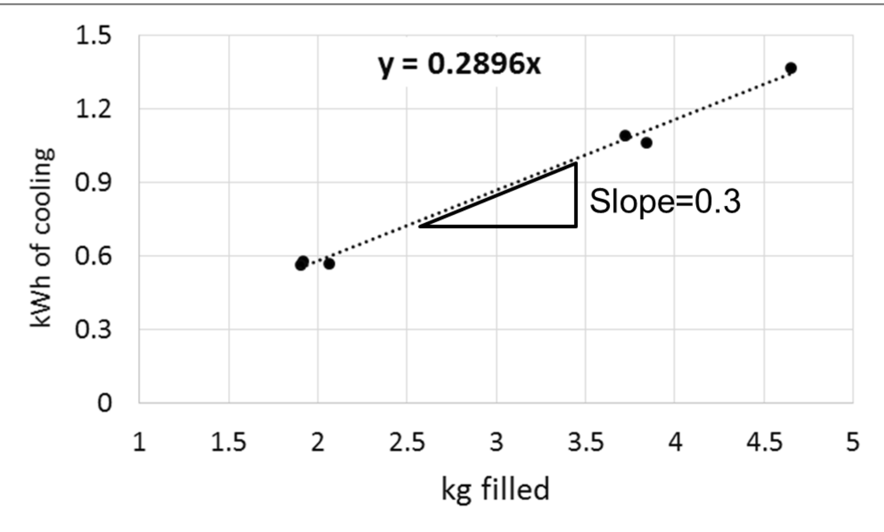
- J-T temperature increase must be mitigated before inlet to precooler HX
  - ✓ Locate VACD far upstream of HX to allow for thermal energy dissipation
  - ✓ Install low-cost ambient HX between VACD and precooler HX

Precooling system cost is estimated to drop by 25% with volume production of HX – Accomplishment



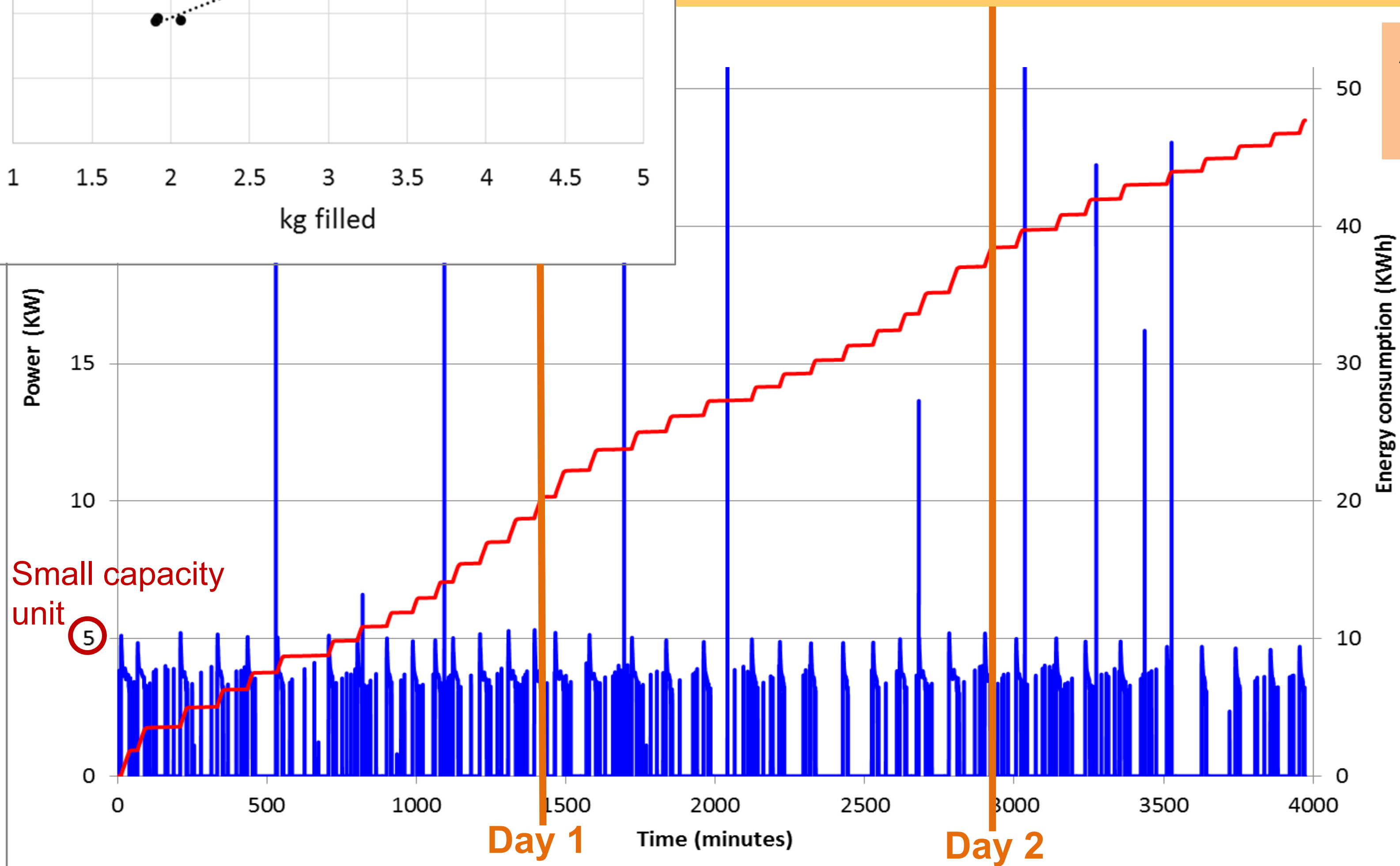
- Needed to estimate potential for cost reduction of current HX technology with mass production

