CHAPTER 13

Benefits of Diagnostics

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Chapter 4: How to Start

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13.0 BENEFITS OF DIAGNOSTICS

Chapter 4 details the results of some research that determines how many of diagnostic techniques are used within utility programs. This work was conducted in late 2014 and indicates that between 56% and 74% of utilities currently do not use diagnostics. Although this figure may appear discouragingly large, when it is taken in context with the results of the 2006 research it shows that there has been an increase in the use of diagnostics throughout the course of this project. Thus before examining the sort of benefits that accrue for the 44% to 26% of utilities that undertake diagnostics it is useful to examine that baseline (no diagnostic) case.

If cable system diagnostics are not employed then there are essentially two options used to manage the reliability of the cable system; one major and one minor (the two right-hand columns of Figure 1):

1. Major: Run To Failure (RTF) – between 54% & 72%
    a. With use of outage data and simple heuristics i.e. "three strikes and out"
    b. Without use of outage data
2. Minor: Service Failure Modelling - use service failure data (accurate outage data segregated at the component level) to develop robust trends – approx. 2%

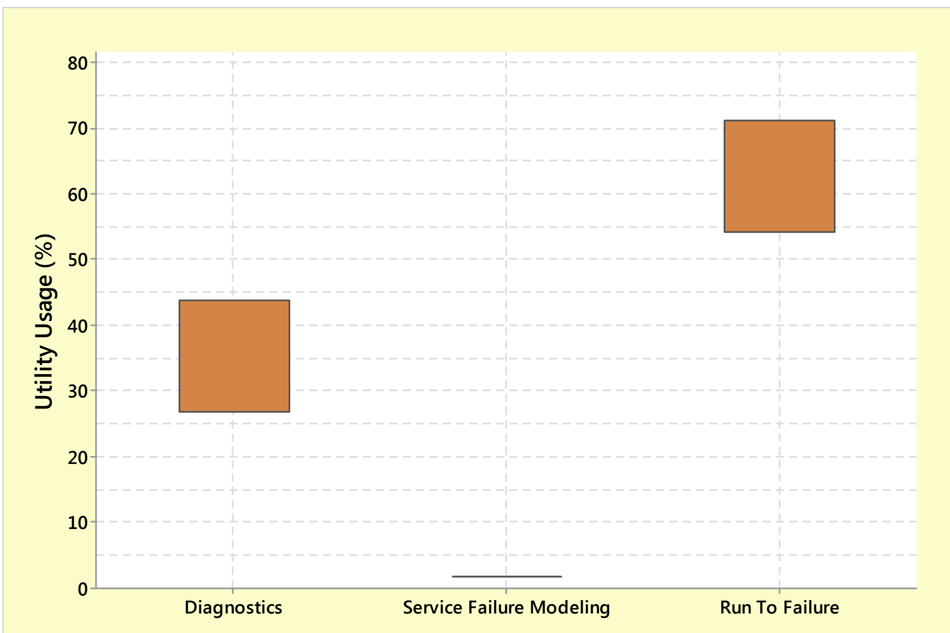

Figure 1: Methods Used To Manage MV Cable System Assets – the results of the research are imprecise, the boxes represent the most likely range of values

Generally speaking utilities face increasing pressure to maintain / improve reliability, and seek to do this with constrained resources (Operations & Maintenance (O&M) and Capital). Thus in the course of numerous discussions with utilities it is clear that twin goals / concepts have evolved:

A. Resource optimized Reliability - - Total Outage Cost reduction per dollar, SAIFI reduction per dollar, SAIDI reduction per dollar
B. Needs based resource forecasting - - how much resource will be required by the year 20xx, how much will I be able to do with today's resource in the year 20xx

Consequently it is useful to view the goals contained in A&B above in the context of the majority of utilities that do not undertake cable system diagnostics (the two right-hand columns of Figure 1). In most cases the metrics available to a utility are outage data and approximate age data. Thus for a utility which does not undertake cable system diagnostics:

I. The utility will not be able to establish the health of their assets in an unbiased way
II. The utility will not be able to establish how the health of their assets change with time or as the result of any repair / replacement / rehabilitation programs
III. In the absence of a) health data and b) how the asset health changes with time, the utility will not be able to accurately forecast
    a. Future resource needs (O&M and Capital) needs
    b. How far current resources will reach
    c. Efficacy of funded programs – determine if specific programs are optimal
    d. Determine the optimal portfolio of programs by running efficacy assessments for various "what if" scenarios

The remainder of this chapter will focus on

- How the cost / benefit of a diagnostic system might be estimated
- The ways in which diagnostics have assisted different utilities or the industry as a whole to address the shortcomings of the Run to Failure approach outlined in I to III above.

In addition the sections will introduce / discuss the useful basic concepts in this area.

13.1 Background/State of the Art

This section discusses the current state-of-the-art approaches to managing cable systems.

13.1.1 Hazard Curves

Hazard functions or rates have recently become of interest to asset managers as they work to predict future cable system reliability. The hazard rate is defined mathematically using conditional probability theory but is more concisely described as follows:

> *The hazard rate is the probability of failure in the next time interval given that the cable system has survived up to the present time.*

Hazard rates can be defined for any parametric distribution, but are most commonly discussed from the perspective of the Weibull distribution. The Weibull Distribution utilizes two (or three if desired) parameters, namely: the shape parameter (β) and scale parameter (α). These parameters are estimated using either a Least-squares or Maximum Likelihood approach using the actual time to failure data. The resulting estimates for α and β are then used to estimate the hazard function. The hazard model for Weibull-distributed data is shown in Equation 1.

$$h(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \qquad \textbf{Equation 1}$$

The changes in hazard rate with age forms the basis for the often referenced "bathtub" curve. A sample bathtub curve is shown Figure 2. As this example shows, the bathtub curve is composed of three general regions each with its own Weibull and, hence, hazard curve:

1. Infant Mortality or Burn-In (Weibull gradient < 1)
2. Normal / Reliable Operation (Weibull gradient = 1)
3. Aging or Wearout (Weibull Gradient > 1)

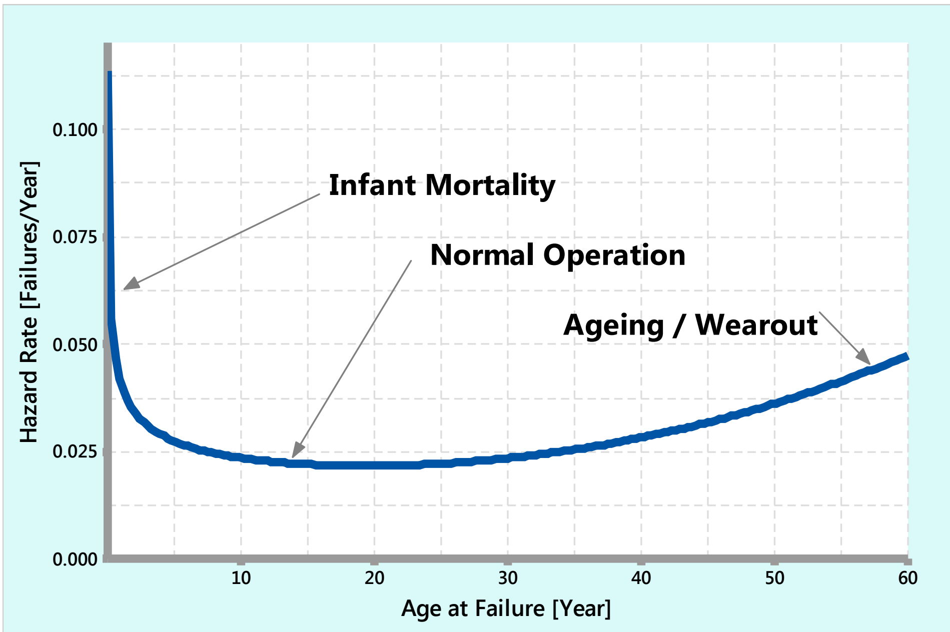

Figure 2: Example Bathtub Curve

The *infant mortality* stage represents only a small percentage of the total operational life of the cable system but can account for a high number of failures over a short period of time. Hence, these are very often "visible" issues. Such failures are sometimes termed as "burn-in" failures since the system reliability improves with time as defects are removed. During this stage it is better to leave things alone as older units are generally more reliable than newer ones.

Once the system passes the infant mortality stage, it operates normally with a low failure rate (purely random failures that are time independent) as represented by the *normal operation* region. Failures that occur during this period are not related to aging, in fact, this is the most reliable period in the system's lifetime. In practice, cable systems should spend the majority of their lifetimes in the *reliable operation* region.

On the other hand, as the cable system ages it moves from *normal operation* into the *aging* stage. This last region is the period during which most aging related failures occur as the failure rate continues to increase with time from this point forward. The actual onset of the aging stage is difficult to identify until the system is well into this stage.

The current state of the art views the bathtub curve and associated hazard rates as essentially deterministic for a given cable system and the age correlates to a single precise failure rate i.e. age is everything. The full curve is constructed from the available population and performance data for the entire utility system. At least three failure modes (regions with different Weibull gradients) should be identified during the analysis for a full bathtub curve to be constructed. Each of these failure modes will have their associated confidence intervals, thereby indicating the presence of several different possible bathtub curves for the same data. This gives rise to families of bathtub curves as illustrated in Figure 3. It is important to note that these curves were generated from the same three distributions using the familiar Monte Carlo approach.

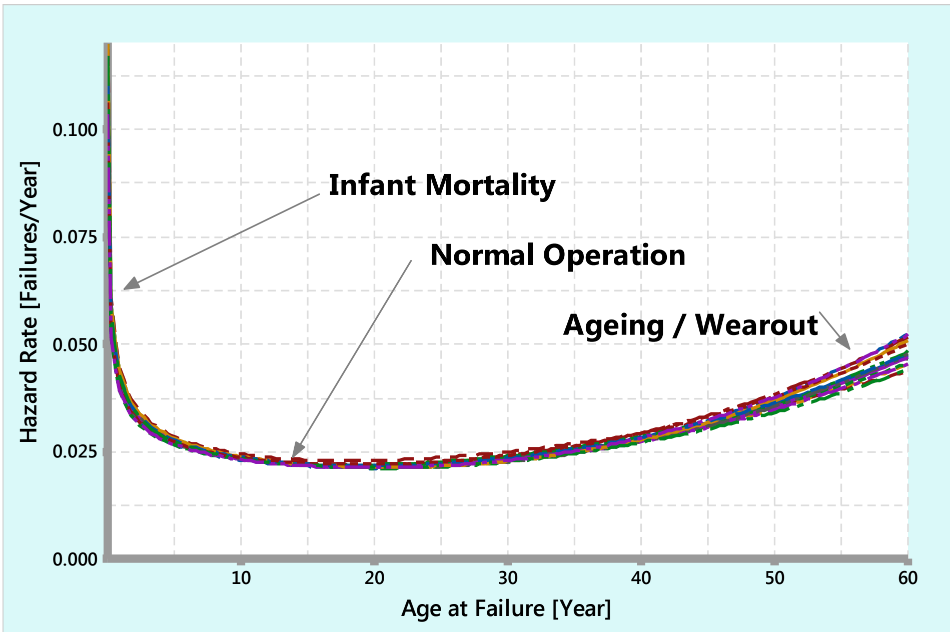

Figure 3: Family of Bathtub Curves for Randomized Data

The challenge where most effort has been focused in the industry is the data mining required to amass enough age-related performance data to be able to construct a complete or partial bathtub curve. Utility performance data rarely includes the age of the cable system at the time of failure and even less often identifies whether the failure occurred in the cable or an accessory. This is an ongoing problem that will continue to be a challenge for the industry.

