

It's About Time: Capturing the Benefits of High Maintenance for Steam Traps

Joseph St. John and Miriam Goldberg (DNV)

Sharon Jones (Lexicon Energy)¹

ABSTRACT

Operations and maintenance (O&M) measures are evaluation challenges with behavioral components and uncertainty about persistence. Traditionally, O&M measures such as steam trap repairs, compressed air leak repairs, and retro-commissioning are treated as one-time events with the failed state as the baseline. In practice, the benefits of these measures can accrue from repeated attention over time rather than one-time fixes.

This paper focuses on a common gas measure, steam trap testing and repair, to illustrate a methodology for assessing the effective measure life for repeatable O&M measures. The methodology characterizes how the program modified the customers' behavior around the repair frequency, rather than addressing point-in-time deficiencies. With this approach, the attribution question is not whether the customer would have taken a given one-time action without the program, but how the program changed the frequency of the O&M.

Shifting to a behavior-change perspective from a one-time event lens affects lifetime savings calculations considerably. This paper presents an updated formulation for quantifying lifetime impacts by incorporating the change from baseline repair frequency to with-program frequency, rather than assuming the customer would have perpetually forgone repair work absent the program. Trap failures over time are estimated in baseline and post-case scenarios with data collected on repair frequencies with and without the program. The analysis output is an "adjusted measure life" that depends on the time between repair events with and without the program, and the survival curve of the equipment. The results are illustrated with examples for various conditions. This paper offers a template for other sustained-action O&M measures.

Introduction

This paper presents a methodology for determining the effective measure life of a maintenance measure based on the program's effect on the frequency of the maintenance. The specific measure addressed is steam trap test and repair.

The paper begins with some background information on steam traps, as well as the theory behind how energy losses can be reduced from regular steam trap maintenance. We then present the methodology for assessing the years of savings attributable to a trap repair program and illustrate the method for various scenarios. The paper also summarizes some of the ongoing work that the research team is engaged in related to steam traps.

We conclude with some observations on the implications of this approach for the specific measure studied and for other maintenance measures.

Steam Trap Background

The main purpose of a steam trap is to contain steam until it has done useful work and has given up its latent heat of vaporization, or more simply, condensed. The trap allows the

¹ The authors thank Sue Haselhorst, Olav Hegland, Cameron Kinney, Ryan Brown, George Sorin Ioan, and Chad Talarico for helpful discussions during the development of this work.

condensate, i.e., liquid water, to escape while holding back the steam. In addition, some steam traps can allow air and other non-condensables trapped within steam lines to vent, either during startup, or normal operation. Air is undesirable in a steam line because it takes up space, reducing the carrying capacity of the steam line and reducing heat transfer. In addition, the oxygen contained in air can cause oxidation and pitting in the steam line, ultimately requiring more repairs, and carbon dioxide in the condensate return line can create carbonic acid and corrode metal pipes (Dyer, 1987).

Malfunctioning traps waste a lot of energy and money and can be a result of either the traps themselves or problems that originate in the steam line (such a lack of strainers, or poor boiler feedwater treatment). Dirt, corrosion, water hammer, and exposure to sub-freezing temperatures are some of the primary reasons that traps fail. Traps are commonly designed to fail open so that condensate does not back up into the steam lines (Dyer, 1987). A trap that fails open wastes energy by short-circuiting useful steam back to the boiler before it can be used effectively. There is typically no immediate indicator when a steam trap fails, so generally, traps need to be tested by trained technicians periodically, and the failed traps are either repaired or replaced.

Apart from addressing issues with the steam distribution system itself (strainers, improved boiler feedwater treatment), there are three primary ways for a facility to reduce energy losses from malfunctioning steam traps, which are listed below:

1. Increase the frequency of steam trap test/repair.
2. Keep the frequency that steam traps are tested and repaired the same but install steam traps that are known last longer than standard traps (James D. Acers Company 2011).
3. Install self-monitoring traps that can alert the steam plant operator when a steam trap has failed and needs to be replaced (or repaired) (New York State Joint Utilities 2020).

