Modeling Flare Destruction and Removal Efficiency

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Background

- The 2010 TCEQ Flare Study measured DRE for test flares under various operating conditions:
  - Steam- or Air-Assisted, assist rates
  - Lower Heating Value
  - Vent Gas composition and flow rates
  - DRE and Control Efficiency (CE)

- The study found that DRE and CE are sensitive to assist rates, and over-assisted flares may achieve DRE values lower than the assumed 98 or 99%, even if operated in compliance with 40 CFR §60.18.

Background

- The 2011-12 HRVOC Flare Survey requested in-use data from 81 entities with 175 flares (30 TAC §115).
  - Speciated hourly HRVOC emissions
  - Exit velocity
  - Flare tip unobstructed cross-sectional area
  - Assist type (Steam, Air, or None)
  - Height, location
  - Hourly assist rates if available (voluntary), or minimum assist rates otherwise

Background

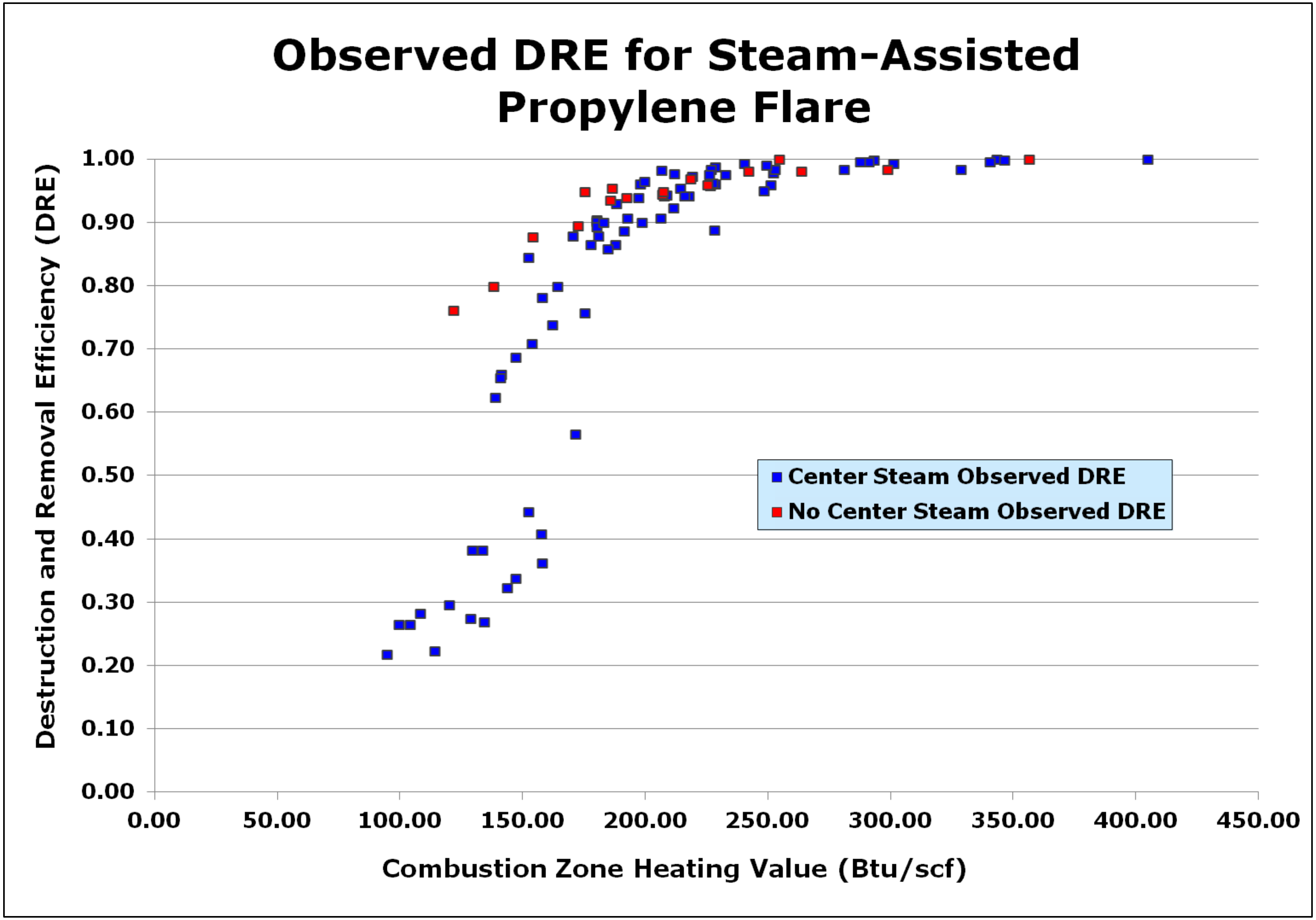
- The purpose of this work is to develop a model, based on the Flare Study, which can be used to estimate the DRE of flares using information in the Flare Survey.

- Two key quantities (best single predictors of DRE):
  - Combustion Zone Heating Value (CZHV) for Steam-assisted flares
  - Excess Air for Air-assisted flares