Multiple Hazard Plots or Bathtub Curves are most often shown as examples. This leads to the question of whether this framework exists in reality of is just a theoretical construct. Many projects within the Reliability Group at NEETRAC has shown that the Bathtub Curves do exist and the areas are identifiable - Figure 4 & Figure 5 are two examples of where Bathtub Curves are valuable in understanding MV & HV / EHV cable system ageing respectively.

If a hazard plot is successfully constructed from field data, then the issue becomes how to assign a dollar value to each failure. In principle, there is a cost associated with each cable system failure.

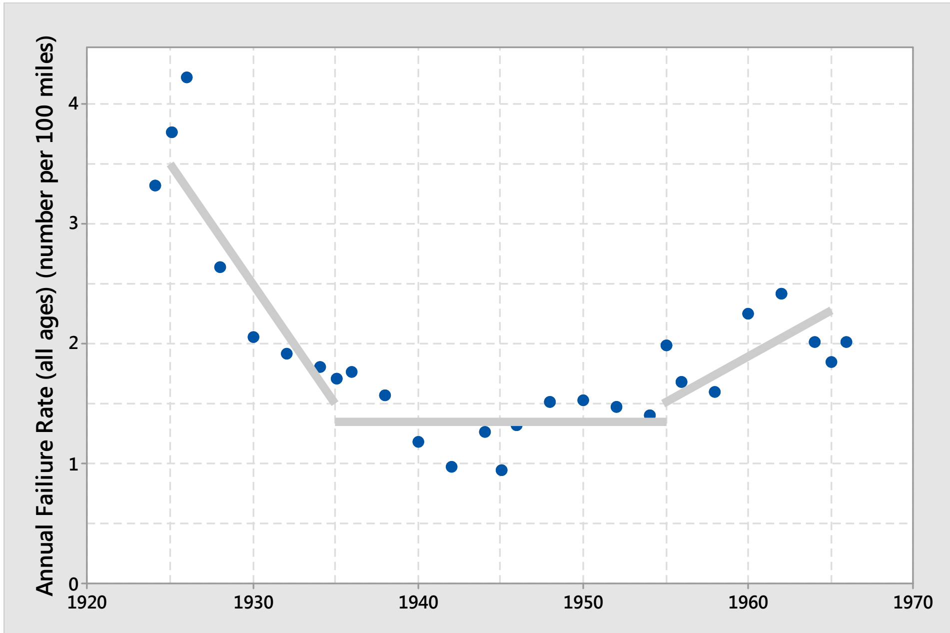

Figure 4: Bathtub Curve for PILC Cable Systems – Thue & Lawson

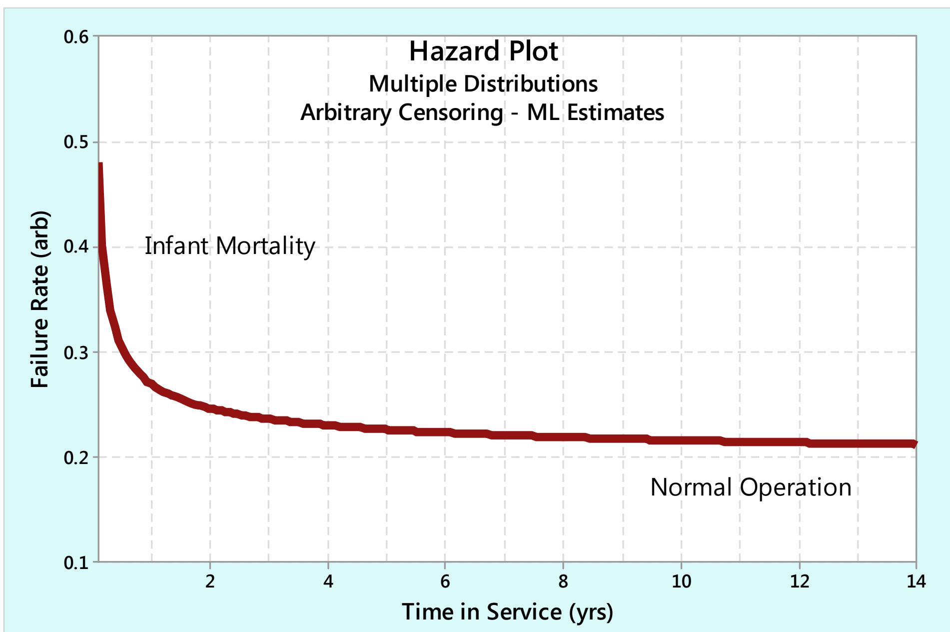

Figure 5: Bathtub Curve for HV and EHV Cable Systems – NEETRAC Member Research

13.2 Cost Elements for Life Costs

There are many costs associated with cable systems (MV and HV / EHV); the terminology and relationships used in this work is provided in Table 1. Rather than provide dollar estimates on the values as these vary widely between utilities, this section attempts to provide the cost components in terms of the costs of the cable. It is important to note that this table takes the perspective of "total cost of ownership" rather than the more commonly discussed installed cost

Table 1: High Level Definitions of Cost Terms

Cost Terms		Cost Element		Approx. Cost Multipliers (where input has been received) – rel to cable = 1
"Total Cost of Ownership"	"First" or "Installed" Cost	Standards		?
		Supplier Oversight		?
		Permitting / Approvals		?
		Cable	Accessories	1.1 – 1.3
		QA		.001
		Installation		10
		Commissioning		.1
		TOTAL		>12
	"Cable System Operational Life" Costs {excl cost of losses}	Maintenance	Diagnostics	See later
			Cost of Outage [$]	See later
			Service Restoration	See later
			Repair / Replace	See later
	Reliability Upgrade Costs	Diagnostics		See later
		Rehabilitation		3 – 6 (25% to 50% of "First Costs")
	"End of Life" Costs			?

$ experienced by the customer
? Costs are not known but they are incurred by utilities

The cost elements that comprise the "Cable System Operational Life" Costs (Table 1) are set out in Table 2 for both the Proactive (Diagnostics Used) and Reactive (Run to Failure) options. Where appropriate the differences in the costs associated with the two options are identified. This table again looks at relative costs but shows the relationships between the different elements. As an example, the number of outages for the Reactive Case will be larger than those experienced in the Proactive Case - denoted by X and x respectively.

Clearly the Costs most relevant for this work are those that comprise "Cable System Operational Life" Costs. Ultimately what we are, looking to compute is the difference between the "Proactive" and "Reactive" approaches to failures. The elements of these two costs are detailed in Table 2. It is generally assumed that Proactive Costs are lower than the Reactive Costs. If this hypothesis is true then D (the cost of a diagnostic program) must be less than the cost of unplanned outages to the customer and the cost of unplanned repairs.

Table 2: Definitions of the components within Proactive (Diagnostics Used) and Reactive (Run To Failure) elements of "Cable System Operational Life" Costs

Cost Terms	Cost Element	Proactive Approx. Cost Indications for x outages	Reactive Approx. Cost Indications for X outages (where X>x)
"Cable System Operational Life" Costs	Maintenance	M	M
	Diagnostics	D	
	Cost of Outage[$]	O*x	*O**X more failures in service X>x at a higher cost *O*>O
	Service Restoration	S*x	S*X more failures in service X>x
	Repair / Replace	R*x	R*X more failures in service requiring attention in an unplanned (expensive) manner X>x

$ experienced by the customer

During both CDFI phases, attempts were made to obtain cost data for each of the utility participants. The most challenging cost to understand was the impact a service failure or sequence of failures have on a utility's SAIDI, SAIFI, etc. as well as their customer impact. Through discussions with a number of participants, it is clear that these costs exist and are quite substantial but are difficult to quantify as they are not directly paid or identified by the utility. Crew, cable replacement, cable rejuvenation, switching, etc. costs are far more tangible and for purposes of this discussion will be termed as "Tangible" costs (Section 13.2.1). The other costs mentioned above may then be referred to as "Intangible" costs (Section 13.2.2). The interaction of these cost elements is somewhat similar to that of real and reactive power. Our ac systems cannot operate without both types of power even though reactive power is a far more abstract concept than real power. The Tangible and Intangible costs are similar in this respect.

13.2.1 Tangible Costs

The Tangible Costs have been garnered and estimated from a variety of sources. The ranges shown in Table 3 are judged to be a reasonable consensus from the variety of sources. It is not particularly useful to look for a single cost as this changes with technology, location, accounting practices, time acceptance of risk, etc. Thus it is best to accept that there is uncertainty and consider the ranges.

As shown in Table 3 there are different ways of describing the costs in terms of either "per foot" or "per segment" (length independent). This is an important distinction to be aware of as the cost of any remediation (repair / replacement / rehabilitation) will be driven by length. The diagnostic testing on the other hand is generally by segment – thus a 500 ft segment will cost the same as a 200 ft or a 4000 ft segment.

Table 3: Tangible Cost Elements for "Cable System Operational Life" Description and Guidelines		
Cost Element	**Description**	**CDFI Cost Range [$]**
Emergency Switching (assuming looped system)	Cost of identifying failed cable run and switching loop from normal condition to abnormal condition so that service is restored. This activity effectively determines SAIDI in the case that there is no second failure before the first is repaired	$400 – $800 per event
Repair Cost	Locating failure site within cable run and repairing with 1-2 repair splices as needed.	$1,500 - $2,500 per event
Replacement Cost	Install new run of cable	$15 - $25 per ft (single phase)
Rejuvenation Cost	Rejuvenate a single cable run	$4 - $13 per ft (single phase)
Diagnostic Testing Cost	Diagnostic testing by service provider	$3,400 - $6,700 per day or $850 - $1,600 per segment
	Diagnostic testing by utility	$1,600 - $2,500 per day or $400 - $650 per segment

13.2.2 Intangible Costs

Like reactive power, Intangible costs are essential to the estimation of the "Cable System Operational Life" cost. Yet these elements are the most difficult to understand in terms of value and impact. These costs are related to SAIDI, SAIFI, CAIDI, etc. and therefore quantify the effect of outages on customers. Thus, it is important to understand their numbers, types, locations, and importance in order to estimate the impact of unscheduled outages. Each cable run, if it were to fail, impacts a different group of customers which means its "Do Nothing" curve will look quite different from other similar cable runs in other areas.

