Tuning Up Your Facility's Steam Trap Assessment

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ABSTRACT

The authors refined a steam trap survey tool that estimates steam losses and energy savings for failed steam traps as a function of up to twelve coefficients and parameters, including:

- Trap pressure
- Orifice size
- Hours of operation
- Leak factor
- Boiler efficiency
- Presence of condensate return

For the variables that are not directly observable, the authors developed values based on a combination of pre-/post-retrofit billing analysis-based regressions of steam trap savings at participating Massachusetts facilities and review of methodologies used by others. This multi-pronged approach resulted in a steam trap savings calculator and new deemed per-trap savings values. While the study found wide variability in actual savings per trap, these relationships and results are believed to be an improvement on industry standard practice and can be used by facility staff to accurately determine the savings opportunities that lay hidden inside their steam systems.

INTRODUCTION

The core principles of steam trap operation have been understood for centuries and the unique mechanisms by which the majority of trap types operate have not changed fundamentally in the last one hundred years.[1] Nevertheless, the realized savings for steam traps often vary wildly from survey estimates. The actual savings delivered by steam trap repair and replacement remains notoriously hard to predict. Facility personnel and decision-makers rely on the savings estimates generated by vendors and utility program staff in order to weigh the benefits of an upgrade against the cost of doing said work. A more consistent, accurate, and practical method for estimating the savings associated with repaired traps is needed by both the facility managers and policy makers to ensure that savings goals are met.

Unfortunately, the size and complexity of steam systems make the standard practices used to identify the energy lost at a trap anything but practical, and the industry has not standardized a single computational approach. At least four different empirical formulas are used in the industry as the basis for calculating loss: Grashof, Napier, "modified" Napier, and (rarely) Rateau.

There is a consensus among facility managers and industry professionals on the benefits of having a regular steam trap maintenance program in place. One of the primary benefits from inspecting and fixing traps on an annual basis is the avoided cost of steam system-related issues such as condensate buildup in the main header, live steam in the condensate loop and waterhammer (among others) that may arise without regular preventative maintenance. Along with these avoided costs, facility operators may also expect to see recovered energy costs that would have otherwise been lost due to defunct traps allowing live steam to leak or blow by. Trap surveys and repairs are also sold on this basis.

The variation between estimated and realized energy savings is attributable to a number of factors including the differences in employed savings equations and trap diagnostic methods as well as the size and complexity of most steam systems and the variability in the leaks themselves. The inherent qualities of steam traps make standard measurement and verification procedures used to predict energy savings anything but practical. And while trap survey vendors seem to have reached a consensus on diagnostic methods (ultrasonic and thermal measurements), the industry has yet to agree upon a single standardized computational approach.

[1] For a very brief history see http://www.tlv.com/global/TI/steam-theory/history-of-steam-traps-pt1.html.

The authors first addressed the structure of the savings calculation formula by reviewing engineering texts and secondary sources, consulting a variety of industry experts, and using program participant data to revise the savings equation. The authors then used primary data collection activities and site specific savings calculations to empirically derive values for the most uncertain variables in the revised savings equation. In addition to generating a new custom method, the authors used the updated technique and Massachusetts program participant firmographic and historical trap incentive application characteristics to calculate a new per-trap deemed savings value.

This paper provides a brief overview of the data collection and analysis methods employed to perform this research as well as a discussion of the findings and ensuing conclusions and recommendations made.

METHODS

The overall methodology of developing the custom savings calculator and deemed savings value consisted of two distinct activities: data collection and analysis.

Data Collection

Stakeholder group engagement. The authors engaged a group of program administrator (PA) implementers to help refine the research approach, provide expert input and guidance, and ensure that the methodology was in step with current and future program designs in the state of Massachusetts.

Secondary research. The authors reviewed a selection of other states' technical resource manuals (TRMs) to determine how other governing bodies assess steam trap savings compared to Massachusetts.

Pre-installation vendor ride-alongs. The authors joined multiple steam trap survey vendors during pre-project inspections to assess the methodologies employed on-site and understand how trap-level characteristics are captured and eventually turned into actual energy savings estimates.

Steam trap program participant data. Site specific savings analyses and billing data from program participants were collected, screened, and used to ensure that the results produced were characteristic and representative of the Massachusetts steam trap program participants. Selected characteristics and a breakdown of the facilities are presented later in this paper.