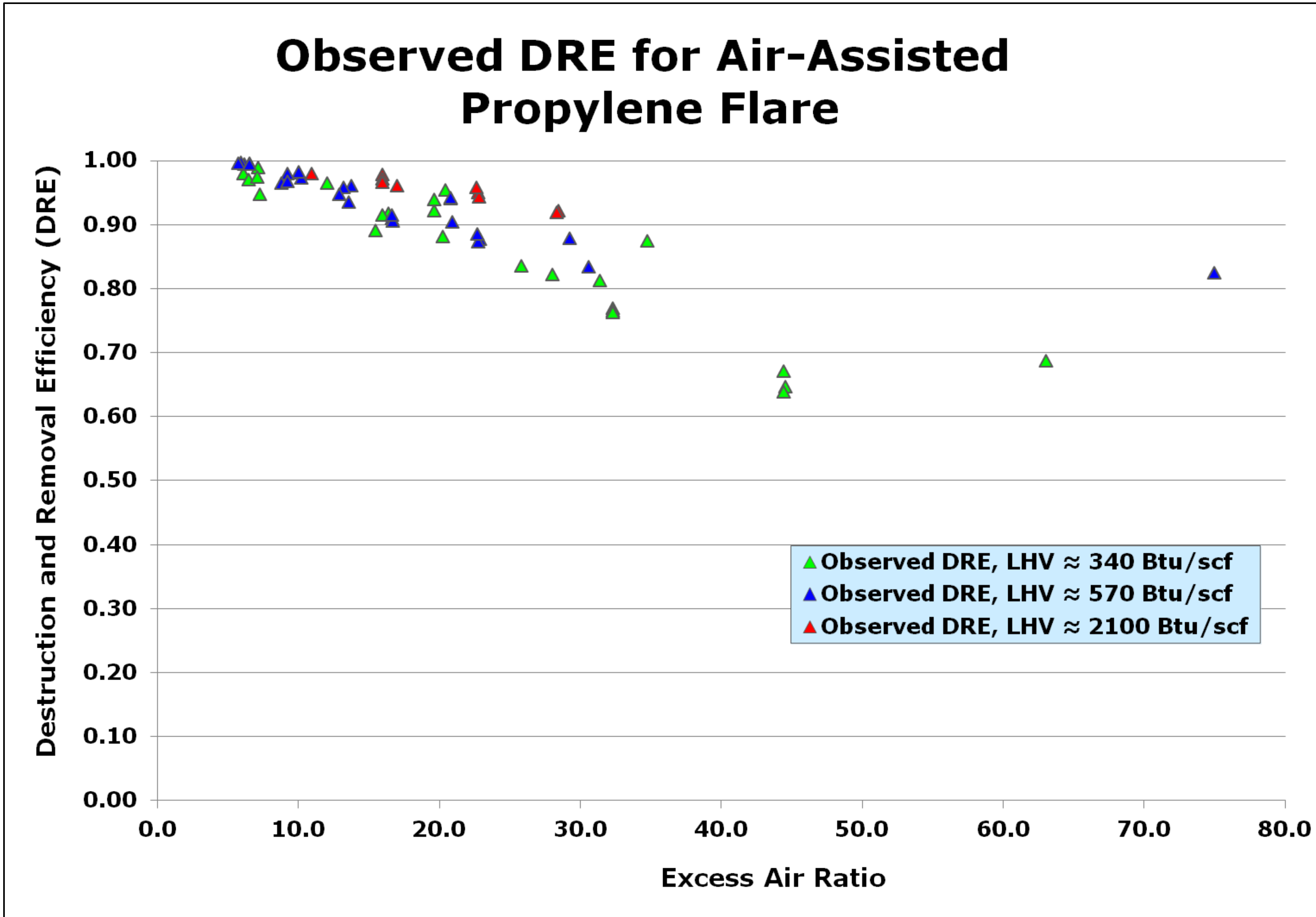
Background

- CZHV is the heating value of the vent gas, also accounting for the steam content, which lowers CZHV. It is expressed in Btu/scf (British thermal units per standard cubic foot).
- Excess air is the dimensionless ratio of total air flow through the flare, divided by the amount of air required to combust all the vent gas under ideal conditions (i.e. the *stoichiometric amount* of air).

Steam Flare: DRE as a Function of CZVH



Air Flare: DRE as a Function of Excess Air



Model for Steam-Assisted Flare

- We tested most of the possible predictor variables in the data spreadsheet provided by the University of Texas to see which provided the best prediction of DRE:
  - Used SAS Proc Stepwise to eliminate variables with little predictive ability.
  - Examined a variety of linear, second-order, and non-linear functional forms.
  - Removed variables which, though possibly significant, only marginally improved measure of goodness-of-fit (R^2).

Model for Steam-Assisted Flare

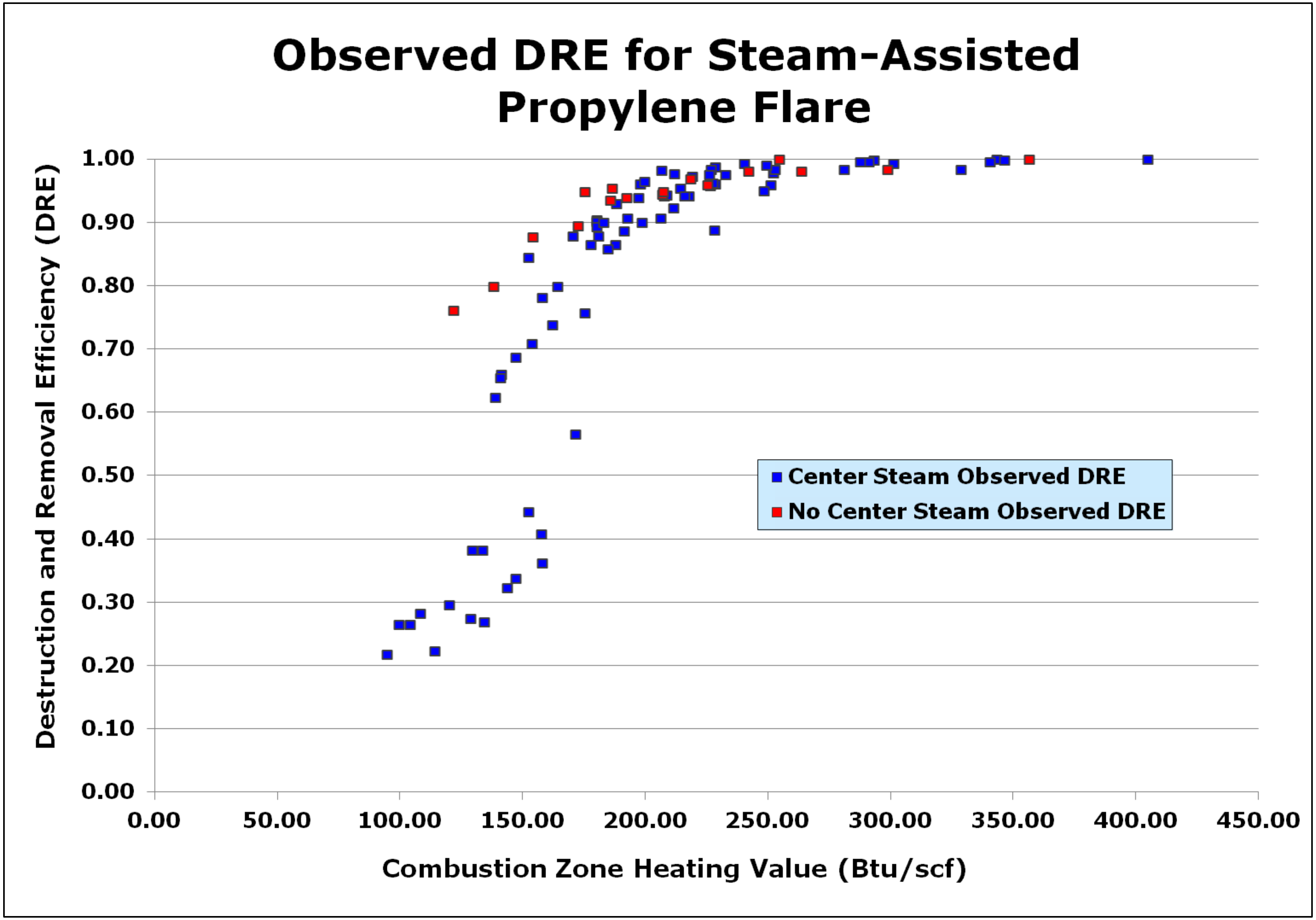
- A sigmoid function approximates the observed shape of DRE vs. CZHV very well.
  - Similar in form to the W126 weighting function proposed for calculating design values for the secondary ozone standard:

$$DRE = 1/(1+\mathbf{A}*e^{\mathbf{B}*CZHV}) \qquad (1)$$

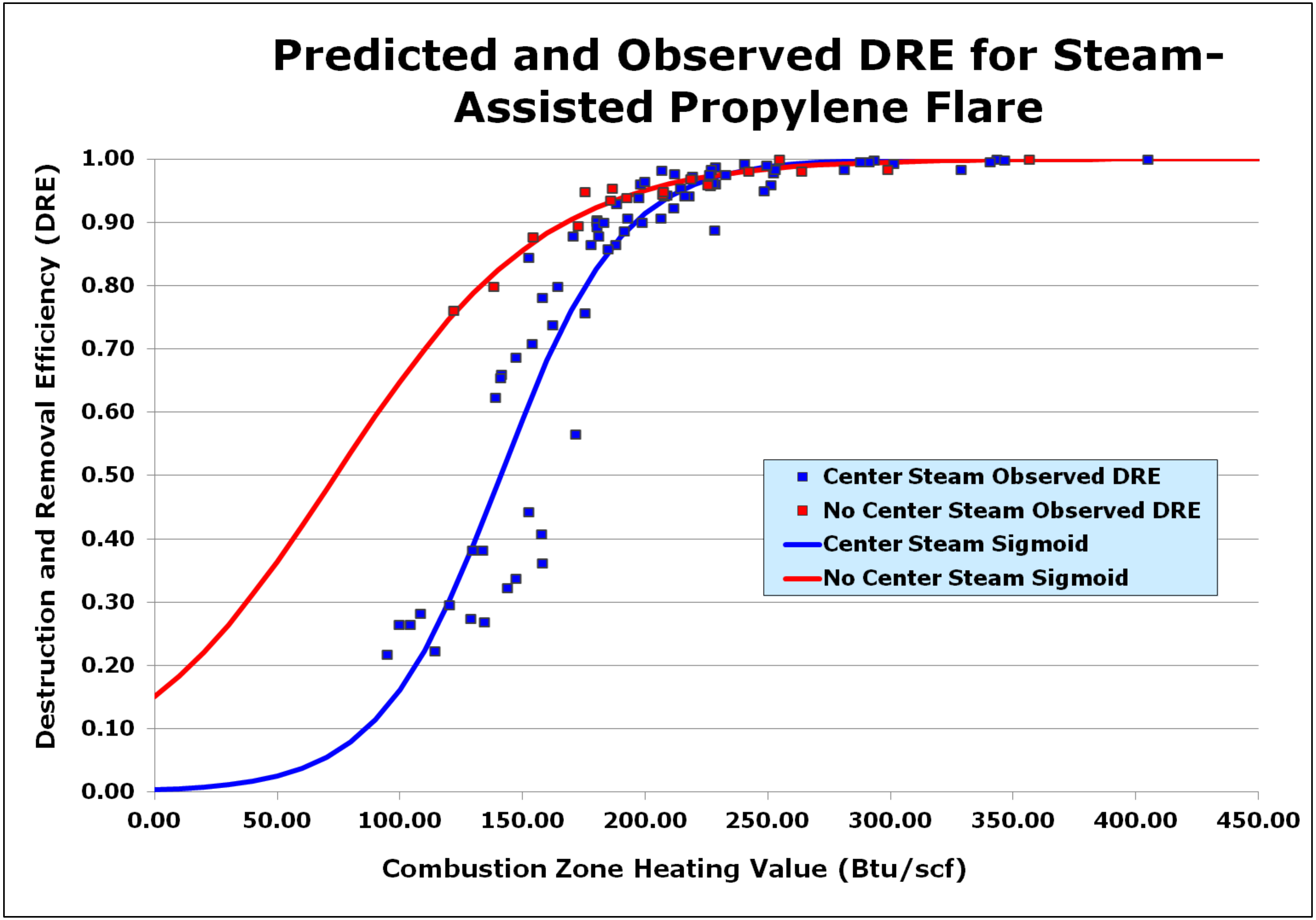
where **A** and **B** are constants to be determined.

  - **A** and **B** were fitted separately for flaring with and without center steam, using the SAS NLIN nonlinear regression procedure.

Steam Flare: DRE as a Function of CZVH



Steam Flare: DRE as a Function of CZVH



Model for Steam-Assisted Flare

- Now least-squares regression minimizes the sum of squared residuals

$$\sum(\text{predicted} - \text{observed})^2 \qquad (2)$$

- Problem: Residuals for DRE values near 1 tend to be small, while those for smaller DREs are often much larger, giving lower DRE values too much “pull” in equation (2).

Model for Steam-Assisted Flare

- Problem is further compounded by the relative importance of correctly predicting values near 1.
- Example: a facility sends 100 lb/hour of propylene to a flare.
  - If the flare operates with a DRE of 0.98, the flare emits 2 lb/hour.
  - But if it operates with a DRE of 0.8, it emits 20 lb/hour.
  - Assume we under-predict the flare's DRE by 0.02. Then in the first case, we predict DRE of 0.96, which is double the actual emissions.
  - In the second case, the predicted DRE is 0.78, which is only 10% higher than the actual emission rate.

Model for Steam-Assisted Flare

- Solution: use weights to increase the "pull" of residuals of DRE's near 1. The regression now minimizes