The Department of Energy provides an "Interruption Cost Estimate" (ICE) Calculator to enable estimates to be made – upgraded in 2015. The ICE Calculator is a tool designed for electric reliability planners at utilities, government organizations or other entities that are interested in estimating interruption costs and/or the benefits associated with reliability improvements. Thus it is a useful tool for this work – specifically estimating the Cost of Outage in Table 2. In this case the Proactive Cost O would be associated with low values of SAIDI and SAIFI, whilst Reactive Cost *O* would be associated with higher values of SAIDI and SAIFI (see Table 2). The ICE tool requires cable system performance data (SAIDI etc.), location, load mix & income data (median income &

multiplier to median income). It is important to realize that the ICE Calculator only covers outages up to 16 hours; it is not intended to model sustained outages or blackouts.

In order to determine suitable customer impact values for use in the estimates in this document, a designed experiment was developed and executed which used the Interruption Cost Estimate (ICE) tool to estimate the impact of SAIDI and SAIFI on customers in different states. These data and the subsequent analyses were used to determine, for the US, the importance of the selected factors outlined above. The factors that are statistically significant are shown in Table 4. It is interesting that the Region / State did not show as a significant factor.

Table 4: Significant Factor Analysis for the Cost of an Outage Based on the ICE Calculator for Different Load Mixes

Importance of the Factors	Cost of Residential Customer Outages	Cost of Outages Small Industrial Customers	Cost of Outages Medium to Large Industrial Customers
First in Importance	Multiplier to Median Income		
Second in Importance	SAIFI	SAIDI	
Third in Importance	SAIDI	Interaction between SAIDI & SAIFI	Median Income

Each analysis resulted in an equation that may be used to estimate the cost of an outage. Considerable arithmetic simplification results if the Region / State can be omitted. In addition any estimates that are made can be assumed to be valid for any part of the US if the appropriate values for Median Income and / or Income Multiplier are used. The equations that resulted from the analysis are shown in Table 5.

Table 5: Outage Cost Estimate Equations from Analysis of ICE Calculator Output

Value Calculated	Best Fit Equation
Cost Residential [$/1000 Customers]	0.2941 Median Income+3228.9 Median Income Multiplier+5544 SAIFI+33.6 SAIDI [Min]+1.7 SAIFI*SAIDI [Min]-28470
Cost Small Commercial & Industrial [$/1000 Customers]	179924+0.10 Median Income+93380 Median Income Multiplier+157632 SAIFI+5226 SAIDI [Min]-1323 SAIFI*SAIDI [Min]
Cost Medium & Large Commercial & Industrial [$/1000 Customers]	46.2 Median Income+579098 Median Income Multiplier+919131 SAIFI+29613 SAIDI [Min]-6655 SAIFI*SAIDI [Min]- 3827412

Figure 6 to Figure 10 present a graphical representation of the results of the analyses for the main cost elements and provides a final summary.

Inspection of the curves shows that the SAIDI & SAIFI relationships to cost are very different for Commercial & Industrial installations when compared to Residential. Interestingly in Commercial

& Industrial installations the SAIFI has little effect (one plausible explanation is that there is no escalation factor the cost for interruption 1 is high and is equally high for interruption 3), whilst there is a clear SAIFI / SAIDI interaction in the Residential arena. Furthermore, the magnitudes of the associated outage costs are very different for the different installations.

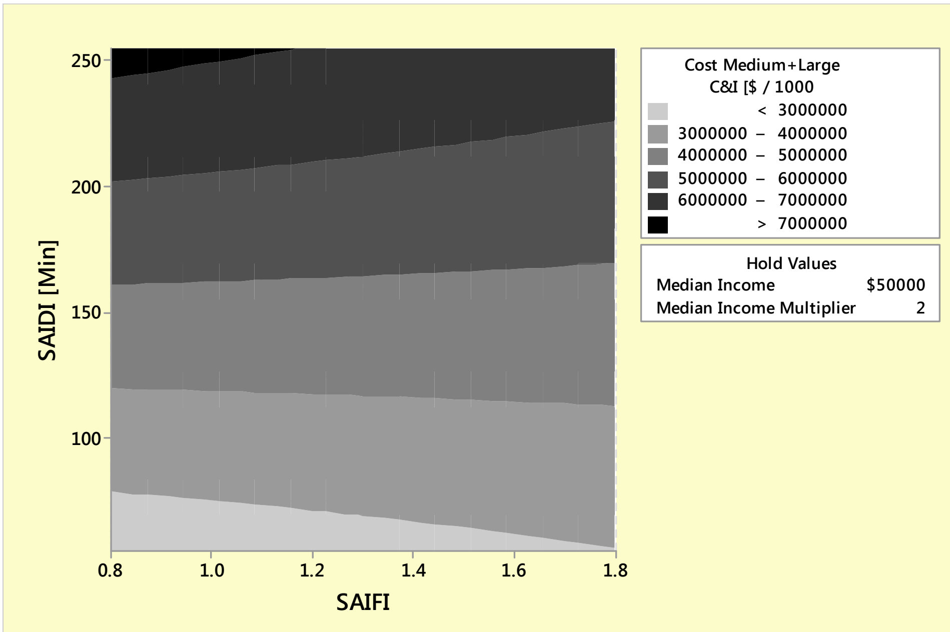

Figure 6: Impact of SAIDI & SAIFI on the outage Cost Medium & Large Commercial & Industrial [contours are $/1000 Customers] – median income = $50,000, median income multiplier = 2

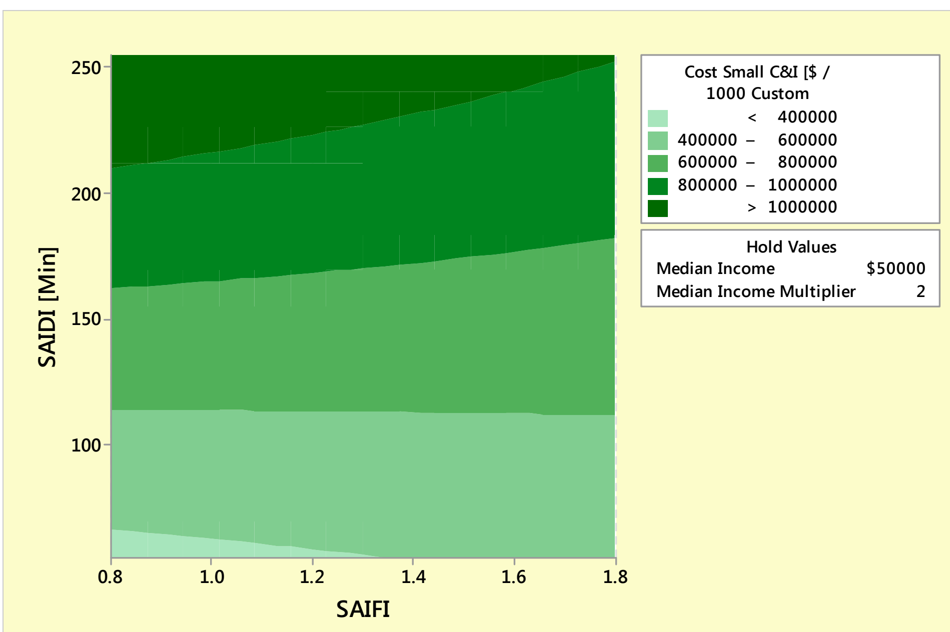

Figure 7: Impact of SAIDI & SAIFI on the outage Cost Small Commercial & Industrial [contours are $ / 1000 Customers] – median income = $50,000, median income multiplier = 2

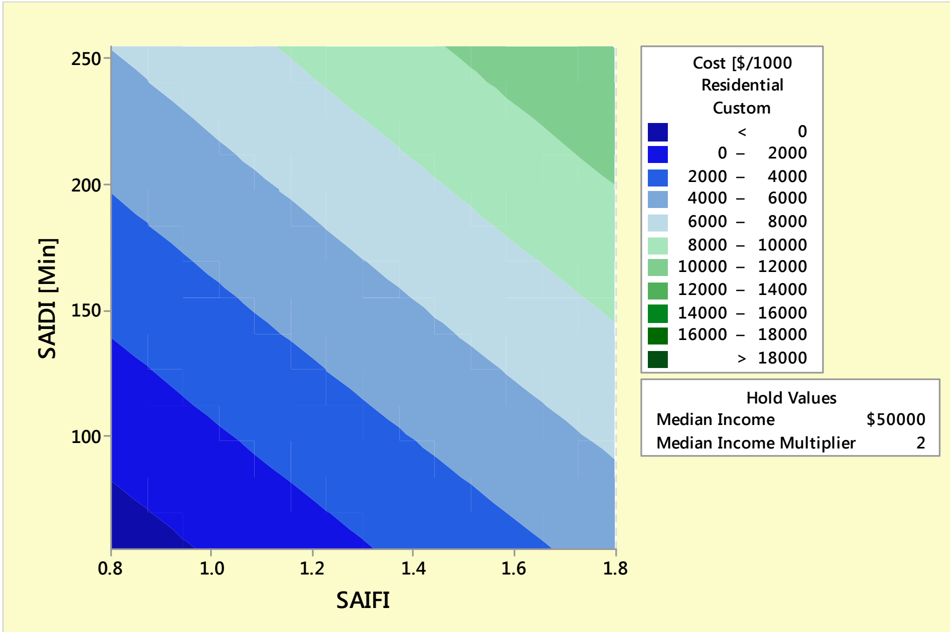

Figure 8: Impact of SAIDI & SAIFI on the outage Cost for Residential [contours are $ / 1000 Customers] – median income = $50,000, median income multiplier = 2 – the same levels are used for the contours in Figure 8 & Figure 9

