Residential Water Heater Test Procedures: Why You Should Care

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I. Background
II. Current Test: Simulated use
III. Using test results in models
IV. A few pitfalls
V. Proposed new test: Input-output
VI. Appendix: Model calibration
I. Background

Building America Program:

• Domestic water heating:
  – 13% of residential source energy
  – Percentage of load increases with envelope/HVAC efficiency
  – Options: storage tank: gas/elec; tankless, condensing, heat pumps, solar

• Water Heater (WH) options analysis
  – Teams compare and recommend products
  – Currently, test results apply only to the test use volume/patterns
  – Realistic/BA draws very different from the test
  – Need to simulate under BA conditions

• Problem: deriving simulation inputs from WH test data
II. Current Water Heater Test

Doe Standard Test conditions:

- One day duration
- 64.3 gal draw (> average?)
- 6 equal draws 1 hr apart
- Same draw for all sizes
- $T_{set} = 135 \, ^\circ F$
- $T_{in} = 58 \, ^\circ F$
- $T_{env} = 67.5 \, ^\circ F$

- Correction made for stored energy change over cycle:
  \[ \delta E_{store} = C_{store} \delta T_{store,avg} \]
Standard vs. Realistic Draws

**Draws: Volume vs. Time**

- **Doe Standard Test**
- **Realistic Draws**

- **Y-axis**: Draw Volume [Gal]
- **X-axis**: Time [hr]

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Test results

- **Energy Factor:** \( EF_{\text{std-test}} = \frac{E_{\text{out,day}}}{E_{\text{aux,day}}} \) (\( E = \text{energy} \))
  - \( E_{\text{out,day}} = M_{\text{draw}}c_p\Delta T_{\text{out-in}} = 41,092 \text{ Btu/day} \)
  - \( E_{\text{aux,day}} = \text{auxiliary energy used over the day} \)

- **Recovery Efficiency:** \( RE_{\text{gas}} = \frac{E_{\text{out,dr}}}{E_{\text{aux,dr}}} \)
  - \( E_{\text{out,dr}} = \text{energy withdrawn in one 10.6 gal draw} \)
  - \( E_{\text{aux,dr}} = \text{energy input recovering from that draw} \)
  - Lower than conversion efficiency because of tank losses
  - \( RE_{\text{elec}} \approx .98 \) for all tanks (by fiat)

- **Input power:** \( P_{\text{aux}} = \) measured auxiliary input

- Measured \( V_{\text{st}}, U_{\text{st}} \) not reported: change?
Energy Factor Uncertainty

- **Energy Factor:** $EF_{std-test} = \pm \sim .01-.02$ (Lutz $\sim 1999$)
  - Dominant error: $T_{store,avg}$ as avg. of six point sensors
    - Used in stored energy correction: $\delta E_{store} = C_{store} \delta T_{store,avg}$
    - Bottom sensor near or in thermocline at bottom element in electric tanks

- Compare $\pm \sim .02$ to min-max range $\sim .89 - \sim .96$ for electric WH
III. Tank Models

• Algebraic Models
  – Time-integrated energy balance:
    – \( E_{aux} = draws + losses = M_c \Delta T_{set-in} + UA \Delta T_{set-env} \Delta t_{period} \)
    – E.g.: WATSMPL

• 1 Dimensional finite difference
  • Account for stratification, draw and heat source dynamics,
  • Still simple: appropriate for annual simulations
  • E.g.: TRNSYS

• 2-3 Dimensional finite element (CFD)
  • \( T, v \) fields; hardware design tools
  • Slow: inappropriate for annual simulations
Electric Tank

\[ \eta_{\text{conv}} \equiv 1 \]

Electric elements

Skin insulation

Thermal shorts

Volume

Height of element

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Gas Tank

- Gas Tank
- Additional inputs
  - $U_A_{flue}$
  - $\eta_{conv}$
- Gas Burner/pilot
- Central flue
- Convection loop

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Key parameter: Conversion Efficiency

• Conversion efficiency: \( \eta_{\text{conv}} = \frac{P_{\text{to-water}}}{P_{\text{aux-in}}} \) (\( P = \)power)
  - \( P_{\text{to-water}} = C_{\text{tank}}(dT_{\text{tank,avg}}/dt) \) only when \( T_{\text{tank,avg}} = T_{\text{env}} \)
    - Tank losses are NOT to be included
  - RE includes tank losses during the recovery period

• For ELECTRIC: \( \eta_{\text{conv}} = 1 \)
• For GAS: \( \eta_{\text{conv}} \) must be calculated from RE, UA
**Inputs from Test Data**