$$\sum W*(\text{predicted} - \text{observed})^2$$

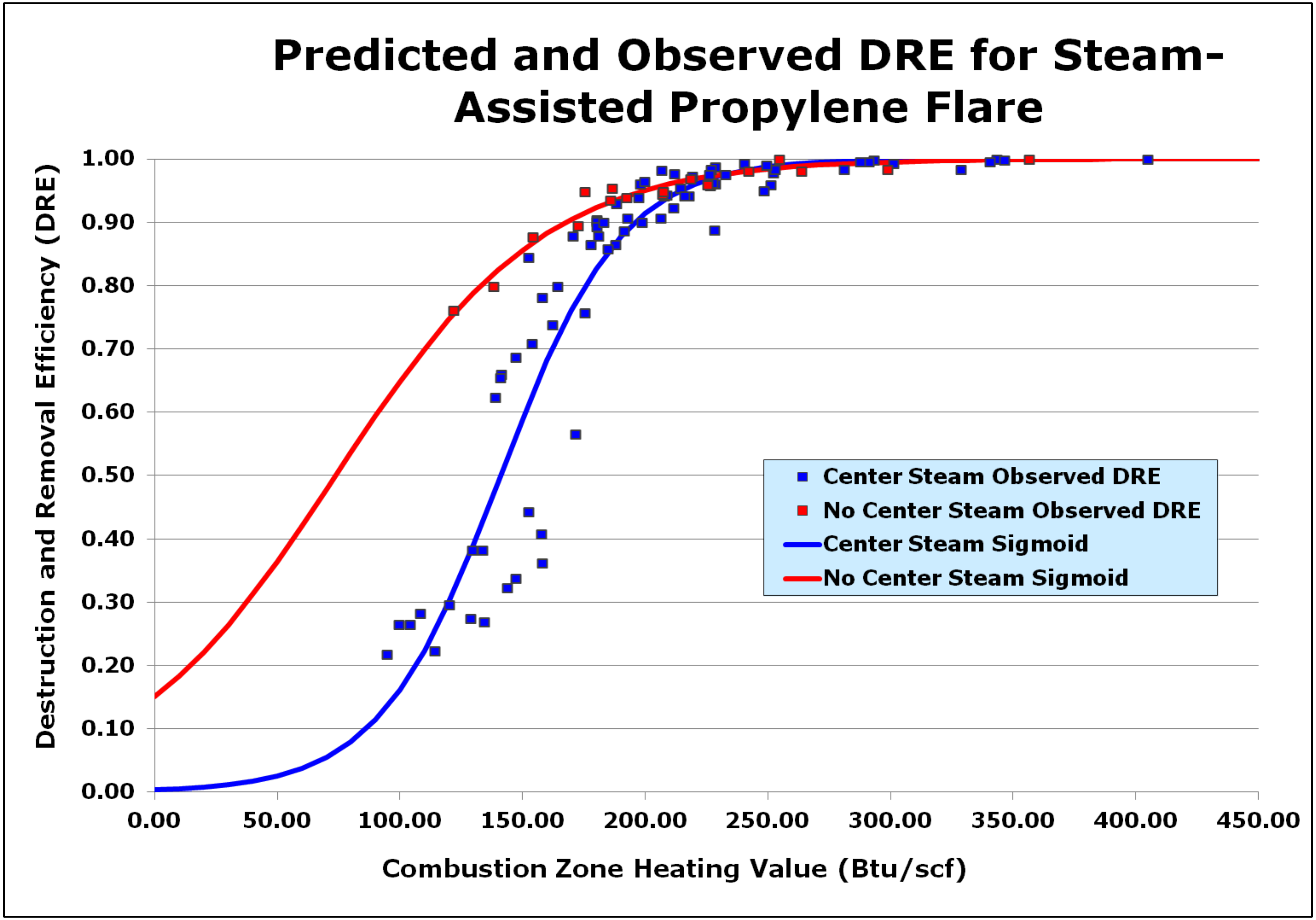
where

$$W = 1 / (1-\min(DRE, 0.98)) \qquad (3)$$

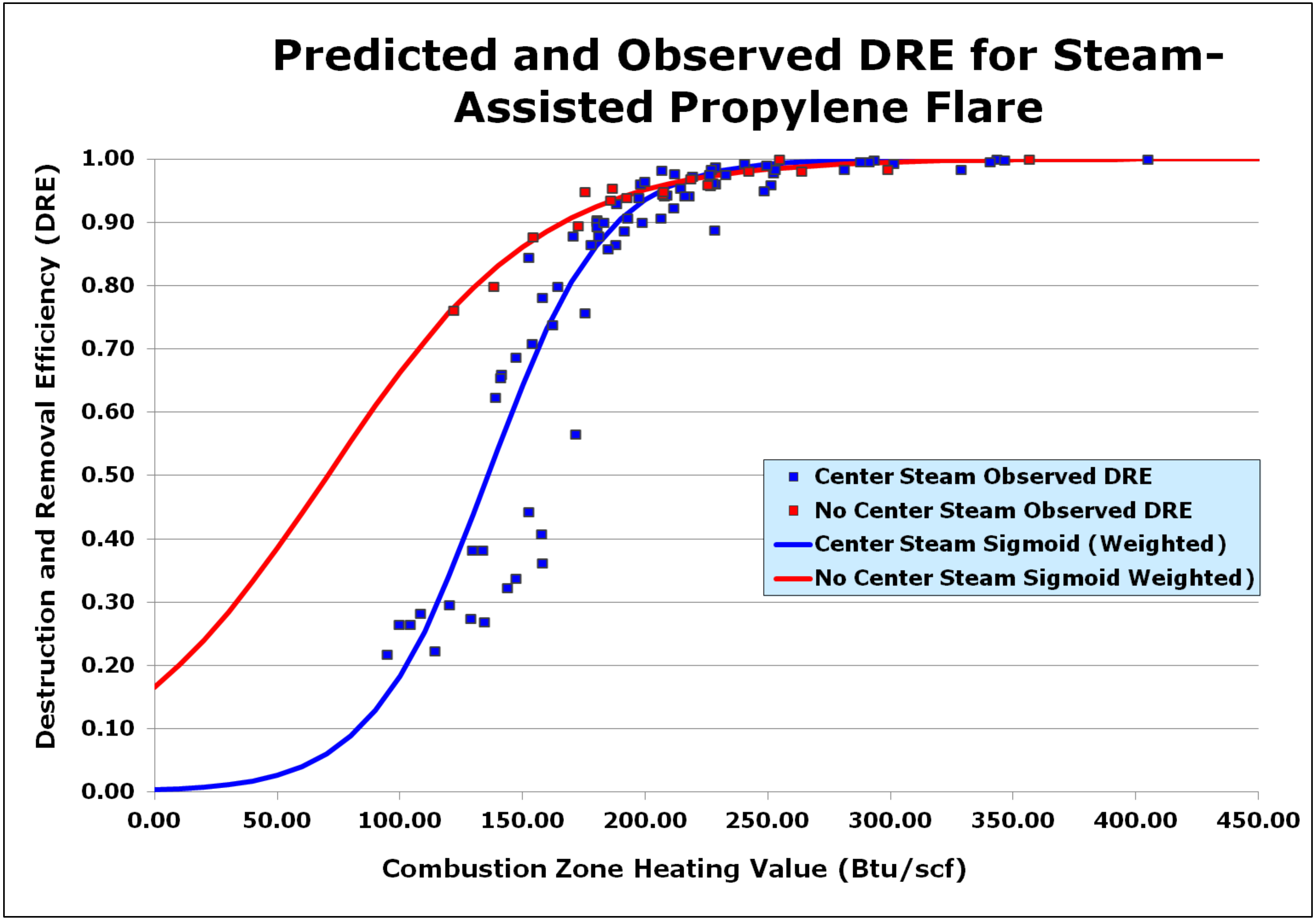
For DRE between 0.98 and 1.0, W = 50.

For DRE of 0.80, W = 5.