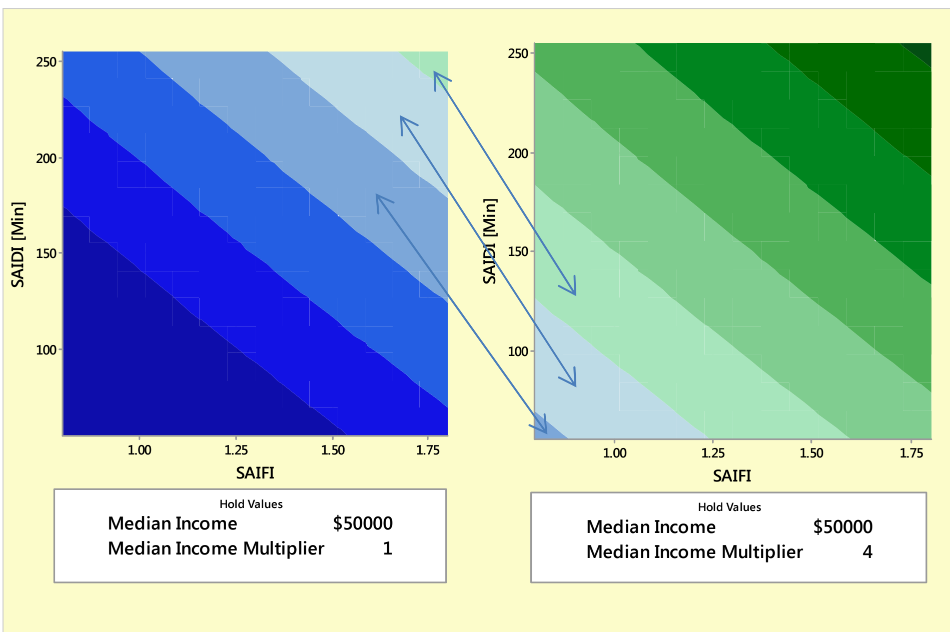

Figure 9: Impact of SAIDI & SAIFI on the outage Cost for Residential [contours are $ / 1000 Customers] – median income = $50,000, median income multiplier = 1 & 4 – the same levels are used for the contours in Figure 8 & Figure 9

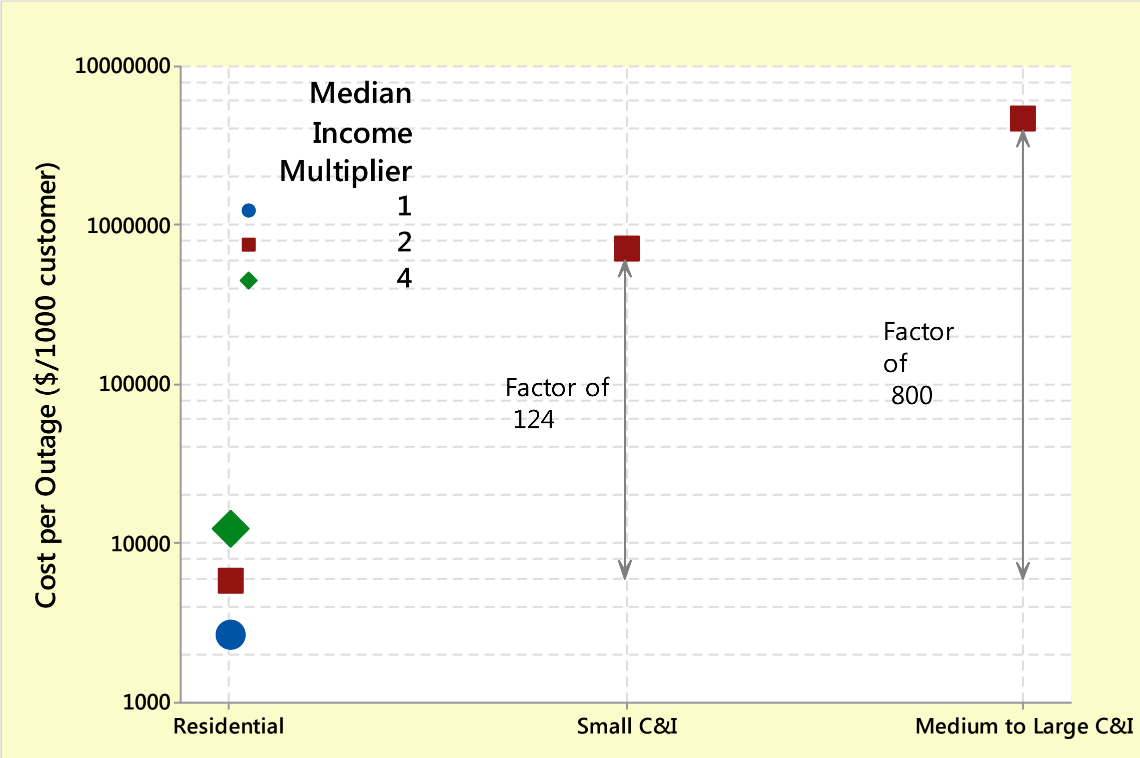

Figure 10: Impact of Median Income Multiplier and the Type of Customer Served on the Outage Cost [$ / 1000 Customers], Factors Estimated for Twice Median Income – Median income = $50,000, SAIFI=1.4, SAIDI=155mins

13.3 Selected Examples of Benefit Estimation

This section provides examples of benefit estimation and thereby sets out a framework whereby the benefits of conducting Diagnostics can be estimated. The basic premise is that the employment of a diagnostic is compared in terms of cost (tangible and intangible) with the default case which, for these examples, is "Run to Failure" (RTF).

The basic steps in the methodology deployed here are:

1. "Build" a typical cable system
2. Determine appropriate Diagnostic and Remediation Scenario
3. Use results from CDFI studies on real Utility systems to estimate
   a. Likely outages as a function of time
   b. Likely diagnostic outcomes
4. Determine likely classifications to guide subsequent remediation activities
5. Estimate Failures on Test (FOT)
6. Estimate costs of undertaking diagnostics
7. Estimate the cost of remediation resulting from diagnostic outcomes
8. Estimate costs associated with outages
   a. Cost of remediation
   b. Customer Cost
9. Accumulate Costs

10. Display Benefits
    a. Avoided Costs (Costs without diagnostics (RTF) – Costs with diagnostics)
    b. Avoided Outages

It is useful to reconfirm some definitions that are particularly useful:

Outages – failures that occur at unanticipated times which interrupt customer supply and where the full system fault is experienced by the cable system

Failures on Test – failures that occur at an anticipated time (during the test) which does not interrupt customer supply and where only the fault current available from the test equipment (much less than the full system fault) is experienced by the cable system

The scenarios considered are:

- New 132kV cable system commissioning test – 13.3.1
- Aged MV cable system Diagnostic Test – 13.3.2
    - Withstand Diagnostic conducted by a Utility
    - Diagnostic Tests conducted by a Service Provider

13.3.1 Commissioning Test Estimations

As noted in earlier chapters Commissioning Tests are generally conducted in HV / EHV cable systems with the goal of reducing infant mortality (Figure 5). Figure 5 shows the early life reliability prognosis for modern (installed since 2000) HV & EHV cable systems. Clearly the issue is to conduct an effective commissioning diagnostic program so that the service failures may be avoided by addressing them whilst the cable system is in the control of the contractor rather than the responsibility of the utility.

It is possible to estimate the effects and hence the benefit of a commissioning diagnostic tests by examining a utility case. The details of the utility case (modeled on http://www.pesicc.org/iccwebsite/subcommittees/C/Presentations/2010Spring/C1-SpringHVandEHVCableSystemsforAbuDhabi.pdf) are given below; here the utility has been installing a considerable amount of HV XLPE cable system in the 2010 to 2012 time frame

Voltage:	132 kV
Length:	325 km / 225 cable segments
Accessories:	114 terminations, 675 joints

In this scenario we have chosen to consider a near power frequency resonant test voltage (DAC is not considered resonant) of 1.7 U_0 for 60 min (based on IEC recommendations) with Partial Discharge (PD) monitoring. This approach is acknowledged (CIGRE B1.28) to be effective with no outages having been reported following this test. The alternative IEC voltage levels (1.4U_0 or U_0 for 24 h) are not considered for this scenario as it is known that these voltages are not effective (outages are reported) at reliably eliminating outages.

NEETRAC research suggests that a reasonable failure rate in the early years of a cable system is of the order 0.0016 failures per km per year, recognizing the uncertainty in these estimates. Within this rate, 67% of the failures are likely to be associated with accessories. In addition Figure 5 shows that the likely infant mortality failure rate is 2 to 3 times that of normal operation.

Thus for a given cable system architecture the outages with and without Infant Mortality failures may be estimated. In this system, assuming a 15 year horizon, with and without Infant Mortality failures are 3-5 (X in Table 2) and 2-3 (x in Table 2), respectively. This scenario assumes that the Infant Mortality (early) failures are completely avoided and that the remedial actions result in a lower (25% lower) failure rate for normal operation.

The repair of accessory or cable failures requires considerable effort and resources and their cost (S from Table 2) are estimated at between 0.5 % and 0.8 % of the "First Cost" (Table 1) per event. These are lower (conservative costs) as they assume that a failure only require remediation to that phase i.e. that there is no collateral damage. The cost for a three phase repair is unlikely to be three times the single phase cost as the civil / construction work is unlikely to be tripled. Furthermore the estimates are for the size of system under study here; as the size of the system decreases then the cost of the remediation increases as a percentage of the "First Cost". On very short systems it can approach 20 – 30%. In all the estimates that follow the lower cost has been used.

Thus the benefit (S*(X-x) from Table 2), using the avoided outage model, is 0.5 to 1.6% of the "First Cost" (Table 1) **plus** the "Cost of Outage" (O*(X-x) from Table 2). Clearly the "Cost of Outage" depends upon the number of customers but a conservative estimate can be obtained from Figure 6 to Figure 9. Using a conservative approach for customer numbers (low) and residential / industrial mix (highly residential); then the ICE models estimate that benefit is between 1.3 & 2.6 $M (unadjusted for inflation) over the 15 year horizon. These benefits are represented by the "difference arrow" in Figure 11.

It may be argued that in many cases at HV, no outages occur due to the fact that there are alternate feeds. Thus the ICE costs estimated above are best considered as a "Risk Cost" as should a second fault occur then the outage cannot be recovered without the full repair of one of the two faults. Furthermore the repair time is much longer than the 16 hours covered by the ICE estimates; thus it is likely that the true Risk Cost will possiblly be significantly higher than used in these estimates. Thus if there is a benefit with diagnostics using these lower ICE estimates then there will certainly be a benefit with the true value.

Figure 11 shows the cost difference between the commissioning test program and the alternate (no commissioning test) program. The size of the bubbles represents the number of outages. Clearly the commissioning test case yields fewer outages each of whoich is less expensive.