**Electric tank:**

\[
UA_{t,\text{elec}} = \frac{Q_{\text{out,day}}(1/EF-1)}{[(\Delta T_{t-env}\Delta t_{day})(f_{\text{above}} - f_{\text{below}} \frac{\Delta T_{in-env}}{\Delta T_{set-env}})]}
\]

\[\eta_{\text{conv}} \equiv 1\]

**Gas tank:**

\[
UA_{t,\text{gas}} = \frac{(RE/EF-1)}{[\Delta T_{set-env}(\Delta t_{day}/Q_{\text{out,day}}-1/(P_{aux} \cdot EF)))]}
\]

\[\eta_{\text{conv}} = RE + UA_{t,\text{gas}}(\Delta T_{set-env})/P_{aux}\]

\[\eta_{\text{conv}} = \sim RE + .01-.02\]
Spreadsheet Tool

Implements input formulae derivation, with paper on method

<table>
<thead>
<tr>
<th>Calculation of TRNSYS inputs from DOE test/AHRI data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>User Input</strong></td>
</tr>
<tr>
<td>Derived/constant</td>
</tr>
<tr>
<td>Calcd TRNSYS Input</td>
</tr>
</tbody>
</table>

| **Known values from DOE test**                      |
| WH type ("gas" or "electric" only)                  |
| Electric                                            |
| Energy factor (EF)                                  |
| 0.92                                                |
| RE NOT USED for electric                            |
| 0.8                                                 |
| Rated input power (Pin)                             |
| 15.354                                              |

| **Standard DOE test conditions & constants**         |
| Volume drawn                                        |
| 64.3 gal/day                                        |
| Ttank                                               |
| 135 F                                               |
| Tin                                                |
| 58 F                                                |
| Tenv                                               |
| 67.5 F                                              |
| Qload                                              |
| 41092 Btu/day                                      |
| Density                                            |
| 8.2938 lb/gal                                      |
| Cp                                                 |
| 1.0007                                             |
| Draw mass (M)                                       |
| 533.3 lb                                            |

| **Geometry**                                        |
| Height                                             |
| 44.75 inches                                       |
| Height of lower element                             |
| 0.01 inches                                        |
| Nominal Volume                                      |
| 42 US gallons                                      |
| Assumed = Nominal Volume?                          |
| no US gallons                                      |
| Assumed Volume                                      |
| 38.2 US gallons                                    |
| Diameter                                           |
| 15.840 inches                                      |
| Surface Area - British                             |
| 18.201 ft²                                         |
| Surface Area - SI                                  |
| 1.691 m²                                            |
| Area below lower element - British                 |
| 1.372 ft²                                          |
| Area above lower element - British                 |
| 16.829 ft²                                         |
| Area below lower element - SI                      |
| 0.127 m²                                            |
| Area above lower element - SI                      |
| 1.563 m²                                            |

| **TRNSYS Inputs**                                   |
| Height                                             |
| 1.137 m                                             |
| Volume                                             |
| 0.145 m³                                           |
| U stdby-TRNSYS units                                |
| 2.710 kJ/hr-m²-C                                   |
| Input Capacity                                      |
| 16.198 kJ/hr                                       |
| Number of Nodes                                     |
| 10 -                                                |
| UA/TRNSYS                                          |
| 4.583 kJ/hr-C                                      |

| **Comparison to Nominal UA-skin**                   |
| Insulation R-english/inch (nominal)                 |
| 5.00 hr-4°F/Btu-in                                  |
| Insul Thickness (nominal)                           |
| 2.00 inches                                        |
| U-skin (nominal)                                    |
| 0.100 Btu/hr-4°F                                   |
| UA-skin (nominal)                                   |
| 1.820 Btu/hr-4°F                                   |
| UA stdy / UA-skin (nominal)                         |
| 1.33 -                                              |
| Consistency check                                   |
| EF=Qload/(Qload+Qloss)/n_c                           |
| 0.920 -                                             |

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Common Blunders:

• RE is not equal to $\eta_{\text{conv}}$
  • $\eta_{\text{conv}}$ is the model input for efficiency, not RE

• EF is not $\eta_{\text{conv}}$
  • $E_{\text{auxiliary}} = E_{\text{thermal}}/\eta_{\text{conv}}$ is correct
  • $E_{\text{auxiliary}} = E_{\text{thermal}}/EF$ is wrong
• $\frac{\delta U}{U} = EF \frac{\delta (EF)}{1 - EF}$

Error in U value vs. EF

Bad news for electric

$\delta (EF) = .02$
Sensitivity to unheated volume
(in electric tanks only)

Inferred U value (Btu/hr-ft²-F)

Unheated Volume (gallons)