Steam Flare: DRE as a Function of CZVH



Steam Flare: DRE as a Function of CZVH



Model for Steam-Assisted Flare

- Fitted model for steam flare with center steam:

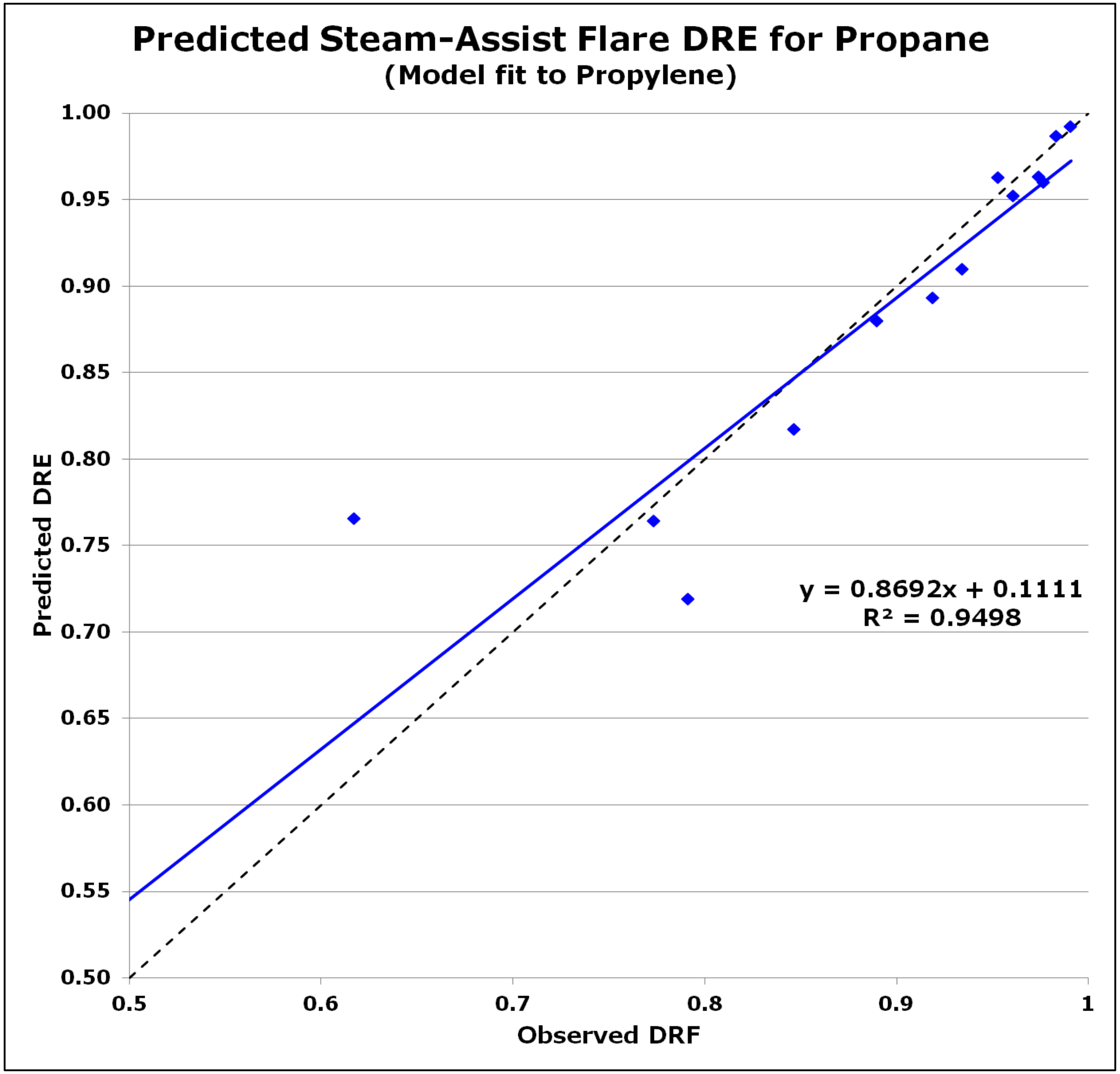
$$DRE = 1/(1+\mathbf{288.8}*e^{\mathbf{-0.0417}*CZHV}) \qquad (4)$$

- Fitted model for steam flare without center steam:

$$DRE = 1/(1+\mathbf{5.0181}*e^{\mathbf{-0.0229}*CZHV}) \qquad (5)$$

- Combined R^2 = **.875**

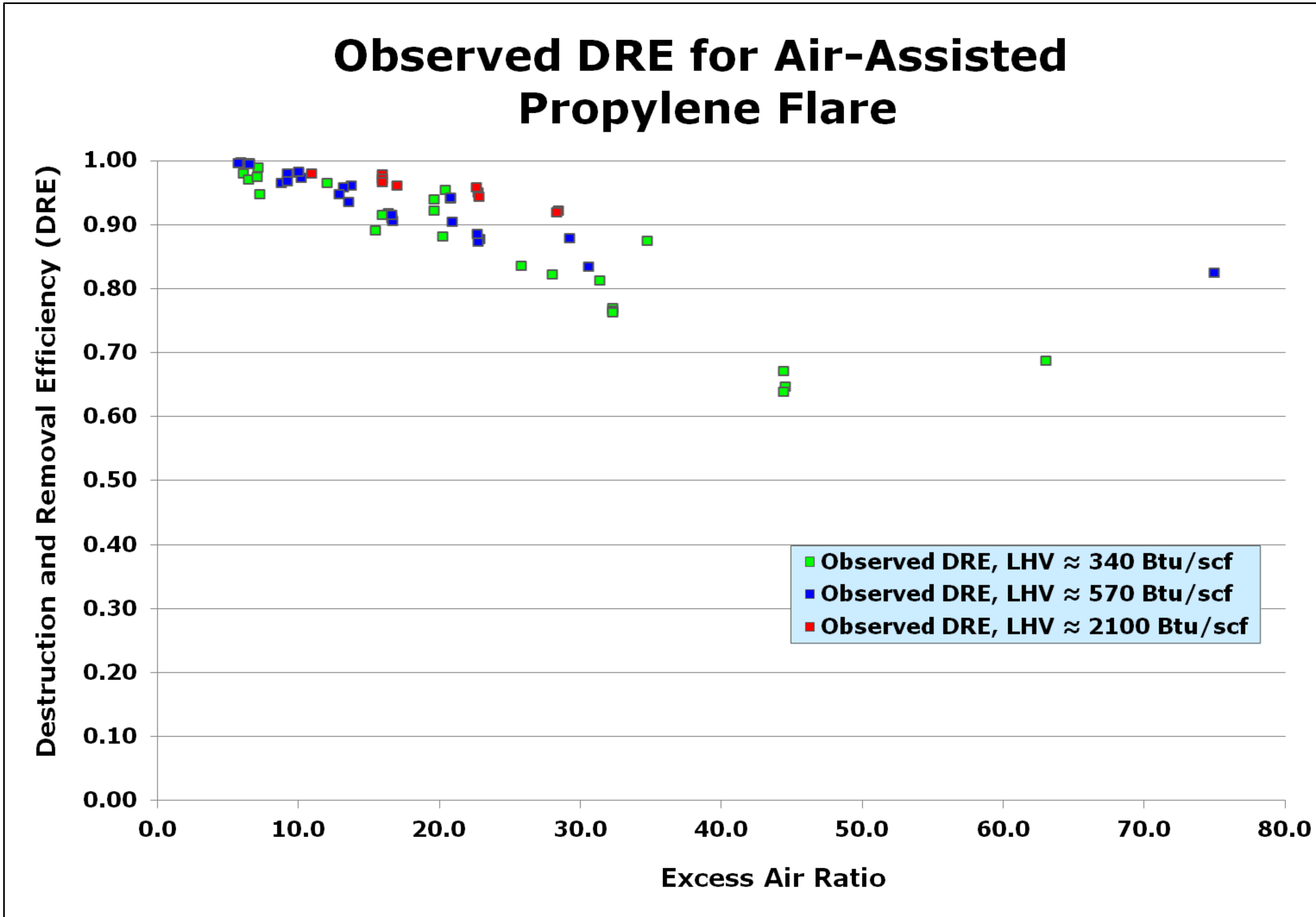
Model Cross-Check: Propane



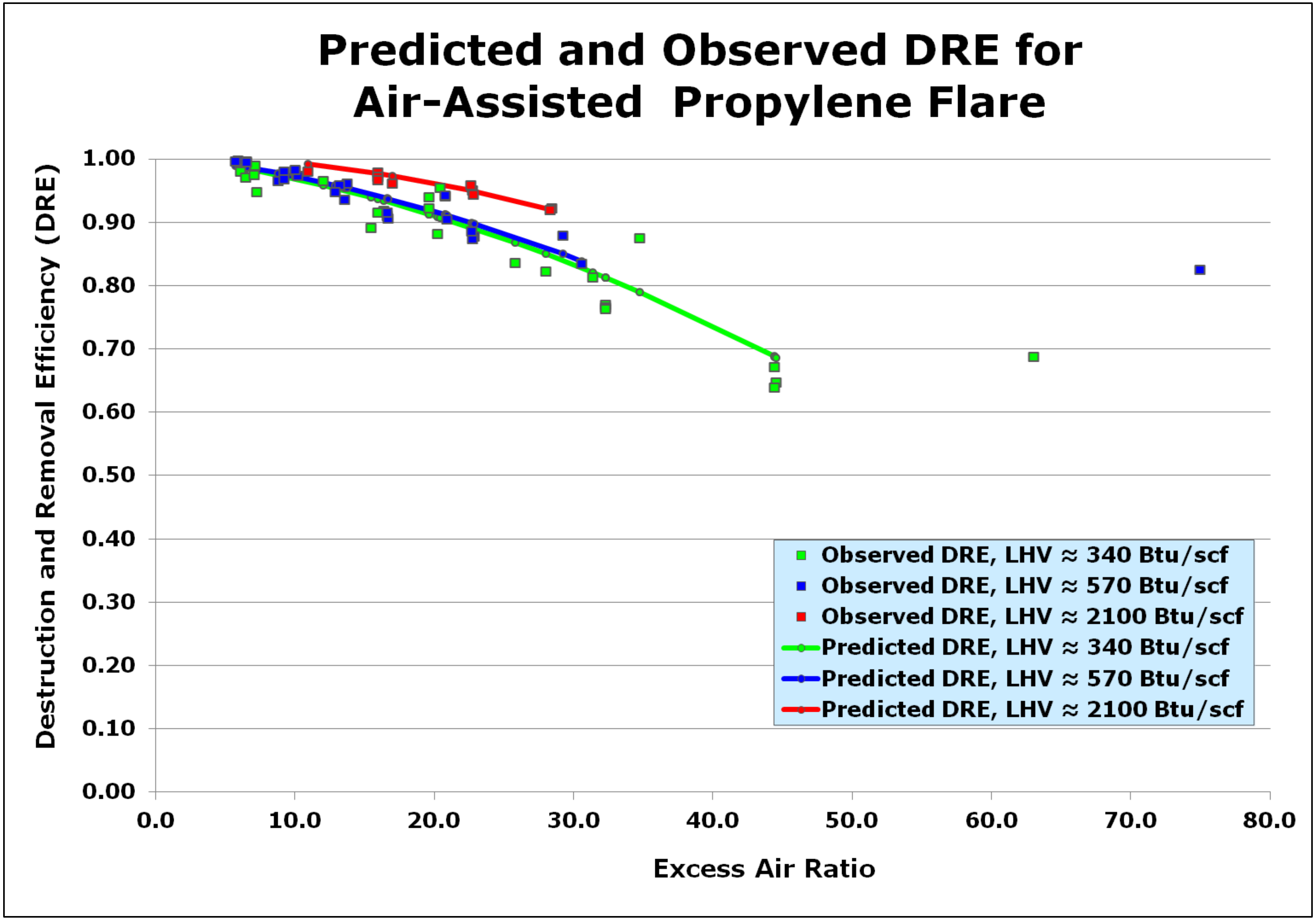
Model for Air-Assisted Flare

- We tested most of the possible predictor variables in the data spreadsheet from UT to see which provided the best prediction of DRE:
  - Discarded values with excess air ratio > 50.
  - Used SAS Proc Stepwise to eliminate variables with little predictive ability.
  - Examined a variety of linear, second-order, and non-linear functional forms.
  - Removed variables which, though possibly significant, only marginally improved measure of goodness-of-fit (R^2).
  - Included the same weighting function as for steam-assisted flare.