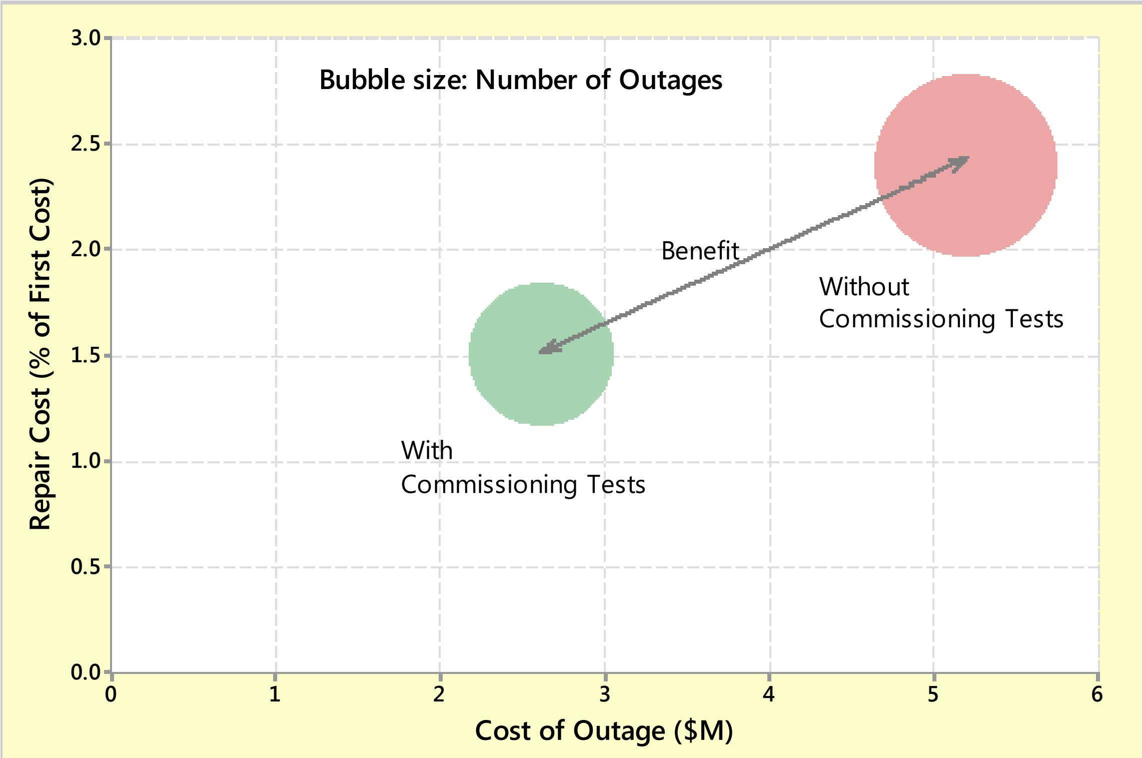

Figure 11: Graphical Representation of the Costs (see Table 2) for a Selected Utility HV System With and Without Commissioning Diagnostics

13.3.2 Diagnostic Test Estimations

Previous chapters have noted that diagnostic testing is mainly carried out on aged MV assets. Thus it is convenient for us to use this common scenario to investigate the benefits of diagnostics as it is possible to postulate the differences between the with and without diagnostics cases.

The scenario we have chosen is a cohort of 100 segments with an average segment length of 400ft. These are aged cable systems which have shown reliability issues in the past; hence are viable candidates for testing (recall that diagnostic testing is not recommended to be carried out on new systems as there is little benefit to be derived). The basic parameters for the diagnostic performance model in are provided in Chapter 9.

The tangible cost estimates are taken as single values from within the ranges given in Table 3.

The intangible costs are drawn from the ICE Calculator (Figure 6 to Figure 10) for 1000 customers (980 residential) and a SAIDI of 120 minutes. The cost for a SAIFI of 1.2 is taken as a single value and is $54/customer/per outage. This cost has been used for both of these analyses. There has been no estimate for the risk cost that results from the difference in the time it takes to isolate the fault (120 min) and to complete a final remediation (7 days). This is a “Risk Cost” as should second fault occur then the outage cannot be recovered without the full repair of one of the two faults.

Two further cases can be considered:

a) Testing carried out by the utility
b) Testing carried out by a Service Provider

Case a): Testing carried out by the utility

Earlier chapters (Chapter 4) have identified that the most commonly used diagnostic by utilities is a VLF Withstand. In this approach the general premise is that failures on test are preferable to outages as although they have the same cost to repair, the failure on test does not expose the cable system to the full fault current and does not incur the cost of the outage. In this scenario we have chosen two test applications, each two years apart. The cable system performance and hence benefits are considered over a four year period. It is assumed that a segment is replaced should it fail in service or on test.

The scenario is

- 30 year old cable system serving 1,000 customers (98% residential)
- 100 segments of average length 400 ft
- SAIDI = 120 min and SAIFI =1.2
- VLF Withstand Diagnostics conducted by a Utility
- Withstand Diagnostics applied at year 0 and year 2
- Repair is made by replacing the cable segment with new cable

The evolution of failures (outages and failures on test) is shown in Table 6 for the two testing scenarios. Inspection shows that the total number of failures is higher when diagnostics are employed, though the number of outages is lower: 9 & 19 for the "with" and "without" cases respectively. In this model the 4 year time scale has been selected as this is reasonably short and thus we can assume that the population does not significantly age. Any longer term scenarios would need to address this extra sophistication.

Table 6: Failures (Failures On Test and Outages) for a MV Scenario for Test Programs With and Without Diagnostics
Testing Conducted by the Utility

	With Diagnostics			Without Diagnostics		
	Outages	**Failures on Test**	**No of surviving segments**	**Outages**	**Failures on Test**	**No of surviving segments**
Start			100			100
End of 1st test period		13	87			
End of Year 2	5		82	10		90
End of 2nd test period		10	72			
End of Year 4	4		68	9		81
TOTALS	**9**	**23**	**68**	**19**		**81**

The failures detailed in Table 6 are shown graphically in Figure 12. At first sight the lower number of failures (higher number of surviving segments) would be expected to be correlated with the lowest cost. This is not the case as the costs of an outage is not the same as the cost of a failure on test – the failure on test has a lower cost because in the vast majority of cases no customer outage occurs. The costs associated with these failures are detailed below in Figure 12.

Table 3 identifies the ranges for the tangible costs. This estimate uses the lowest values in the ranges. A more complete analysis would employ Monte Carlo simulations using the identified ranges. As the goal of this chapter is to demonstrate the methodology and typical values, there is no need to expand the sophistication of the analysis at this stage. Customers with this style of system typically replace a segment upon failure.

Thus for this analysis we assume:

- The repair costs for a failure on test are 400 ft*15 $/ft per failure on test: $6,000
- The repair costs after an outage are $400+400 ft*15 $/ft per outage: $6,400
- Test costs are 100*400 $/segment: $40,000
- The Outage Costs 1,000 customers*$54 per outage per customer: $54,000/outage

The detailed buildup of costs over the 4 years considered here are shown as waterfall diagrams in Figure 13 and Figure 14.

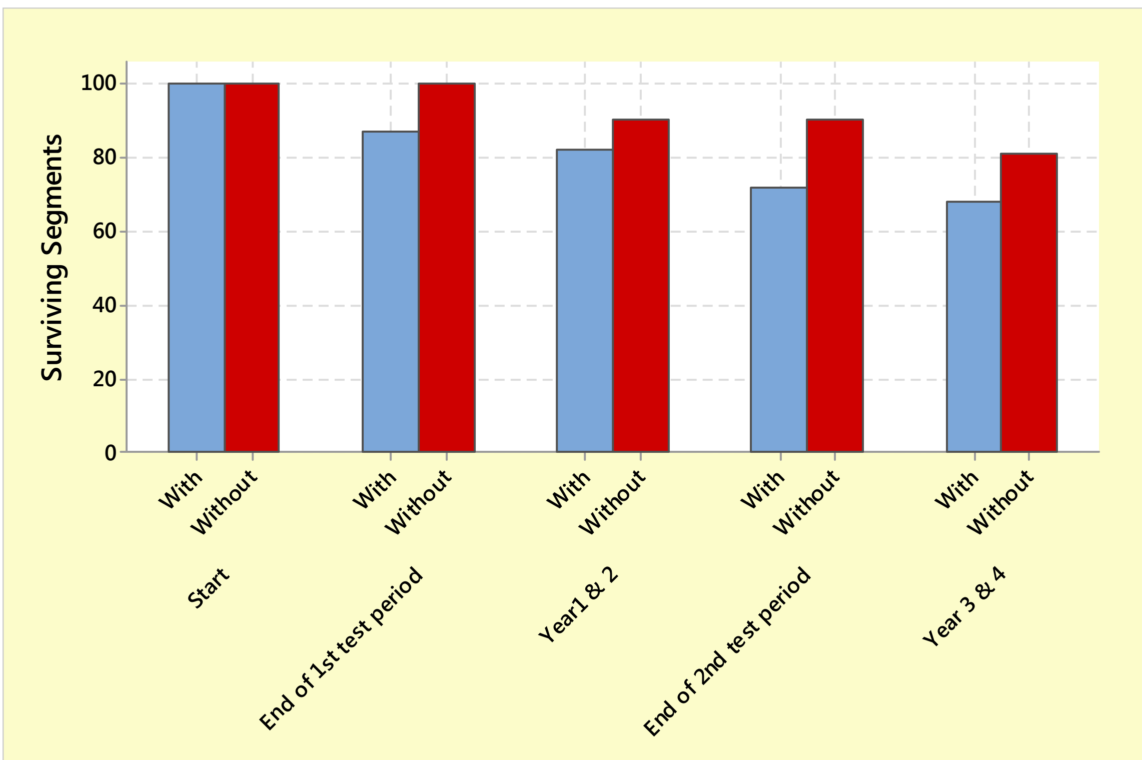

Figure 12: Reduction of Original Segment Population over Time for Programs Detailed in Table 6