This paper presents an approach based on assessing how much a program increases the frequency of steam trap test/repair. Most steam trap energy efficiency programs currently are not designed to encourage longer lasting traps, or traps that self-monitor, although there are some who are starting to offer incentives for self-monitoring traps (New York State Joint Utilities 2020).

For purposes of this paper, we assume a constant savings per year for a trap that is in a repaired rather than failed state; this allows us to focus on the number of avoided years in a failed state per repaired trap.

Current Measure Life Estimates

Table 1 provides estimates of steam trap technical equipment life² from various sources. DNV GL (2015) found that most technical reference manuals cite the 2006 Southern California Gas steam trap workpaper (SCG 2006), which assumes a 6-year technical equipment life for steam traps, based on interviews with several vendors. Estimates from DNV GL (2015) are in

² Technical equipment life is the time when 50% failure rate is reached absent any testing and repair events. So, if the historical failure rate is 8.3% per year, the technical equipment life can be estimated by 50% failure rate / 8.3% failed per year = 6 years.

line with the SCG estimate, assuming the same percentage of all traps failing each year. The James D. Acers (2011) analysis produced a similar estimate using a parametric model form, and a somewhat shorter estimate with the non-parametric Kaplan-Meier method. Based on these results, we assume 6 years as the median time to failure for a repaired trap for purposes of the illustrations in this paper.

Table 1. List of sources for steam trap technical equipment life

Description	Citation	Technical Equipment Life (Years)	Notes
Steam Traps and Mean Time to Failure: An Analysis of Steam Trap Survival Over Time	James D. Acers Company (2011)	4.5 (Descriptive/ Non-parametric, Kaplan-Meier)	Mean time to failure based on data collected from 2,800 thermodynamic disc traps between 1999 and 2011 on a 150-psig steam system
		5.9 (Predictive/ Parametric, Weibull)	
2006 Southern California Gas Steam Trap Workpaper	SCG (2006)	6.0	Based on conversations with several vendors.
Massachusetts 2013 Prescriptive Gas Impact Evaluation Steam Trap Evaluation Phase 1	DNV GL (2015)	6.0 (linear)	Average failure rate for 2013, 2014, and 2015 of 242 float and thermostatic traps at a high-rise office building is 8.3%. So, 50% failure / 8.3% per year = 6.0 years ³
		5.9 (linear)	Average failure rate for 2012 and 2013 of 650 traps of many different types is 8.5%. So, 50% failure/8.5% = 5.9 years ⁴

Avoided Years in a Failed State Attributable to the Program

The technical equipment life values in Table 1 estimate the median time to failure for a repaired trap, absent other intervention. However, this median time to failure is not the same as the number of years of avoided failure attributable to the program.

Suppose that at time 0 the program tests a certain set of traps, and repairs⁵ any that are failed, and that, without program intervention, the facility would normally be conducting a next test/repair event for the same set of traps in, say, 4 years. Then all the traps that were repaired by

³ Technical equipment life is the time when 50% failure rate is reached. So, if the historical failure rate is 8.3% per year, the technical equipment life can be estimated by 50% failure rate / 8.3% failed per year = 6 years.

⁴ Ibid.

⁵ For simplicity, this paper uses “repair” to indicate “repair or replace.”

the program at time 0 would have been found and repaired at the end of 4 years. In this case, it wouldn't make sense to credit the program with more than 4 years of savings.

The phrase “attributable to the program” is deliberate here. The phrase means the difference in time between how long failed traps are in service with the program in place compared to how long failed traps would have been in service absent the program. Thus, assessing the effective measure life in terms of the program-attributable reduction in the time in failure is consistent with net savings, as defined by the Uniform Methods Project, Chapter 21 (Violette and Rathbun, 2017). That is, when evaluating a maintenance measure that may be conducted at varying frequency, rather than attempting to determine whether a specific maintenance event would have occurred absent the program, net-to-gross surveys need to address how the program has changed the timing and frequency of these events.