Post-installation phone interviews. The authors assembled a large sample of past steam trap program participants for phone interviews and screened each facility for the feasibility of using a weather-normalized billing analysis to accurately characterize gas savings at the site. The intent of the phone screening was to eliminate facilities where changes may have occurred concurrently with the steam trap project that would affect the outcome of the billing analysis.

Post-installation on-site evaluations. The authors conducted on-site visits to follow up with a selection of the facilities screened over the phone, to confirm the trap-level parameters as well as facility-level characteristics, including boiler combustion efficiency and maintenance practices.

Analysis

Refine formula structure. The authors modified the steam trap savings equation's parameters based on the interviews and secondary research, to simplify and increase the accuracy of the semi-prescriptive calculator to develop a more consistent and accurate custom savings equation.

Trap-level savings calculation. Trap-level savings were replicated using the original, PA-specific savings formula for each of the 9,450 steam traps from the participant's trap survey inventories; 2,659 (28%) of these traps had savings associated with them.

Site-specific billing analyses. After screening participants for billing analysis feasibility, the authors conducted weather-normalized billing analyses to observe the actual impacts of steam trap projects at 28 facilities.

Engineering algorithm refinement. Each variable in the steam trap savings equation has some degree of uncertainty, but some are easier for a vendor or steam trap auditor to estimate than others. Trap size, for example, is easily estimated based on model number. Steam pressure at the trap is capable of estimation as well. Hours per year of trap exposure to pressurized steam is not as easy to estimate but site-specific estimation is likely to be more accurate than applying a single generalized value to every facility. On the other hand, estimating the percent of possible steam leaking through a particular trap is difficult, even with an experienced ear and/or ultrasonic devices.

The authors assigned values to every savings calculation parameter for less uncertain variables using expert judgment. The variables associated with the highest uncertainty (i.e., condensate return and leak factors) were defined empirically using the results of the billing analyses in a parameter calibration analysis. This method entailed adjusting the identified variables in the savings algorithm with the goal of matching calculated savings to the qualified billing analysis results while minimizing the statistical uncertainty of the calculated savings and realization rate-equivalent values.

Deemed savings estimation. The authors used the refined engineering algorithm with input assumptions that were representative of the program population to define a single deemed savings value. We used median values for continuous variables and weighted averages for discrete variables.

FINDINGS

This section provides an overview and discussion of the author's subsequent findings.

Formula Structure Refinement

This section presents the revised savings equation with a discussion of each of the input variables considered for inclusion in the equation. The authors drew on findings from a number of different sources in order to refine the existing savings algorithm(s) into one that would be more accurate and consistent among users. The proposed custom equation for steam traps is as follows:

$$\text{Energy loss}\left(\frac{\text{Btu}}{\text{yr}}\right)=\frac{60\times a\times P^{0.97}\times LF\times C_D\times(h_g-h_f)\times CR\times\frac{\text{hr}}{\text{yr}}}{\eta}$$

Equation (1)

where,

60 = Empirically derived factor in Grashof equation ($lb_m/[in^{0.06}\text{-}lb^{0.97}\text{-}hr]$).

0.97 = Empirically derived factor in Grashof equation (unitless)[2] [3].

a = Area of orifice at throat (sq. in). This parameter can be easily identified during the site visit (via trap model number & lookup) and is critical for calculating savings.

P = Pressure in steam line at trap (psia). This property can be easily identified during site visits, has significant variance within a single steam system, and is critical for calculating savings.

LF = Leak factor (0–100%) to discount for partially obstructed orifices or non-ideal steam flow, entered as one of five different values from trap status pick list based on field observation. Each trap is designated as OK, not in service (NIS), plugged, leaking, or blowing by. OK, NIS, and plugged traps are 0% by definition (yielding no savings) while the leaking and blowing by are established in the analysis below. These values are subject to the most uncertainty. A number of changes have been made to the leak factors including reducing the maximum leak rate to less than 100%, adding a "Not in Service" option, and reducing the total number of leak status options. The prior custom tool had six different statuses (four non-zeros) including OK, Plugged, Partial Leak, Full Leak, Partial Blow-by, and Full Blow-by. The number of partial leak rate options exceeds the level of resolution practical to expect from field staff and leaves the tool open to the interpretation of the steam trap surveyor. In order to minimize the likelihood of a trap being interpreted incorrectly, and with the endorsement of interviewed experts, the number of non-zero status options was reduced to two. The values for these two leak factors are highly uncertain, impossible to inspect, and significantly affect savings; thus they are prime candidates for parameter calibration.