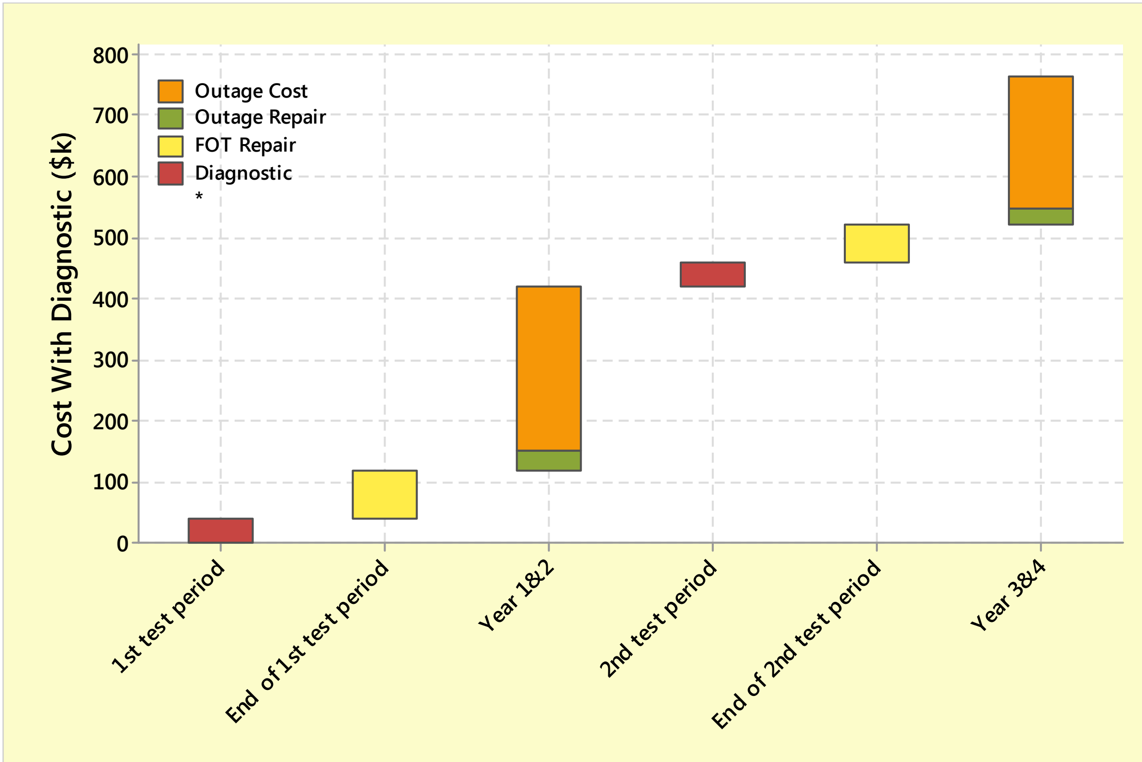

Figure 13: Diagnostic Program Cost - Uses Failure on Test and Outage Data in Table 6 – Testing Conducted by the Utility (9 Outages, 9 Outage Repairs and 23 Test Repairs)

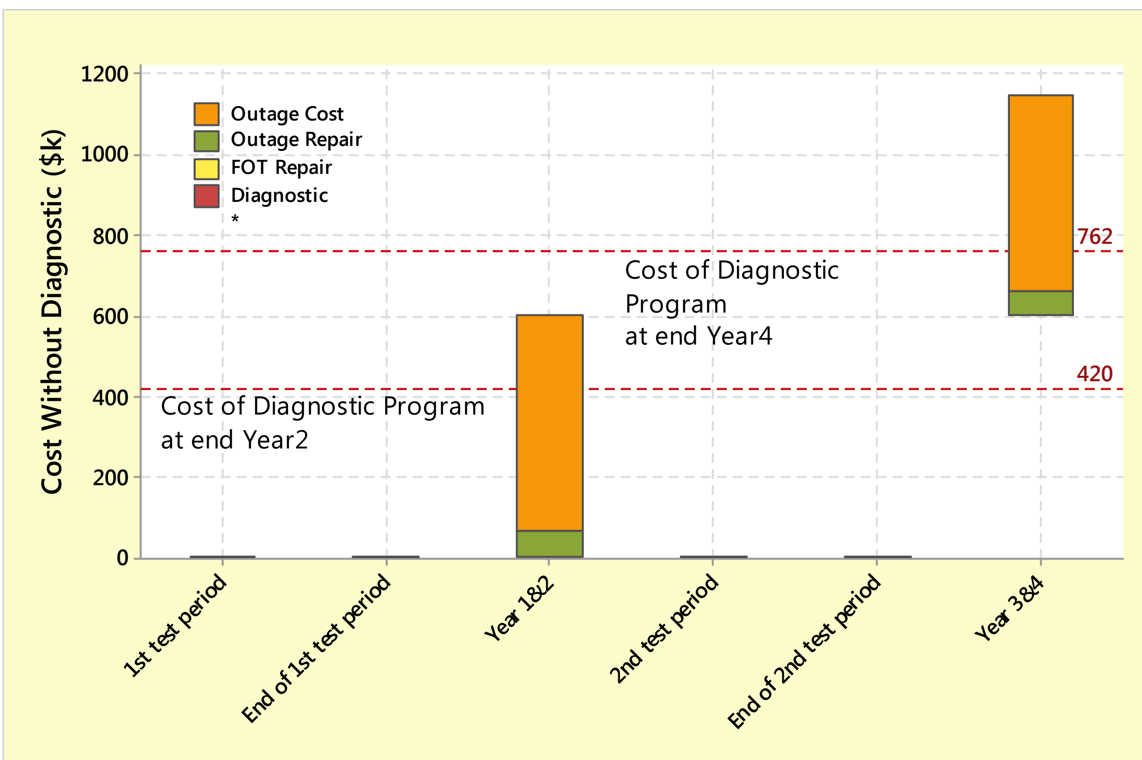

Figure 14: Cost Build Up Without Diagnostics - Uses Failure on Test and Outage Data in Table 6 – Testing Conducted by the Utility (19 Outages and 19 Outage Repairs)

Examination of Figure 14 and Figure 15 shows that, for this case, the VLF diagnostic program yield lower costs than the Run to Failure approach: approximately $350 k or four to five times the cost of the diagnostic testing. The benefits of lower outages (9 vs 19 for with and without respectively) are in addition to the reduced cost of outages and can easily be described (lower amounts of system shock due to fault currents, extra degradation due to locating / thumping etc), however ascribing a financial value to then is not straightforward. We content ourselves with noting that these benefits are in addition to the decreased costs.

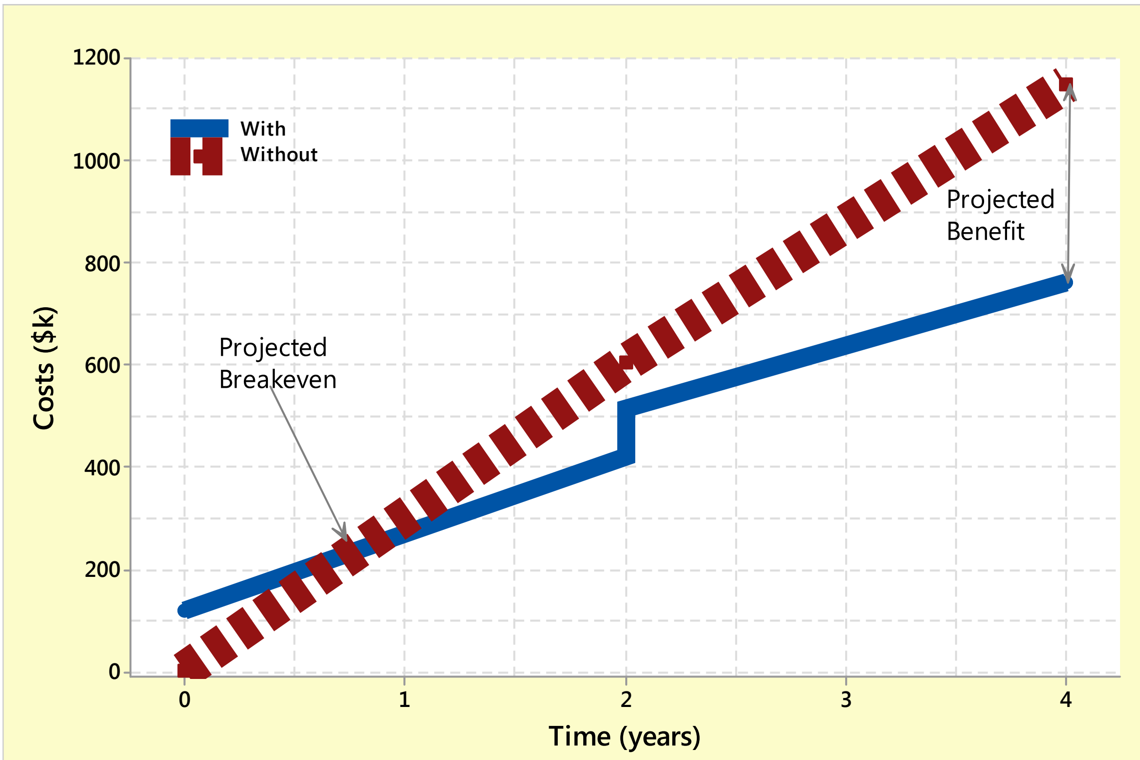

Figure 15: Cost Evolution With and Without Diagnostics
Width of Lines Represents the Number of Outages (9 and 19, respectively)

The scenario represented in Figure 15 above is

- 30 year old cable system serving 1,000 customers (98% residential)
- 100 segments of average length 400 ft
- SAIDI = 120 min and SAIFI =1.2
- VLF Withstand Diagnostics conducted by a Utility
- Withstand Diagnostics applied at year 0 and year 2
- Repair is made by replacing the cable segment with new cable

<u>Case b): Testing carried out by the Service Provider</u>

Earlier chapters have identified that some utilities use a Service Provider to perform their diagnostics. In these cases it is uncommon to undertake a withstand diagnostic. It is most common for PD or Tan Delta diagnostics to be used. In these approaches the general premise is that failures on test are very rare and that repairs are carried out at the time of a utility's choosing, thereby avoiding outages. Thereby they have the same cost to repair, but the cable system is not exposed to the full fault current and does not incur the cost of the outage; both of which are advantageous.

In this scenario we have elected to consider 30 year old segments as the aged population and to replace only those cable systems in the Action Required (AR) class as these have the highest risk (20% see Outcome Lines in Chapter 6) of leading to an outage in a five year horizon. The members of the Further Study (FS) and No Action (NA) classes are not repaired as these have lower risks of leading to outrages (13 and 6% respectively). Thus at age 30 the segment population is comprised of 5 AR / 25 FS / 70 NA. The utility elects to replace the 5 AR with the expectation of avoiding one outage (i.e. 20% of 5 AR) and chooses not to replace the 25 FS thereby deciding not to avoid three outages. At age 35 the original population of 100 is reduced to 88 (100 – 5 (proactively replaced) – 7 (outages)). If both AR and FS classes were proactively replaced at age 30 then the population at age 35 would be 66 (100 – 30 – 4).

The scenario is

- 30 year old cable system serving 1,000 customers (98% residential)
- 100 segments of average length 400 ft
- SAIDI = 120 min and SAIFI =1.2
- PD (online or offline) diagnostics conducted by a Service Provider
- PD (online or offline) diagnostics applied at year 30 and year 35
- Repair is made by replacing the cable segment with new cable

The evolution of failures (outages and repairs due to test results) is shown in Table 7 for both the "with diagnostics" and "without diagnostics" scenarios.