Using this information, we calculate the Adjusted Measure Life (*AML*) as the avoided trap-years of failure per repaired trap. This calculation is shown in Equation (1):

$$(1) \quad AML = (TYF_{BL} - TYF_P)/R_P$$

Where for a given time period equal to the baseline test/repair cycle length:

TyF_{BL}	=	Total trap-years in failure under the baseline test/repair regime
TyF_P	=	Total trap-years in failure with-program test/repair regime
R_P	=	Number of traps repaired by the program

Both the total trap-years in failure, *TYF*, and the number of traps repaired, R_P , are expressed as fractions of all traps inspected in each iteration of the cycle. That is, *TYF* is the total trap-years in failure per tested trap per baseline cycle.

The next section describes how the total years in failure *TYF* and proportion of traps repaired, R , are determined for the baseline and with-program cases.

Exponential Model of Time to Failure

To estimate the effect of more frequent test/repair events, we assume an exponential failure model. The exponential model is a common assumption for time to failure and is consistent visually with the data presented by James D. Acers Company (2011). With an exponential failure model, the proportion of initially working traps that fail in a given time span is a function only of the length of time. That is, the proportion of initially working traps that fail each year (or each week or each day) is a constant.

Exponential Model Basics

Under the exponential model, starting from time 0 at which there are no failed traps (test/repair cycle just completed) the proportion, $F(T)$, of traps that have failed by time T , and the corresponding proportion, $S(T)$, surviving to time T are given by:

$$(2) \quad F(T) = 1 - e^{-T/\mu}$$

$$(3) \quad S(T) = e^{-T/\mu}$$

Where:

T = Elapsed time
 μ = Mean time to failure

Figure 1 illustrates the failure and survival curves for an exponential failure process with median time to failure of 6 years, indicated on the time axis by the dashed green line. That is, at 6 years, half of the traps have failed, and half are surviving. Mathematically, at $T = 6 \text{ years}$, $F(T) = S(T) = 50\%$. This is the point on the graph where the failure curve, $F(T)$, and the survival curve, $S(T)$, cross. For the assumed median time to failure of 6 years, the mean time to failure, indicated on the time axis by the dashed orange line, is 8.7 years.⁶

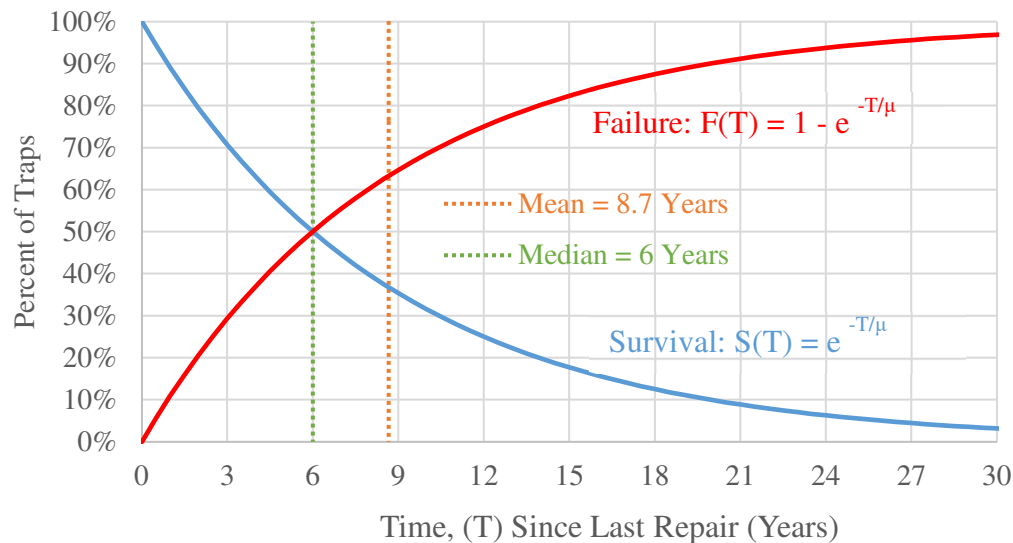


Figure 1. General Exponential Model, for median technical equipment life of 6 years

Time in Failure

Using the exponential model, we can calculate the average time in failure for traps failed within a given test-repair cycle of length L . Specifically, let

μ_L = the average time to failure for traps that fail between time 0 and time L
 η_L = the average time that traps failed between time 0 and time L remain in failure before being repaired at time L .