C_D = Discharge coefficient (70%) to account for trap hole not being a perfect orifice, generalized value from secondary research.

h_g,h_f = Enthalpy of saturated steam and liquid, respectively (Btu/lbm). This is an extensive property associated with steam trap pressure and can be determined using a lookup table.

CR = Condensate return factor (30%–100%) accounts for energy returned from condensate line. The governing equation assumes that steam is discharged through the building envelope into the atmosphere. If a trap discharges into a condensate return system, then some of the leaked energy in that discharge returns to the boiler and is not "wasted." Whether or not the condensate returns to the boiler significantly impacts savings estimates. If there is no condensate return line, the value is 100% and the factor has no effect on the savings estimate. If there is condensate return, which is typical, the current value employed by one model uses a factor of 30% (discounting savings by 70%). This value is theorized

[2] The Grashof and Napier equations are similar in structure and generally give results within 5% of one another at typical commercial and industrial steam pressures and orifice sizes. Grashof is regarded as being more accurate.

to range anywhere from 30%–100%. The high variability of this value makes it a great candidate for parameter calibration.

hr/yr = Hours per year that trap is exposed to pressurized steam (site-specified value). A pre-determined value with selection from a list based on field observation of trap application. Based on past experiences, experts and stakeholders both recommended retaining a pick list of hours associated with specified trap applications rather than direct entry of hours, which would be theoretically more precise. This past "lesson learned" eliminated confusion regarding field staff entering system rather than trap hours exposed to steam or highly variable estimates that had no sound basis.

η = Overall steam generator marginal combustion plus heat exchange efficiency. Current savings calculations use a default value of 80%. Combustion tests from the facilities in which on-site visits were conducted all yielded boiler efficiency values within 5% of this value. As the range on this value is relatively limited, the authors kept this value fixed and instead focused on parameters with higher variability.

The leak factors and condensate return factors were identified as the variables with the most uncertainty within the equation, and therefore were the focus of the parameter calibration in the algorithm refinement section. The four parameters C_D, η, CR, and LF are present in every trap calculation and multiplicative with one another. If the assumed value of C_D or η is incorrect, the research on CR and LF inherently corrects for this.

Annual gas billing data. While not included in the savings equation, the annual gas billing data was indicated as being an important value for screening project savings. There was a consensus among program staff that a cross-check against the annual facility gas usage to anchor savings to reality should be required. It was agreed that this should be helpful to add a warning flag for high savings to the standardized calculator used by PAs to review vendor applications. The appropriate fraction of savings relative to the annual gas usage that should trigger flagging is likely in the range of 20%–30%. This factor is not part of the individual trap loss equation but is used as a crosscheck.

Below are other factors that were considered but not included in the revised savings equation.

Repair/replace factor. This value was intended to serve as an indirect measure-life discount factor, penalizing the savings for traps that are repaired rather than fully replaced. There was a consensus among the stakeholders and other industry professionals that this should no longer be used [2][5]. Repaired traps save as much in the first year of repair as a replaced trap, and for all but one trap type (thermodynamic disc [1]) a repaired trap should last as long as a new one.[3]

Steam system loss factor. Used in some models as a 5% reduction in overall efficiency, its intent is to capture the effect of boiler radiant and distribution system losses on effective boiler efficiency. This value was excluded from the equation, as system losses remain relatively constant regardless of trap leak or repair. There is potential for this value to be looked at in future studies in conjunction with pipe insulation, envelope improvements, or other heat-load related measures, but like combustion efficiency, the variability is minimal so the authors did not focus on it too intently.

Flash steam heat recovery. Flash steam is created when condensate passes from the pressurized trap into a lower pressure return line. This characteristic discounts trap savings further than the condensate return factor by recovering flash steam energy by way of a heat recovery device. For a facility to have a viable flash steam heat recovery system, there must be sufficient high-pressure condensate and there must also be a suitable low-pressure application for the recovered flash steam. Of the 9,450 steam traps included in the program trap inventory, none included this feature. Experts corroborated findings that the rate of incidence was rare [6]. For this reason the authors excluded it from the revised custom savings equation.