Air Flare: DRE as a Function of Excess Air



Air Flare: DRE as a Function of Excess Air



Model for Air-Assisted Flare

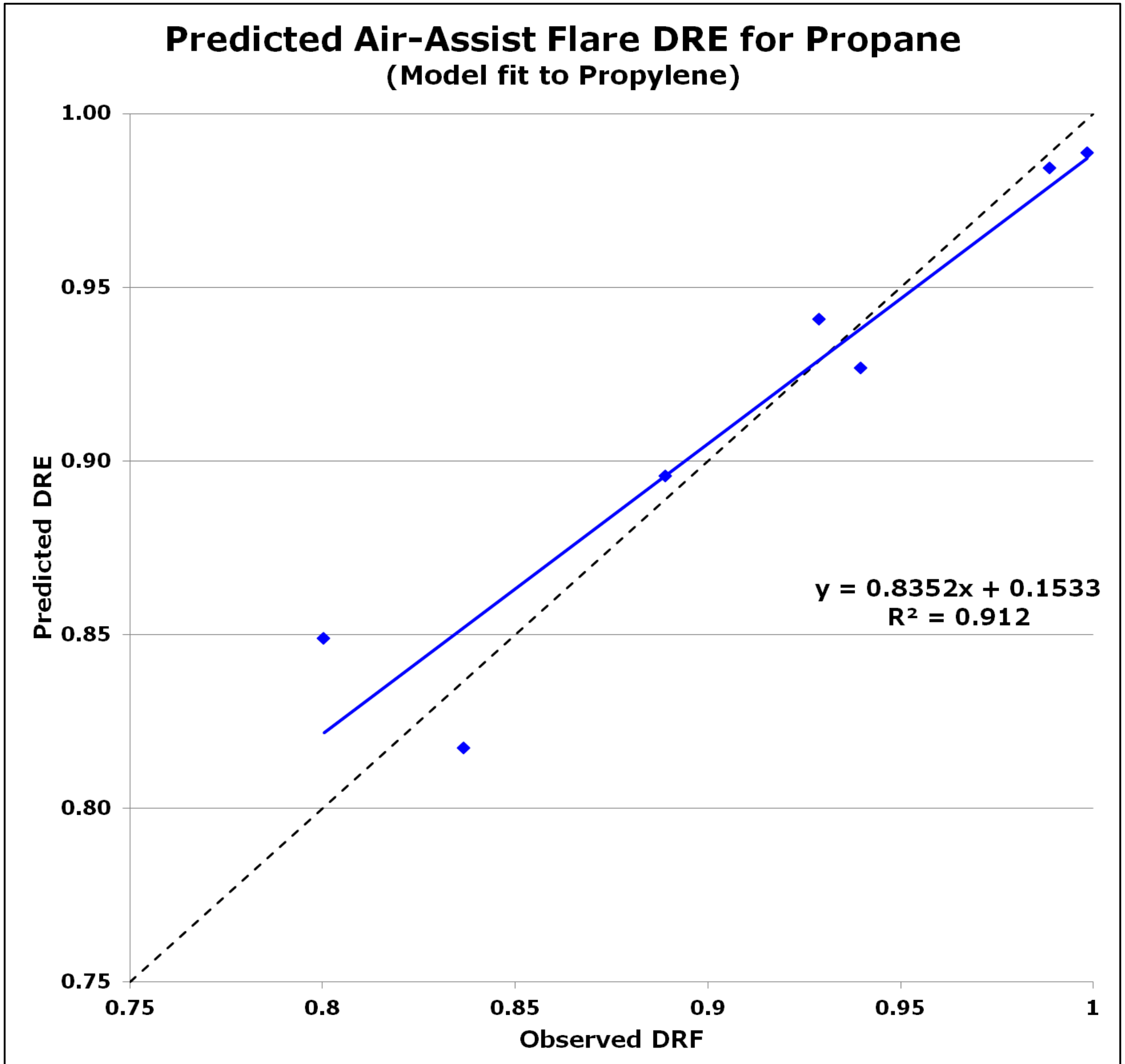
- Fitted model for air-assisted flare:

$$DRE = \mathbf{1.00824} - \mathbf{0.003485} * Ex\_Air - \mathbf{0.0000947} * Ex\_Air^2 + \mathbf{0.000001447} * Ex\_Air * LHV \quad (6)$$

where Ex_Air is excess air ratio and LHV is the lower heating value of the vent gas.

- R^2 = **.921** (excluding points with Ex_Air>50)

Model Cross-Check: Propane



Emissions

- For either type of flare, actual emissions of the vent gas can be calculated as:

  VG Emiss = VG Flow Rate * (1–DRE) (7)

- But the flare may emit some products of incomplete combustion in addition to unburned vent gas. Control Efficiency (CE, always ≤ DRE) measures how much of the vent gas is completely combusted, i.e. is emitted as CO_2 and H_2O.