The average time to failure given that failure occurred within elapsed time T is calculated from the exponential distribution as the conditional expectation $E(t|t \leq T)$ of the failure time t given that $t \leq T$. It is possible to show that for any elapsed time T :

⁶ In general, for an exponential model, the median is equal to $\ln(2)$ times the mean.

$$(4) \quad E(t|t \leq T) = \mu - T \frac{e^{-T/\mu}}{1 - e^{-T/\mu}}$$

Thus, when the elapsed time of interest is the test/repair cycle length L ,

$$(5) \quad E(t|t \leq L) = \mu - L \frac{e^{-L/\mu}}{1 - e^{-L/\mu}}$$

The average time, η_L , that a failed trap stays in a failed state is the difference between the cycle length, L , and this conditional expected failure time. That is,

$$(6) \quad \eta_L = L - \mu_L$$

Figure 2 shows the expected time to failure for traps failed within cycles of varying length L . This conditional expected age at failure, μ_L , is always less than the unconditional mean μ , indicated in the Figure by the dotted line blue line. (Recall that $\mu = 8.7$ years in this example).

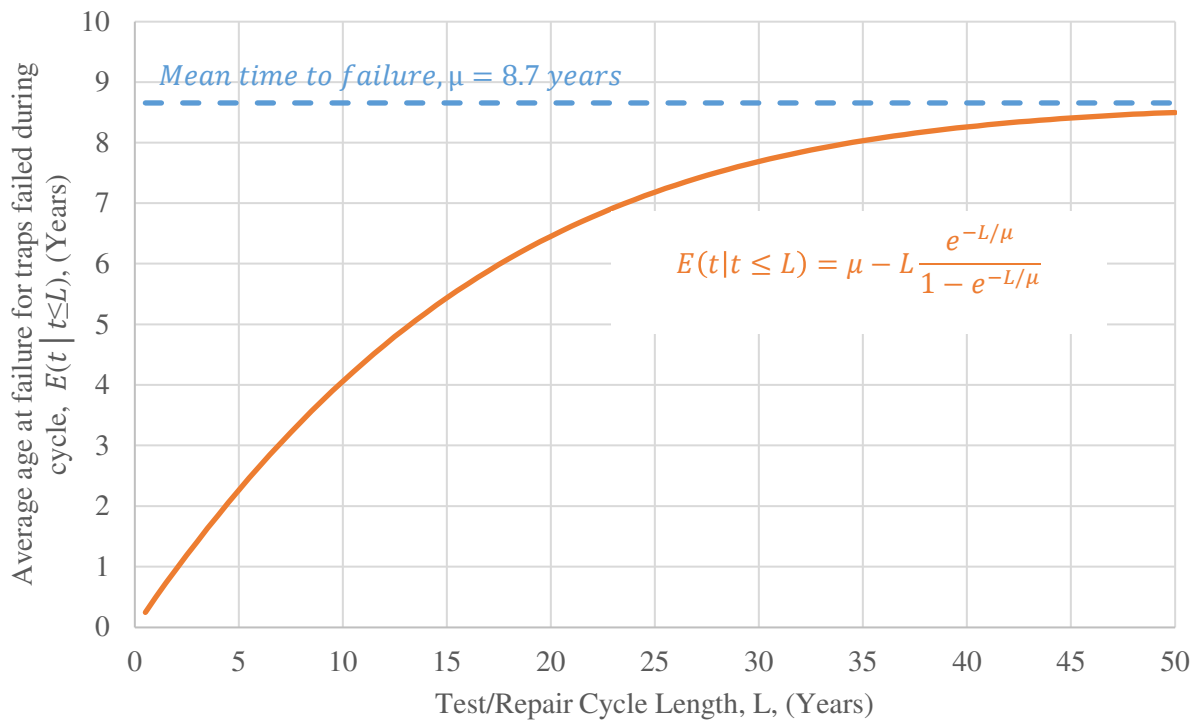


Figure 2. Average time to failure for traps failed within cycle length L , exponential failure distribution with median time to failure = 6 years

Thus, for a baseline cycle length, L_B , the proportion of traps failed and repaired at the end of the cycle will be $F(L_B)$, and the average time in failure for these traps will be η_{L_B} .