Condensate back pressure. Some condensate systems are slightly pressurized relative to atmospheric pressure, either unintentionally (e.g., a low-pressure system with backups or highly excessive leaks) or, rarely, intentionally (e.g., a high-pressure industrial system that uses the condensate return system as a low-pressure supply). This factor would reduce savings by virtue of less steam leaking since there is a smaller pressure differential between the trap and condensate return line. This value is not

[3] Review of different algorithms found that one PA discounted savings for repaired traps while another gave a bonus for traps being replaced.

used in the existing savings formula and was not added to the revised formula. Field experts indicated that pressurized condensate is rare and unless part of the design, hard to detect during a survey[4] [6].

Lighting interactivity factor. The high incidence of lighting projects in past years gives rise to concerns about the interactive heating effects affecting the results of a weather-normalized billing analysis used to calculate steam trap savings. During the site interviews, the authors inquired with facility staff about the installation of other energy-related projects within the time frame of the steam trap project. Of the 24 projects used in the parameter calibration analysis, 8 sites confirmed that they had performed lighting upgrades in recent memory. Five of those sites indicated that the project had occurred over a year's time before or after the steam trap project took place. The authors investigated the potential impacts of lighting interactivity effects for the three remaining sites using a lighting power density (LPD) reduction method. [4] The calculation yielded a total heating penalty value less than 9% of the combined tracking savings for the three sites and less than 1% of the total overall savings used in the parameter calibration analysis. The results indicate that this parameter does not have any sort of meaningful effect on their results. This value is not used in the existing savings formula and was not added to the revised formula.

Site-Specific Assessments

Sites were screened on an individual basis to determine if the results of their billing analyses would be fit for parameter calibration. An illustration of the site counts for each phase of the screening process can be seen in Figure 1.

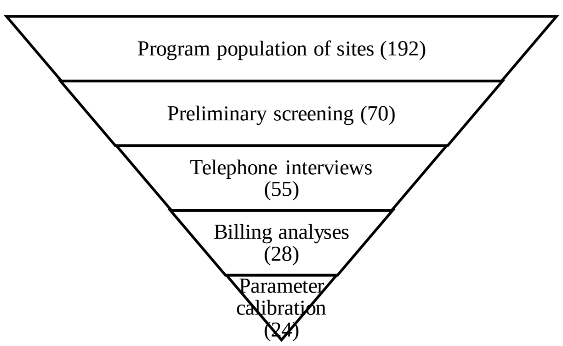

Figure 1. Site-Screening Process Flow

The authors performed a high-level review of 252 custom and prescriptive natural gas projects completed at 192 unique sites using project tracking and natural gas billing data at each facility. Each project was screened to validate the use of billing data to assess trap savings via a weather-normalized billing analysis. This was done by filtering out sites that had tracked savings lower than 5% of their annual gas usage. The preliminary screening yielded 105 projects at 70 sites that would be eligible for a billing analysis.

Project files were obtained for each of the custom projects (which included savings calculation worksheets), while trap counts and installation dates were provided for prescriptive projects. Trap-level details were pulled from every custom savings workbook into a master spreadsheet, where the tracked savings were replicated with the existing algorithm used by each PA. Replicating the savings for every site proved difficult, as some applications used the vendor savings (algorithm unknown) over the PA savings while others took an average of the two values. Additionally, some sites did not repair every trap marked for repair in the inventory, which the tracking savings had been updated to reflect. The differences between the tracking, vendor, and replicated workbook savings necessitated using all three values for the sake of comparison.

The authors conducted telephone interviews with contacts at each facility to determine whether the difference in billed usage could be wholly attributed to the steam trap project. The authors asked facility staff about other measures or equipment that may have been installed; notable changes in production, occupancy, or scheduling; fuel switches; or any other event that may have spurred a change in steam and/or gas usage at the approximate time of the project (±1 year from project date). Sites that confirmed that there had been some other change to the facility at the approximate time of the project that would affect natural gas usage were removed from consideration for the billing analysis phase. After repeated attempts at recruiting every site in the population, interviews were completed for 55 out of the 70 sites. The 15 sites for which interviews weren't completed were excluded, along with 14 sites for which other site activity contaminated the billing data, leaving 41 for billing analysis consideration.