Element at 10 inch
V. New Test Method: Input/Output

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From T. Butcher
ASHRAE2010
Model Inputs from I/O

Slope of line:
\[ \eta_{\text{conv}} = \frac{1}{\text{slope}} \]

Y-intercept:
\[ UA = \frac{P_{\text{input-nodraw}}}{\Delta T_{\text{tank-env}}} \]
Input-Output Validation

Low Rate of Use

High Rate of Use

\[ y = 1.2857x + 750.14 \]

Efficiency (total output / total input) = 58.1%

From J. Lutz
ASHRAE2010
I/O Method Validation

Tankless water heater

\[ y = 1.0735x + 211.95 \]

\[ R^2 = 0.999 \]
I/O Method Advantages

- Allows any use profile
  - Get $P_{out}$, $P_{in} = m \cdot P_{out} + b$
- UA, $\eta_{conv}$ error should decrease
- Applies to tank water heaters and tankless (some issues)

- But: Heat pump water heaters? Condensing?
Conclusions

• Current test method: simulated use test
  • Methods for input parameters laid out
  • Uncertainty in U value large for higher EFs

• Future test method: Input-Output test
  • Under development: 1-2 years from now?
  • Major changes for heat pumps?
  • Reduction in parameter uncertainty
Thank you for listening.

Questions?

Time Allowing:
Model calibration tests and tankless
Model-based:
Test \implies Calibrate \implies Rate

Real Water Heater
\implies Test Protocol
\implies Test Data
\implies Generic Model
\implies Calibrated Model

Any rating conditions
\implies Calibrated Model
\implies Rating

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Losses between draws demand modeling of internal mass and losses to ambient
Tankless Thermal Model

This model has three parameters

- $T_{env}$
- $\dot{m}c_p (T_{out} - T_{in})$
- $N_{hx nodes}$
- $Q_{gas,in}$
- $C_{TWH}$
- $\eta_{conv}$

Measured value

Model Parameter
Example Test Protocol

Temperatures
- Temperatures Decay with heat off: capacitance signal

Steady state burn: efficiency signal

Flow rates
- Inlet water
- Outlet water
- Natural Gas

Hot in, low flow $\Rightarrow \Delta T_{hx}$: UA signal

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Draw net efficiency is sensitive to:

- Delay between draws
- Length of draw
A Tale of Two Draw Patterns

Building America 2 Bdrm benchmark
64 gal/day, 30 draws

Net Efficiency: 77%

Building America 2 Bdrm low use
22 gal/day, 12 draws

Net Efficiency: 65%

Tankless efficiency from DOE test is 0.80
Range of Inputs for Given Output?

Gas-fired storage and tankless heaters tested are tested with hour-long draw profiles of equal output.

Varying degrees of draw volume, draw rate, and standby period

**Draw #1**
- Duration: 12 minutes
- Volume: 20 gallons
- GPM: 2.0

**Draw #2**
- Duration: 12 minutes
- Volume: 2 gallons
- GPM: 1.0

**Draw #3**
- Duration: 24 minutes
- Volume: 0.5 gallons
- GPM: 1.0

**Draw #4**
- Duration: 60 minutes
- Volume: 10 gallons
- GPM: 3.0

Extended Standby
I/O validation: tankless

Range of Inputs for Given Output?

Gas-fired Non-condensing Tankless

From Low and High Use testing:
a = 1.163 and b = 96.9

<table>
<thead>
<tr>
<th></th>
<th>Draw 1</th>
<th>Draw 2</th>
<th>Draw 3</th>
<th>Draw 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Rate Measured (Btu/hr)</td>
<td>11,941</td>
<td>11,628</td>
<td>11,702</td>
<td>12,241</td>
</tr>
<tr>
<td>Input Rate Measured (Btu/hr)</td>
<td>13,744</td>
<td>13,497</td>
<td>13,570</td>
<td>14,857</td>
</tr>
<tr>
<td>Input Rate Calculated (Btu/hr)</td>
<td>13,979</td>
<td>13,615</td>
<td>13,701</td>
<td>14,329</td>
</tr>
</tbody>
</table>

Consistent slight underprediction of performance for Draws 1 – 3
Large departure in Draw 4 (large standby between draws)

From P. Glanville, ASHRAE2010
Tankless Conclusions

• Current test method:
  • Badly overestimates performance (6 big draws)

• Proposed I/O method:
  • \( \sim 3\% \) underprediction with draws having long delays
  • Can eliminate error
  • Appears acceptably-accurate

• Potential model-based method:
  • Accommodates any draw patterns/delays
  • Simplest possible test, but complex analysis
  • Demands that generic model exists