Avoided Time in Failure

Now, suppose that with the efficiency program, the time between inspections, or cycle length, is reduced to L_P . Then, within each with-program cycle there will be a proportion $F(L_P)$ traps failed and repaired, each with an average time in failure of η_{LP} . There will be L_B/L_P such cycles within the time L_B of the baseline cycle length. Thus, the total avoided trap-years in failure, $ATYF$, per tested trap in moving from cycle length L_B to cycle length L_P is given by:

$$(7) \quad ATYF = F(L_B) \eta_{LB} - (L_B/L_P) F(L_P) \eta_{LP}$$

The total traps repaired over that same time-frame in the with-program case, as a fraction of the total traps in place, is:

$$(8) \quad R_{PB} = (L_B/L_P) F(L_P)$$

Thus, the avoided trap-years in failure per with-program repaired trap, also known as the adjusted measure life (AML) is given by:

$$(9) \quad AML = ATYF/R_{PB}$$

$$\begin{aligned} &= \frac{F(L_B) \eta_{LB} - (L_B/L_P) F(L_P) \eta_{LP}}{(L_B/L_P) F(L_P)} \\ &= \frac{F(L_B)}{F(L_P)} \cdot \frac{L_P}{L_B} \cdot \eta_{LB} - \eta_{LP} \end{aligned}$$

The calculation is summarized in Table 2, in general form and for the specific case of baseline cycle length $L_B = 4 \text{ years}$, with-program cycle length $L_P = 1 \text{ year}$. For this case, the table shows that the average avoided time in failure per program-repaired trap is $AML = 1.3 \text{ years}$. This is substantially less than the 6-year median time to failure of a repaired trap. The reason is that even in the baseline case the average time a failed trap is in failure is only a little over 2 years. The with-program cycle mitigates a portion of this time in failure.

Table 2. Adjusted Measure Life (AML) calculation illustrated for baseline cycle length 4 years, with-Program cycle length 1 year, median time to failure = 6 years, mean time to failure = 8.7 years

Parameter	Formula		Value	
	Baseline	With-Program	Baseline	With-Program
Cycle length	L_B	L_P	4 years	1 year
Proportion failed at end of cycle, where $\mu = 8.7 \text{ years}$	$F(L_B) = 1 - e^{-\mu/L_B}$	$F(L_P) = 1 - e^{-\mu/L_P}$	37%	11%

Parameter	Formula		Value	
	Baseline	With-Program	Baseline	With-Program
Total failed/repaired by end of baseline cycle	$R_B = F(L_B)$	$R_{PB} =$ $\left(\frac{L_B}{L_P}\right) \cdot F(L_P)$	37%	44%
Average time to failure, where $\mu = 8.7 \text{ years}$	$\mu_{LB} =$ $\mu - L_B \frac{e^{-L_B/\mu}}{1 - e^{-L_B/\mu}}$	$\mu_{LP} =$ $\mu - L_P \frac{e^{-L_P/\mu}}{1 - e^{-L_P/\mu}}$	1.85 years	0.49 years
Average years in failure for failed traps	$\eta_{LB} =$ $L_B - \mu_{LB}$	$\eta_{LP} =$ $L_P - \mu_{LP}$	2.15 years	0.51 years
Trap-years in failure during a baseline cycle period, per trap in place	$F(L_B)\eta_{LB}$	$(L_B/L_P)F(L_P)\eta_{LP}$	0.80 trap – years	0.22 trap – years
Avoided trap-years in failure during a baseline cycle period, per trap in place	$ATYF =$ $F(L_B)\eta_{LB} - (L_B/L_P)F(L_P)\eta_{LP}$		0.57 trap – years	
AML = Avoided trap-years in failure per repaired trap	$AML =$ $ATYF/R_{PB}$		1.31 years	

Within the 4-year baseline cycle length, we would have 1 test-repair in the baseline case, at which we expect to have 37% of the traps failed, with an average of 2.15 years from the time failed until the repair time at the end of 4 years. With the program, there would be 4 test/repair events over the same 4 years, each expecting to find 11 % failed. Thus, the total number of repairs over the 4-year period is 44% of the number tested each time, slightly more than the total for the baseline test/repair. Essentially, all the traps that would fail over a period of 4 years in the baseline case do so also in the with-program case; in addition, some traps repaired each year with the program cycle fail again before the end of the 4 years. Nonetheless, the total trap-years in failure is less with the program cycle than under the baseline cycle.