Weather-normalized billing analyses were completed for each of the remaining sites. Pre- and post-project gas consumption was regressed against actual heating degree days (HDDs) and then normalized against typical TMY3 data from the nearest weather station. Billing analyses were

[4] While difficult to identify, a good indicator of back pressure is an abnormally high failure rate among traps.

removed from consideration for parameter calibration if the analysis yielded indeterminate results by way of billing data anomalies or gas consumption that was found to be predominately production-based. Of the 41 sites screened with a weather-normalized billing analysis, 28 met the criteria for parameter calibration. Of the 28 sites, 4 were prescriptive projects and did not have trap-level details to be used in the parameter calibration analysis. Thus, the final site count for the parameter calibration portion is 24. In more detail, sites were dropped from the initial population for the following reasons. Even after multiple outreach attempts, the authors were unable to complete interviews for 15 sites, and 14 sites were removed because the site contact indicated that there had been some type of change at the facility affecting gas usage within the billing analysis window of the project. An additional 13 sites were removed during the billing analysis review, as the evaluators found the gas usage was either largely production based or that there were too many inconsistencies within the billing data to establish an accurate regression against weather data. Table 1 provides a breakdown of the final site dispositions.

Table 1. Final Site Dispositions

Final Disposition	**Count**
Removed from analysis	**42**
No survey completed	15
Production/occupancy/schedule changes	3
Other projects completed	9
Fuel switches	2
Production-based usage	8
Inconsistent billing pattern	5
Cleared survey and BA screening	**28**
Custom	24
Prescriptive	4
Total	**70**

There is a relatively similar distribution of projects by facility type between the sites used in the calibration and the initial population, with two exceptions. Surveys revealed many health care facilities were undergoing facility expansions or other project work at the time of the upgrade. This is not expected to be a characteristically significant concern with respect to attrition. While 9 of the 11 industrial facilities passed the phone survey screening phase, the majority did not pass the billing analysis screening due to production-based gas usage. There was obvious non-weather and likely production-driven gas use volatility in the majority of the industrial sites. The authors were unable to collect and analyze production data for these facilities and, as a result, this could be a minor vulnerability in the analysis.

Table 2 provides a breakdown of the facility classification types throughout the evaluation screening process, including both custom and prescriptive projects.

Table 2. Facility Types Through Screening Process

Facility Type	**Population**	**Surveyed**	**Passed Phone Screening**	**Passed BA Screening**
Com - other	5	3	1	-
Health care	14	12	8	5
Hotel	2	1	1	1
Industrial	13	11	9	3
Multifamily	3	1	-	-
Municipal	9	6	5	5
Office	5	4	3	3
School	19	17	14	11
Total	**70**	**55**	**41**	**28**

Figure 2 illustrates the breakdown of the annual energy use per facility, comparing the initial population to the final counts used in the parameter calibration analysis.

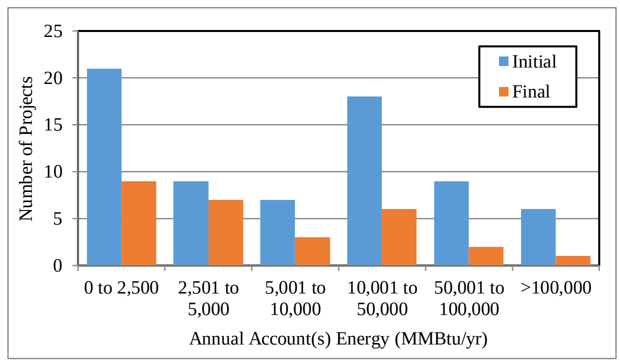

Figure 2. Annual Energy Use Per Premise

While energy intensity is not directly related to the realized steam trap savings at a given facility, Figure 2 illustrates that the sites used in the evaluation approach were representative of the initial population.

Parameter Calibration

The majority of assumptions in the revised savings equation were identical or close to the existing approach assumptions with the exception of the condensate return factor and leak factors, which were calculated empirically using the best fit approach described below. These factors are difficult to observe in the field and potentially vary widely.

The authors used the revised savings equation and trap-level parameters to calculate the revised savings estimates, which were then totaled by site and compared to the billing analysis results of each qualified site. The comparisons consisted of creating a ratio of the realized savings (billing analysis results), to that of the reported savings (or, in this case, our revised savings). The billing analysis results were compared to the ex ante values and the newly developed revised savings by generating both savings weighted and unweighted ratio values, plotting them, and calculating the relative precision of each value.

Using the operating status listed for each trap in the master inventory, a conditional statement was created to assign the "updated" leak factors based on the listed status. Value ranges were assigned to each of the three parameters to be calibrated (CR, LF1, and LF2) along with the overall weighted and unweighted ratios. The authors used Excel's evolutionary solver package to adjust the targeted parameters from the revised savings formula (CRF, LF1, and LF2) within the specified engineering constraints (e.g., the factors cannot be less than 0 or greater than 1) with the goal of minimizing the statistical uncertainty of the overall weighted ratio. Table 3 provides a summary of the savings ratios and relative precision of each set of values.