Inspection shows that the total number of repairs (due to tests and outages) is higher when diagnostics are employed, importantly however the number of outages is lower for the diagnostic program: 13 and 19 for the with and without cases, respectively. In this scenario the 10 year time scale (age 30 to age 40) has been selected, this is too long to assume that subsequent cable system degradation is insignificant. Thus a suitable age line for diagnostic data (Chapter 6) has been used to model the changes with time. Information received from PD practitioners indicates that this approach is a reasonable alias for the PD results. The failures in service have been modeled using the outcome lines (Chapter 6), again these model the PD world reasonably well. The outcome lines are used for the diagnostic case as well as the no diagnostic case.

The failures detailed in Table 7 are shown graphically in Figure 16. At first sight the lower number of failures (higher number of surviving segments) would be expected to be correlated with the lowest cost. This is not the case as the cost of an outage is not the same as the cost of a repair due to a test. The repair for a failure on test has a lower cost because, in the vast majority of cases, no customer outage occurs. Furthermore, no upstream equipment (transformers, overhead lines, substation equipment, etc.) are subjected to the additional stress of providing the resulting fault current.

The costs associated with outages are detailed in Table 7.

Table 7: Failures (Failures On Test and Outages) for a MV scenario Programs With and Without Diagnostics
Testing Conducted by a Service Provider

	With				Without	
	Number of Outages From classes FS + NA	**Class Membership** Segregated by class AR / FS / NA	**Repairs undertaken due to the Test Outcome** Segregated by class AR / FS / NA	**No of segments surviving**	**Outages** From classes AR + FS + NA	**No of segments surviving**
Start Age 30				100		100
End of 1st test period		5/25/70	5/0/0	95		
Age 35	7 (3+4)			88	8 (1+3+4)	92
End of 2nd test period		18/26/44	18/0/0	70		
Age 40	6 (3+3)			64	11 (5+3+3)	81
TOTAL	**13**		**23**	**64**	**19**	**81**

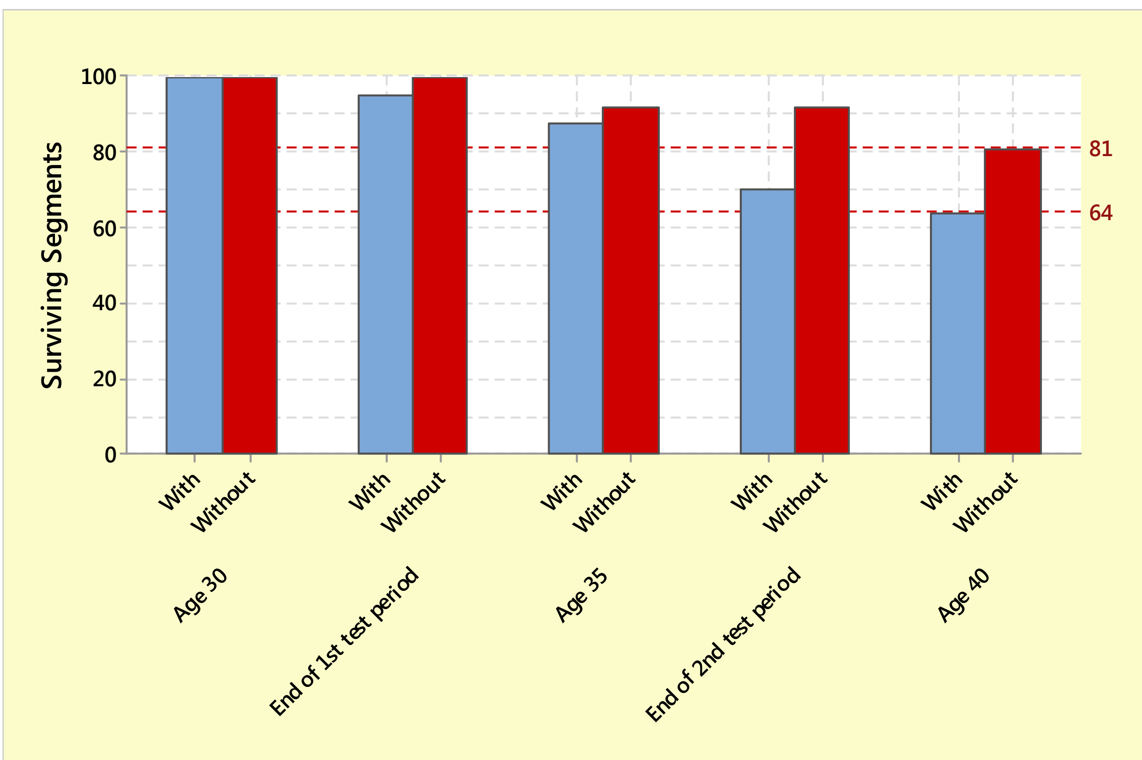

Figure 16: Reduction of Original Segment Population over Time for Programs Detailed in Table 7

Table 3 identifies the ranges for the tangible costs. This estimate uses the lowest values in the range. A more complete analysis (Section 13.4.4) would employ Monte Carlo simulations using the identified ranges. As the goal of this chapter is to demonstrate the methodology and typical values, there is no need to expand the sophistication of the analysis at this stage. Customers with this style of system typically replace a segment upon failure.

Thus for this analysis we assume:
- The repair costs for work indicated by a test are 400 ft*15 $/ft per segment: $6,000
- The repair costs after an outage are $400 + 400 ft*15 $/ft per outage: $6,400
- Test costs are 100 * 850 $/segment: $85,000
- The Outage Costs 1,000 customers*$54 per outage per customer: $54,000 per outage

The detailed evolution of costs over the 10 years considered here are shown as waterfall diagrams in Figure 17 and Figure 18.

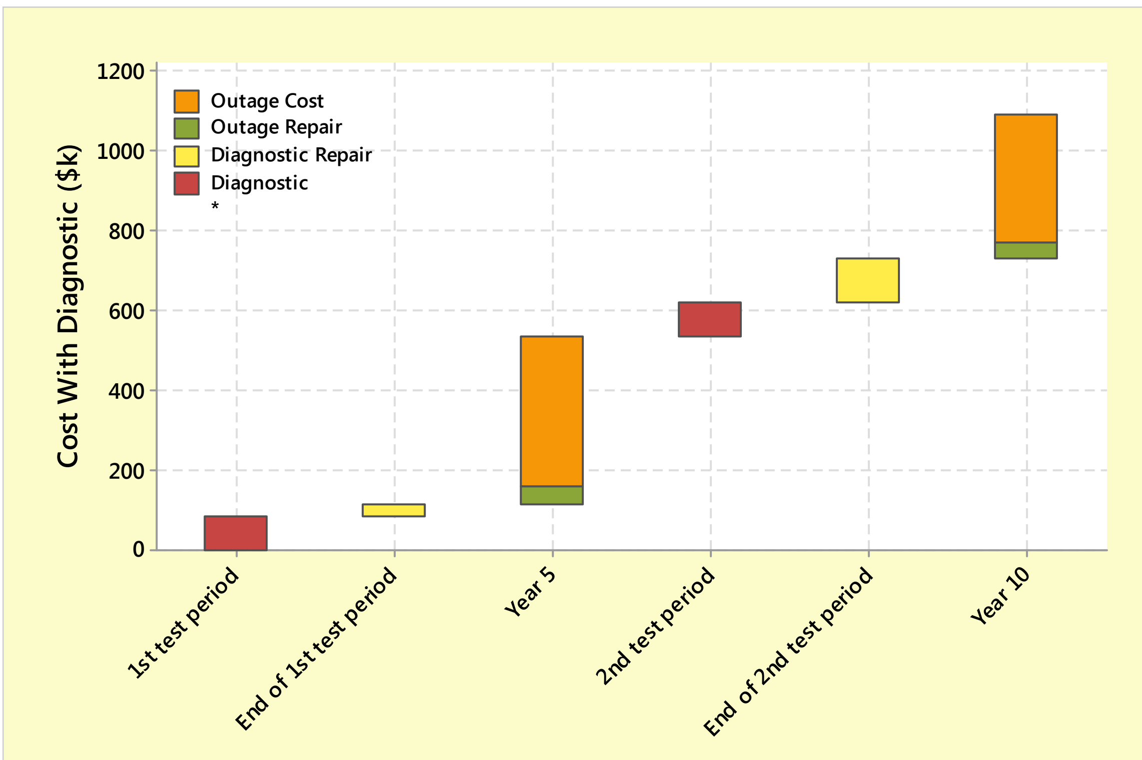

Figure 17: Diagnostic Program Cost - Uses Failure on Test and Outage Data in Table 7 Testing Conducted by a Service Provider (13 Outages, 23 Proactive Repairs and 13 Outage Repairs Over 10 Years)

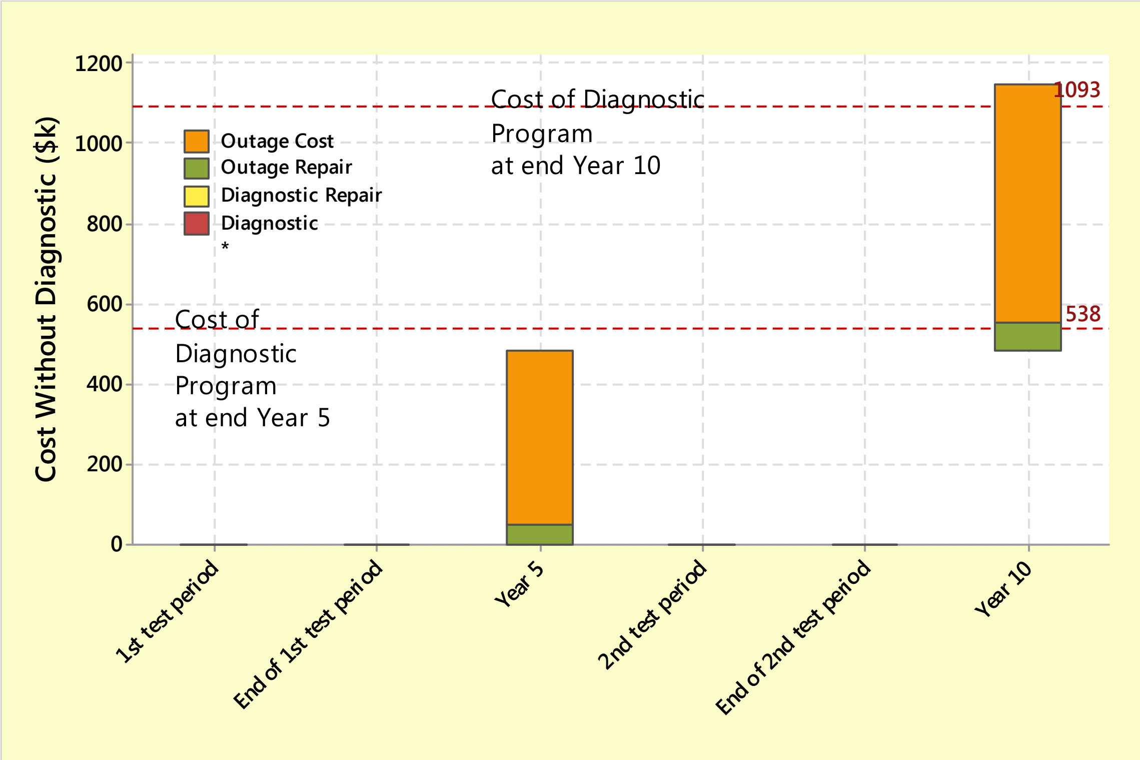

Figure 18: Cost Build Up Without Diagnostics - Uses Failure on Test and Outage Data in Table 7 (19 Outages and 19 Outage Repairs Over 10 Years)

Examination of Figure 18 and Figure 19 shows that for this case the diagnostic program yields lower costs than the Run to Failure approach by Year 10 (Age 40). Figure 19 shows and increase in slope for the Run To Failure (without) case after age 35; this is due to the fact that the cable system is smaller (there have been replacements between 30 and 35) but that the remainder age such that there are more in the Action Required and Further Study categories.