Figure 3 illustrates the failure and repair pattern for the baseline cycle of 4 years and with-program cycle of 1 year. Consistent with Table 2, the figure shows that under the with-program cycle, the number failed at any one time is capped at 11%, the number failed by the end of 1 year, but reaches 37% by the end of the baseline cycle. On the other hand, the cumulative number repaired by the end of a 4-year period is greater under the with-program regime than under the baseline regime, 44% vs. 37%.

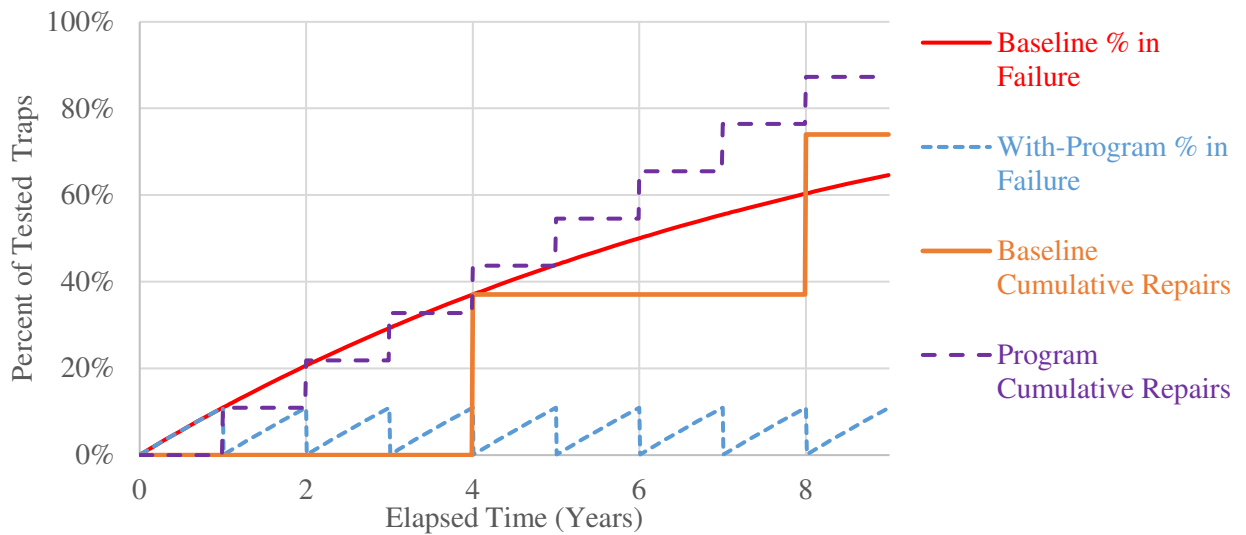


Figure 3. Proportion of traps failed and cumulative repaired versus time for baseline 4-year and with-program 1-year cycles, median time to failure = 6 years

Results for Varying Baseline and with-Program Test/Repair Cycle Lengths

Table 3 shows the AML results for various baseline and with-program test/repair cycle lengths, all with median time to failure of 6 years. The results show that the AML, the avoided years in failure per repair, would approach the median technical life only for very long baseline cycle lengths. A baseline test/repair frequency of every 30 years would imply that test/repair is almost never done, and nearly all traps would be found failed when it is; however, this situation is unlikely, given the problems it would imply for the steam system.

Table 3. Adjusted Measure Life (AML) for varying baseline and with-Program repair cycle lengths

Baseline repair cycle length (L_B)	AML with program repair cycle (L_P) of 2 years	AML with program repair cycle (L_P) of 1 year	AML with program repair cycle (L_P) of 0.5 years
1		0	0.24
2	0	0.5	0.7
3	0.5	0.9	1.1
4	0.9	1.3	1.5
6	1.7	2	2.2
12	3.4	3.7	3.8
30	5.9	6.1	6.2

Other Baseline Scenarios

The results in Table 2 and Table 3 all assume a regular frequency of test/repair in the baseline case which is increased with the program. While regular cycles may not exist either

before or after the program is in place, the analysis can be used as an approximation even when the repair frequency is somewhat irregular under either regime, so long as there are ongoing repairs under the regimes.