Table 3. Realized Savings Ratios

Savings Source	BA Savings / Source Savings	Relative Precision
Tracked	86.2%	73.1%
Proposed model	98.5%	68.4%

The values from Table 3 are weighted by total savings, as taking a straight average of the savings ratios for each site would skew the parameter calibration to "favor" sites with smaller savings estimates. The straight average of savings ratios was calculated to be 107% for the tracked savings, indicating that larger projects were more likely than smaller ones to have overestimated savings compared to the bills. The goal of the parameter calibration was to bring the predicted savings estimate closer to the billing analysis estimate (a perfect match would be a value of 100%). Further illustrating the point, Figure 3, below, plots the reported savings against the billing analysis savings. The goal is for the model based estimates to move closer to the ideal line, as shown by the arrows.

The snowflake plots in Figure 3 show an overall savings ratio value moderately closer to that of any of the initial savings estimates and with a lower level of uncertainty. The net effect is an average savings estimate that is 12.5% lower than the tracking savings, a corresponding 12.3% higher savings ratio, and a modestly improved variability, as measured by relative precision. The average savings ratio of the projects used in the parameter calibration is significantly higher, indicating that savings could be underestimated for the "average" site. Resultant values from the parameter calibration analysis are shown in Table 4, below.

Table 4. Parameter Calibration Results

Parameter	Revised Value
Condensate return factor	36.3%
Leaking factor	26.4%
Blowing by	54.9%