Precooling energy per kg_{H2} for each fill is small ~0.3 kWh/kg_{H2} – Accomplishment



- At COP 0.8-1.0, precooling electric energy use during fill is 0.3-0.4 kWh_e/kg_{H2}
- Overhead cooling electric energy consumption to keep HX cold is in the range of 20-60 kWh_e/day

Ambient
Low: 10°C
High: 18°C



Summary – Progress and Accomplishment

- Examined current pre-cooling system design, operation, and performance at four different HRS
- Updated precooling system components costs
- Developed an algorithm to optimize size of precooling equipment and heat exchanger for lowest cost
  - Impact of number of back-to-back fills
  - Impact of J-T temperature rise across VACD
  - On-demand cooling (high UA) vs. large thermal mass HX
- Identified major factors impacting precooling system performance and cost
  - Optimizing HX size for desired # of B2B fills can reduce precooling system capacity and cost
  - Cooling on-demand is more expensive compared to buffering with large thermal mass HX
  - J-T temperature increase must be mitigated before inlet to precooler HX
    - ✓ Locate VACD far upstream of HX to allow for thermal energy dissipation
    - ✓ Install low-cost ambient HX between VACD and precooler HX
- Evaluated and compared calculated precooling energy use during each fill with field performance data (~0.3-0.4 kWh_e/kg_{H2})

Collaborations and Acknowledgments

Collaborators and Partners:

– PNNL: Daryl Brown provided cost of refrigeration and heat exchanger equipment

– NREL: Danny Terlip shared performance data on precooling equipment at NREL

– Cal. State Univ. LA: Prof. David Blekhman shared precooling performance data for T20 HRS

– Boyd Hydrogen: Bob Boyd provided specific cost and performance data on precooling equipment

– Honda R&D Americas, Inc.: Steve Mathison shared data on precooling equipment performance from Honda's T40 HRS

Future Work

- Evaluate trade-off between other precooling design concepts
  - ✓ various HX designs (brine-based thermal HX, compact HX, etc)
  - ✓ with respect to cost, footprint, B2B fill capability, installation cost, sensitivity to ambient temperature, and temperature increase through VACD
- Quantitatively examine implications of VACD location with respect to J-T temperature rise through modeling and measurements
- Update Hydrogen Delivery Scenario Analysis Model (HDSAM) and Hydrogen Refueling Station Analysis Model (HRSAM) with:
  - updated precooling cost and design options
  - Include optimization algorithm for proper sizing of precooling equipment with desired refueling performance attributes (e.g., # of B2B fills)
- Continue to collaborate with partners to acquire information on cost and performance of alternative precooler design concepts
- Review and publish updated models and analysis results

Project Summary

- **Relevance:** Equipment cost of pre-cooler at HRS is significant ($100K-$200K per hose). Evaluate cost and performance of emerging system designs and implementation practices. Examine implication of various precooling design concepts on energy consumption per kg of dispensed hydrogen.
- **Approach:** Collaborate to acquire information on cost and performance of various precooler design configurations. Evaluate current precooling design concepts at HRS. Analyze trade-off between various design concepts. Identify major drivers for precooling capacity/cost and performance. Develop precooling system optimization algorithm for various component costs and performance specifications. Analyze trade-off between different precooling design concepts.
- **Collaborations**: Collaborated with experts from national laboratories and industry to examine current pre-cooling equipment design and cost. Acquired operation and performance information needed for modeling and simulations, and received valuable input to complete /review modeling results and analysis.
- **Technical accomplishments and progress:**
  - Updated precooler system components costs, and developed an algorithm to optimize size of precooling equipment and heat exchanger.
  - Identified major factors impacting precooling system performance and cost (e.g., # of B2B fills and temperature rise through VACD).
  - Evaluated and compared calculated precooling energy use during each fill with field data.
- **Future Research**: Evaluate trade-off between other design concepts of HX designs. Quantitatively examine various implications of VACD location through modeling and measurement. Update Hydrogen Delivery Scenario Analysis Model (HDSAM) with updated precooling cost and design options. Review and publish updated models and analysis results.

Argonne NATIONAL LABORATORY

Amgad Elgowainy
aelgowainy@anl.gov
Project PD107