However, there are cases where these conditions don't hold.

One-Time Program Events

The *AML* developed above assumes that with or without the program in place the facility tests/repairs periodically, if somewhat irregularly. However, a somewhat different analysis applies if the facility participates in the program only once and not repeatedly.

Suppose as in the first example, that the facility is testing/repairing roughly every 4 years in the baseline case. Further suppose the facility conducts one mid-cycle test/repair with the program, then goes back to its baseline practice. If the mid-cycle test/repair is conducted at the end of year 2, the expected proportion of traps repaired is 21%, as seen in Figure 3, and the avoided time in failure per repaired trap is 2 years—the time until the next “regular” test/repair. This is twice as much as the *AML* indicated in Table 3 for moving from a baseline cycle of 4 years to a with-program cycle of 2 years.

The difference between the two cases has to do with the number of repairs conducted *through the program*. For the analysis indicated in Table 2 and Table 3, we assume that *all* repairs in the with-program case are conducted through the program, including those that would have been conducted under the baseline cycle. The *AML* is the average avoided years in failure *per trap repaired by the program*. For the one-time participation case, only the incremental test event and associated repairs are conducted through the program and contribute to the *AML*.

On the other hand, in the one-time case, it's also possible that future test/repairs are pushed out to the baseline time from the incremental event. That is, rather than having an extra test/repair at year 2 then returning to the regular cycle at years 4, 8, etc., the next test/repairs might occur at years 6, 10, etc. In that case, most of the benefit of early repairs for the traps failed by year 2 are offset by the delayed repairs for traps failed from years 2 to 4. The “increased frequency” model of Table 2 and Table 3 provides a middle ground between these two possibilities.

No Maintenance in the Baseline Case

There may be cases where the baseline is not regular or irregular maintenance but no maintenance. For steam traps, this would correspond to allowing all traps to stay failed open. For such cases, the technical lifetime of the trap repair can reasonably be used as the measure life. As noted, we believe this situation is unlikely, since as noted earlier, not only do failed traps reduce heat transfer effectiveness of the boiler system, but they can also cause pitting and oxidation damage to the steam pipes and components.

Ongoing Non-Program Test/Repair

Another possibility is that the program increases the frequency of test/repair events, but only some of these events are conducted through the program. This might be the case for example if program participation is not allowed more often than annually, and a customer with a 1-year baseline cycle uses the program to move to a more frequent test/repair. In such cases, the *AML* formula becomes

$$(10) \quad AML = ATYF / (q \cdot R_{PB})$$

where q is the proportion of repairs that are conducted by the program, as a fraction of all the repairs that occur under the with-program cycle.

For example, a facility might be testing/repairing annually on their own. If they conduct the same test/repairs with the program that they'd have done on their own, there is no difference between with-program and baseline frequency, so the attributable years of savings is 0. If instead they continue to conduct annual test/repair on their own and add a regular midyear test/repair via the program, the improvement is from a 1-year to ½-year cycle length.

If the program paid for all the repairs under the with-program regime, the AML would be $ATYF / R_{PB} = 0.27 / 11\% = 0.24$ years as indicated in the first row of Table 3. But when the program pays for only every other test/repair event, the attributable years of savings *per program repair* is twice as great, $ATYF / (\frac{1}{2} R_{PB}) = 0.48$ years, because the AML formula has a factor of $q = \frac{1}{2}$ in the denominator. In this case, the years of savings attributable to the program is almost the same as the reduction in cycle length.

Ongoing and Future Work

The research team is currently engaged with a group of program administrators in one state that have been offering incentives for steam trap testing and repair work for more than 10 years. The current research is interviewing past participants to assess baseline and post-case test- and repair frequencies. The work will identify the proportions of program trap repairs that have resulted changes to the frequency of test/repair, and what proportions of repairs are being conducted with and without the program, to develop an average AML value. This research project is also investigating whether billing analyses of past steam trap projects can be used to refine and calibrate a tool which is used to estimate site specific annual energy losses per failed trap, ($ELPFT_A$) values.