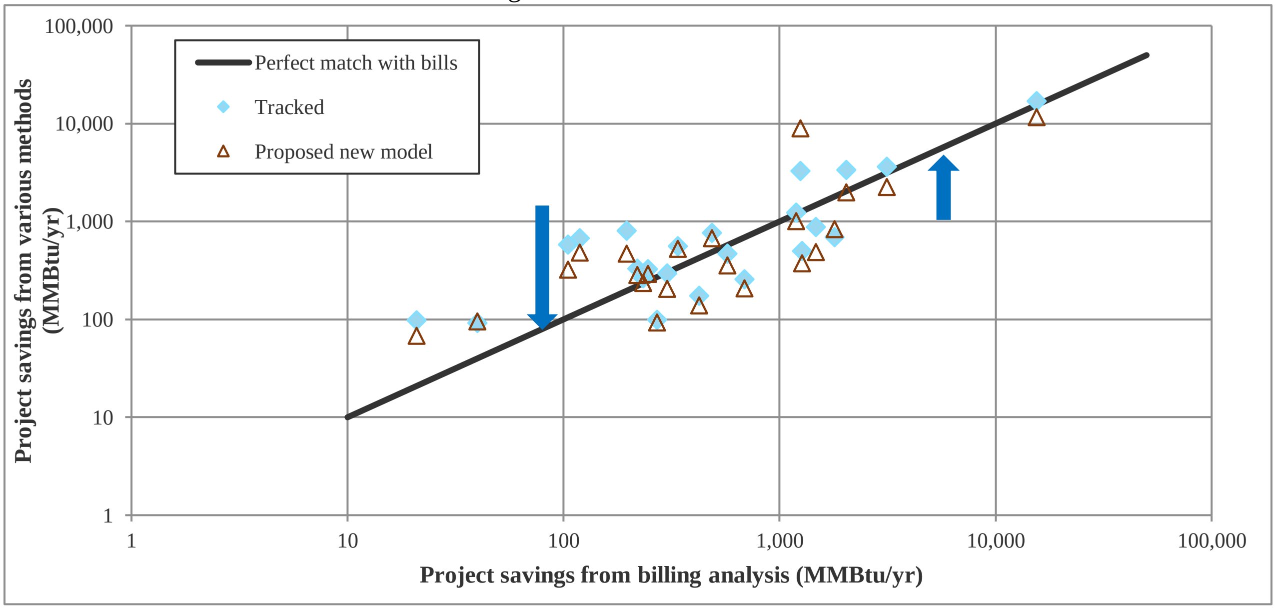

Figure 3. Modeled Savings Compared to Billing Data

Table 5. Deemed Savings Calculation Parameters

Parameter		Value		Basis
a	Trap orifice area	0.05	in^2	Population median (diameter of 0.25")
p	Pressure	22	psia	Population median, low pressure systems
p	Pressure	101	psia	Population median, medium-high pressure systems
h_f	Enthalpy, sat. liquid	196	Btu/lb_m	Engineering parameter, at low pressure
h_g	Enthalpy, sat. steam	1,156	Btu/lb_m	Engineering parameter, at low pressure
h_f	Enthalpy, sat. liquid	295	Btu/lb_m	Engineering parameter, at high pressure
hg	Enthalpy, sat. steam	1,186	Btu/lb_m	Engineering parameter, at high pressure
hr/yr	Annual hours trap pressurized	2,802	hr/yr	Sample weighted average
η	Boiler combustion + HX efficiency	80.0	%	Population median, engineering judgment
C_d	Discharge coefficient	70.0	%	Population median, engineering judgment
CR	Condensate return factor	36.3	%	Sample analysis
LF	Leak factor	36.9	%	Sample weighted average from analysis
LPIR	Low pressure trap incidence rate	90.0	%	Population observation
RoF	Rate of failure in bulk installations	50.0	%	Industry standard value [4]

Deemed Value

The deemed savings estimate was calculated by using the participant averages as the input parameters to the revised savings equation. The participant averages were derived from the custom project trap inventory imported from the project files into the master spreadsheet. This approach is generally preferred to averaging the overall per-trap savings value, as it allows for a combination of continuous and discrete variables. For continuous variables (such as orifice size), the individual trap values were averaged without weighting them. For discrete variables, the individual values were aggregated using a weighted average (based on steam trap counts). The participant average inputs and engineering parameters used to calculate the revised deemed savings estimate can be found in Table 5 while the actual revised deemed savings estimate is shown in Table 6.

Table 6. Deemed Savings Value

Parameter	Revised Value (MMBtu/yr)
Per trap savings	12.2

The revised estimate is 53% lower than the prior value used by MA program staff. The four prescriptive projects that cleared the survey and billing analysis screening criteria yielded an overall savings ratio of 19% and an average value of 35%. This corroborates the results of the updated deemed value but can only be considered suggestive, as the sample is too small to be representative of all prescriptive projects. Furthermore, the total tracked savings values for these four projects represented 85% of the total weather-normalized pre-project annual usage at those sites, highly unlikely estimates.

CONCLUSIONS

While the modern world has seen many advancements in both the central and peripheral technologies impacting the energy consumption of building equipment, modern-day steam traps have not strayed far from their early predecessors. Benefits to performing steam trap maintenance and repairs on a regular basis are generally understood as being a benefit to facility managers. But like the technology itself, the precise understanding of its impacts on a facility's steam use remains unchanged from 100 years ago. While there are a number of factors contributing to this issue that may never be fully resolved, the authors have made strides to objectively examine the observable impacts of steam traps in a realistic manner.

The authors have developed a custom savings equation that can be adopted for statewide use. Input parameters to the savings equation were identified and modified on an individual basis using information gathered from expert interviews and secondary research. Additionally, methodological simplifications were made to the revised equation to reduce the chance of field staff misinterpreting the operating status of an individual trap. Input parameters that were noted by experts as being difficult to observe in the field or estimate with engineering judgement were empirically derived using billing data from 24 custom projects.

An abbreviated overview of the revised savings equation can be found below. An in-depth discussion of each variable in the equation can be found in the Formula Structure Refinement section of the report.

$$\text{Energy loss}\left(\frac{\text{Btu}}{\text{yr}}\right)=\frac{60\times a\times P^{0.97}\times LF\times C_D\times\left(h_g\text{-}h_f\right)\times CR\times\frac{\text{hr}}{\text{yr}}}{\eta}$$

Equation (1)

The leak factors and condensate return factors were identified as the variables with the most uncertainty within the equation, and therefore were the focus of the parameter calibration in the algorithm refinement section. The four parameters C_D, η, CR, and LF are present in every trap calculation and multiplicative with one another. If the assumed value of C_D or η is incorrect, the research on CR and LF inherently corrects for this.

Adopting the revised custom savings equation statewide provides an opportunity for PAs to maintain uniformity and consistency in the estimation of steam trap savings across the state, while moderately improving the equation's predictive ability and reducing the variability of the estimates.

The new revised value has been generated using the updated savings equation and average custom trap inventory parameters. The revised per-trap annual deemed savings value is 12.2 MMBtu.

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