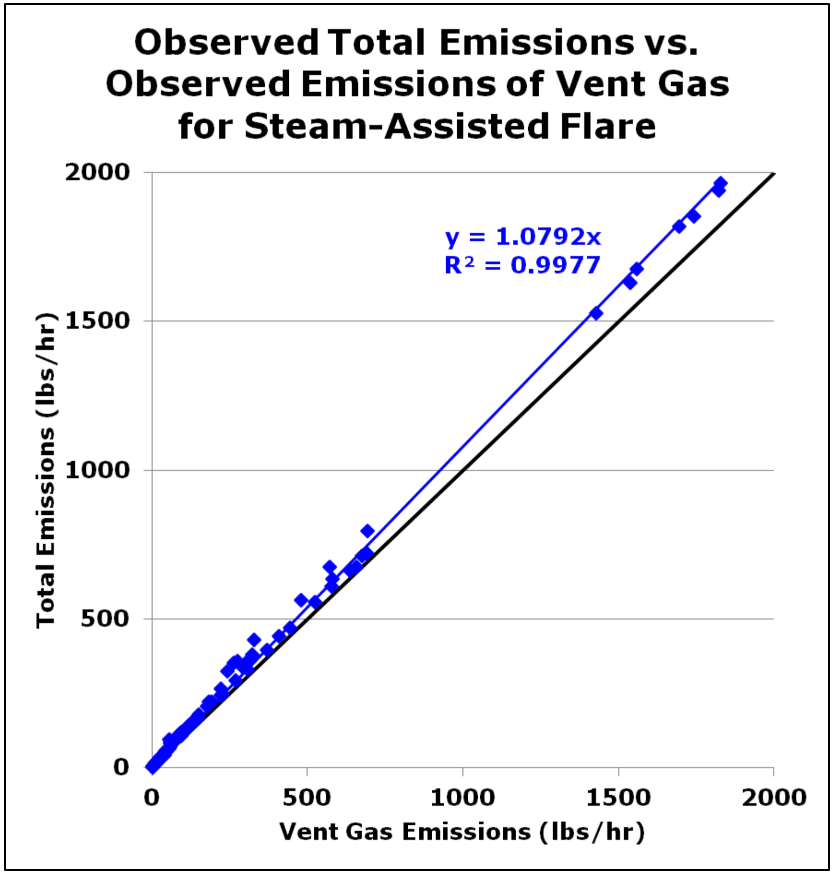
Emissions

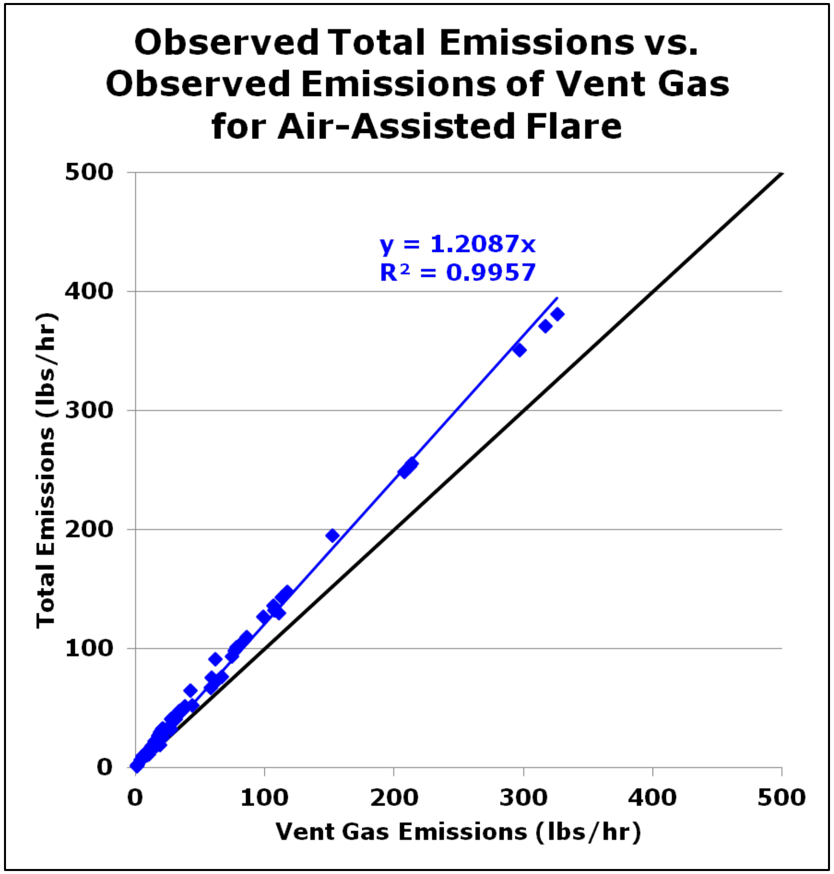
- Total emissions, including partially-burned and unburned vent gas, is calculated as:

  Total Emiss = VG Flow Rate * (1–CE) (8)

- How much partially-burned gas is emitted?

Total Emissions vs. Vent Gas Emissions





The slopes of the regression lines indicate by how much the total emissions exceed the vent gas emissions.

Emissions

- For the steam-assisted flare, the partially-burned gases are about 8% as much as the vent gas emissions.

- For the air-assisted flare, the partially-burned gases are about 21% as much as the vent gas emissions.

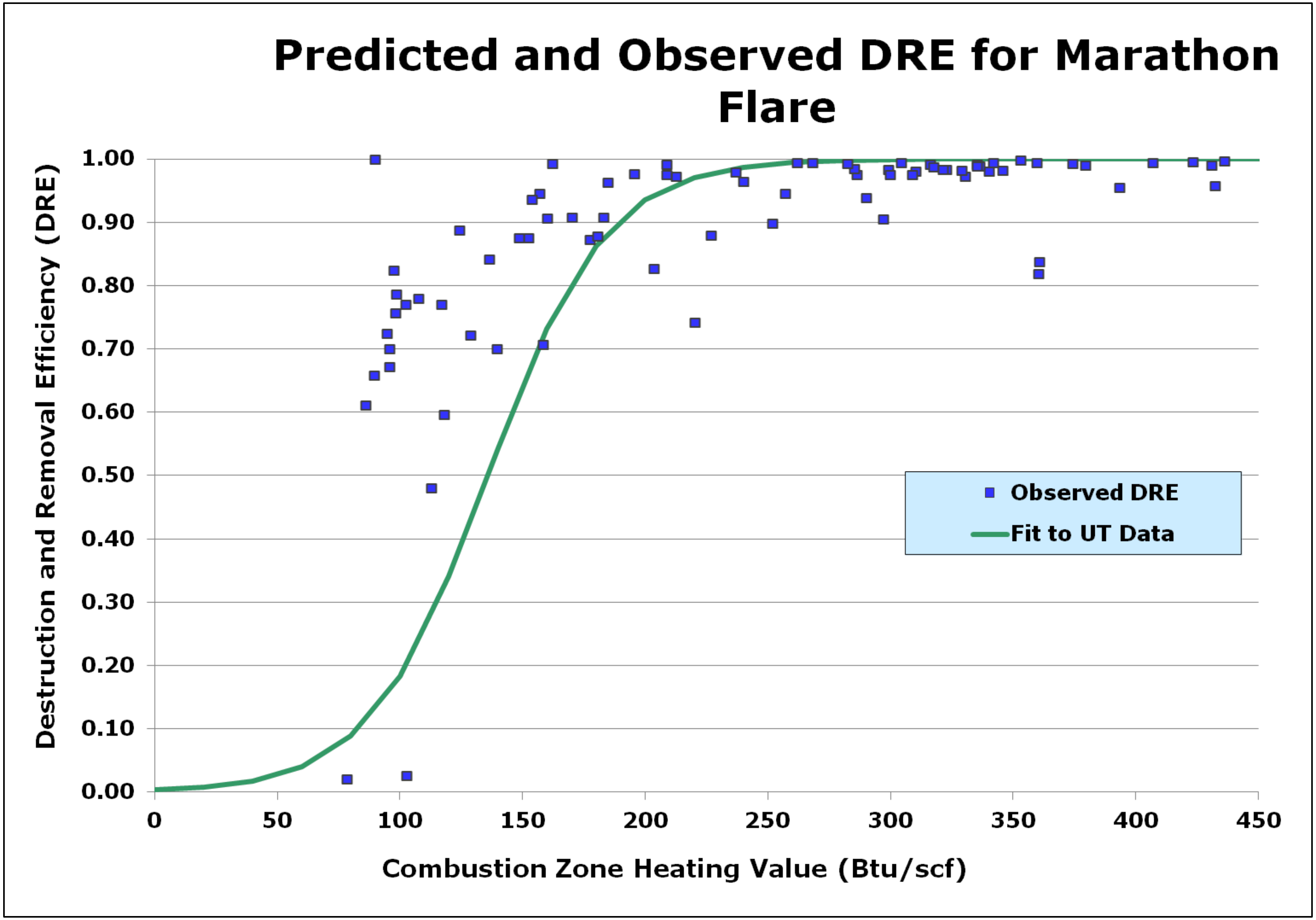
Conclusions and Caveats

- The models fit are good representations of the DRE observed at two flares in the TCEQ flare Study burning propylene.
  - The models also represent the DRE for propane fairly well, but other mixtures have not been evaluated.
  - Other flare configurations (ground flares, different tip designs, different physical characteristics) have not been evaluated.

Next Steps

- We have Marathon flare test results and are starting to evaluate the flare DRE models against it.
- We are applying the models described here to data received from the 2011 HRVOC flare survey to estimate typical DREs for in-use flares.

Preview: Marathon Study



Preview: Marathon Study