Future work may also include interviewing non-participants, possibly in a jurisdiction which does not offer incentives for steam trap testing and repair, as well as in jurisdictions that do, to understand their behavior around steam trap testing and repair. This may help further pinpoint baseline test and repair frequencies for different customer types.

Conclusion

This paper presents an approach to assessing the effective measure life of a common maintenance measure, steam traps. The method characterizes how programs modify customers' behavior around the frequency of the maintenance, rather than being based solely on point-in-time deficiencies. With this approach, the Adjusted Measure Life (AML) is calculated in terms of the average years of savings attributable to each repair conducted by the program, and no further net-to-gross adjustment is required. Applying the method requires an estimate of the technical equipment life (median time to failure), as well as survey data on the frequency of repairs with and without the program.

The analysis shows that the attributable years of savings per program repair are lower than the median technical equipment life except in cases where the baseline repair cycle length is very long or there is no baseline maintenance. By contrast, assigning the median technical

equipment life of the repair as the measure life implicitly assumes that the customer would perpetually forgo repair work absent the program.

The analysis presented assumes that each participating facility has a number of units in place that at any given time are each in either a failed or fixed state, and that the maintenance event fixes any failed units. A similar analysis can be developed for a maintenance measure whose benefit decays over time. Thus, this paper offers a template for other sustained-action O&M measures where it is worthwhile to encourage routine repeat participation.

References

- DNV GL. 2015. *Massachusetts 2013 Prescriptive Gas Impact Evaluation: Steam Trap Evaluation Phase 1*. Massachusetts Gas Program Administrators and Massachusetts Energy Efficiency Advisory Council. <https://ma-eeac.org/wp-content/uploads/MA-2013-Prescriptive-Gas-Impact-Evaluation-Steam-Trap-Evaluation-Phase-1.pdf>
- DNV GL. 2017. *Steam Trap Evaluation Phase 2*. Massachusetts Gas Program Administrators and Massachusetts Energy Efficiency Advisory Council. <https://ma-eeac.org/wp-content/uploads/Steam-Trap-Evaluation-Phase-II.pdf>
- DOE (Department of Energy) 2012. *Energy Tips: Steam, Inspect and Repair Steam Traps*. Advanced Manufacturing Office. https://www.energy.gov/sites/prod/files/2014/05/f16/steam1_traps.pdf
- Dyer, D., G. Maples, and T. Maxwell. 1987. *Steam Efficiency Improvement*. Boiler Efficiency Institute. Auburn, AL.
- James D. Acers Company. 2011. *Steam Traps and Mean Time to Failure: An Analysis of Steam Trap Survival Over Time*.
- New York State Joint Utilities. 2020. *New York Standard Approach for Estimating Energy Savings from Energy Efficiency Programs – Residential, Multi-Family, and Commercial/Industrial Measures Version 8* [https://www3.dps.ny.gov/W/PSCWeb.nsf/96f0fec0b45a3c6485257688006a701a/72c23decff52920a85257f1100671bdd/\\$FILE/NYS%20TRM%20V8.pdf](https://www3.dps.ny.gov/W/PSCWeb.nsf/96f0fec0b45a3c6485257688006a701a/72c23decff52920a85257f1100671bdd/$FILE/NYS%20TRM%20V8.pdf)
- SCG (Southern California Gas). 2006. *Steam Traps: Workpaper for PY2006-2008, B-REP-05-599-21E, Revision E* https://www.sdge.com/sites/default/files/SteamTrap%2520Workpaper%2520%252811Dec06%2529_0.doc.
- Violette, Daniel M.; Rathbun, Pamela. (2017). Chapter 21: Estimating Net Savings – Common Practices: Methods for Determining Energy-Efficiency Savings for Specific Measures. Golden, CO; National Renewable Energy Laboratory. NREL/SR-7A40-68578. <http://www.nrel.gov/docs/fy17osti/68578.pdf>