The benefits of fewer outages (13 vs 19 for with and without, respectively), in addition to the cost of outages can easily be described: lower amounts of system shock due to fault currents, extra degradation due to locating / thumping. However ascribing a financial value to this is not straightforward. We content ourselves with noting that these benefits are in addition to the costs that are already included.

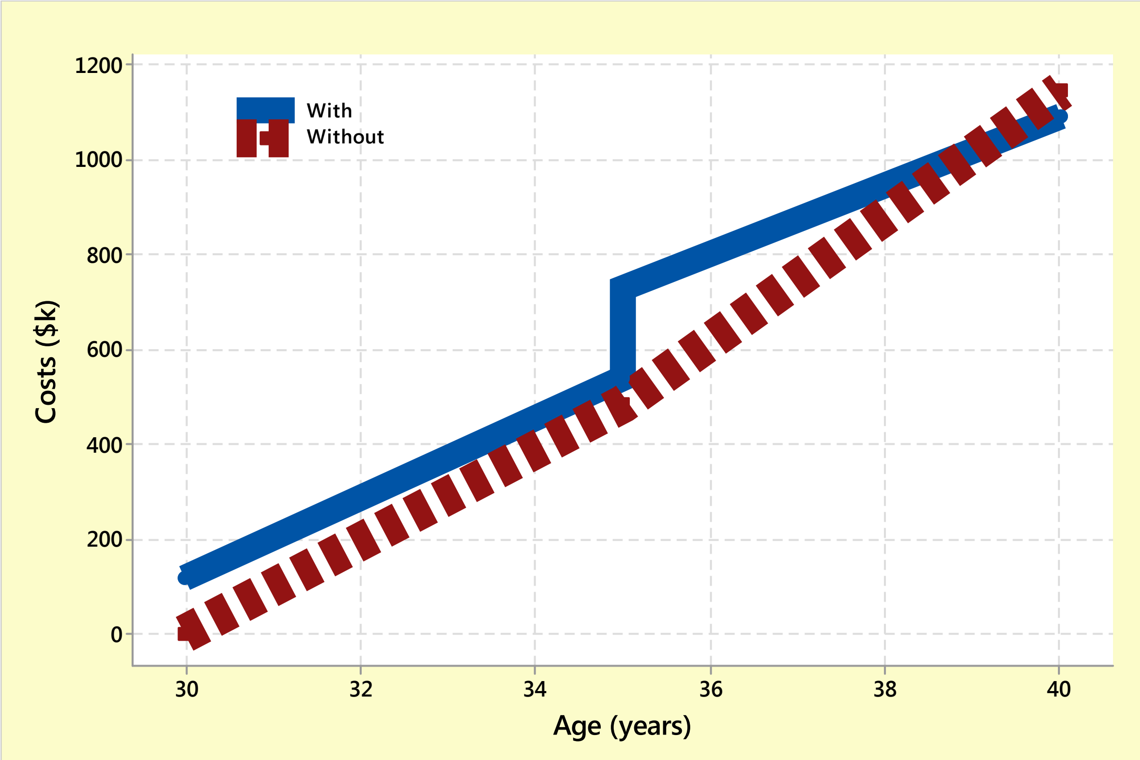

Figure 19: Cost Evolution With and Without Diagnostics
Width of Lines Represent the Number of Outages (13 and 19 respectively Over 10 Years)

13.3.3 Impact of Repair Methods on Aged Cable Systems

Figure 17 through Figure 19 show the different components of cost for diagnostics and Run to Failure (RTF). It is interesting to note that there are other default solutions rather than just RTF. Figure 20 shows the situation when the cases for Complete Replacement and Complete Rejuvenation are included.

In these analyses it has been assumed that

- Complete Replacement results in a new system with a zero failure rate.
- Complete Rejuvenation is assumed to
  - return the accessories to age 0 where the likelihood of failure is vanishingly low and
  - return the dielectric system of the cables to age 20 (where the likelihood of AR is very low) and
  - that the metallic neutrals have aged at a slower rate than the dielectric system.

The alternate case where the dielectric system is rehabilitated but the metallic neutrals become the life limiting factor has not been considered but it is likely to result in some case in between RTF and the Rejuvenation considered herein.

Based on the estimated total costs that include both Tangible and Intangible elements the most attractive is Complete Replacement followed by Rejuvenation, Diagnostics, and Run to Failure.

Clearly this assumes that complete replacement within a one year period is financially and technically feasible.

Based on the estimated total costs that include only Tangible elements the most attractive is Run to Failure, followed by Rejuvenation, Diagnostics, and Complete Replacement.

These estimates show the importance of the Intangible Costs associated with an Outage. Without them Diagnostic Programs are not beneficial. Even though there may be little consensus as to what these intangible costs are, they are clearly real and close to the values used in this study. If they were not real and significant then there would be no techno economic basis for diagnostic programs and we know that between 26% and 44% of utilities undertake diagnostics and that these figures have grown since 2006.

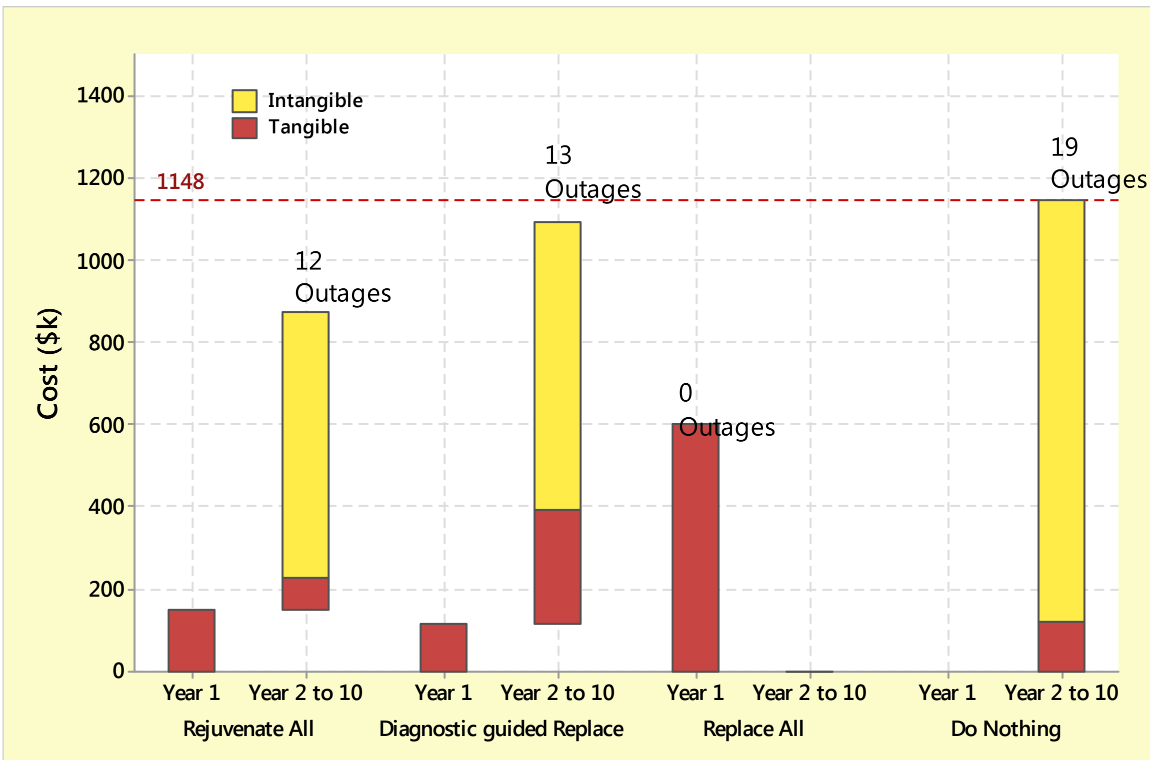

Figure 20: Cost Comparison between Several Remediation Approaches – Costs Separated by Program Year and Type (Tangible or Intangible)

13.4.4 Range of Diagnostic Estimates

The estimates presented in the preceding sections have made deterministic (we assume that we know the cost of repairs / outages / etc.) and conservative (low values selected) assumptions. Thus the benefits that accrue are the largest that may reasonably be expected. However as noted in and the ICE Calculator modeling, there are ranges associated with the input variables. We have chosen not to undertake the preceding estimates using Monte Carlo methods but we have decided to make some calculations to examine how the large uncertainties in costs impact the the benefits.

Cost of an Outage

The first example is the "cost per customer per event" that comes from the ICE Calculator. The calculator provides estimates for different US locations and a single value ($54 per customer per event) has been used in the preceding sections (13.4.4.2 and 13.4.4.3) – the amount of variability the location accounts for. Thus a number of simulations were undertaken to establish the appropriate statistical distribution and thence the uncertainty of this $54 estimate. The results are shown in Figure 21. This graph shows that the uncertainty (90%) in the chosen cost per outage is between 44$/customer/event and 68$/customer/event.

Thus given the sensitivity of the diagnostic benefits to the intangible costs which derive from the cost per customer per event it is possible that the same diagnostic scheme would be beneficial in one location (68 $/customer/event) whilst not being beneficial in another at (44 $/customer/event).

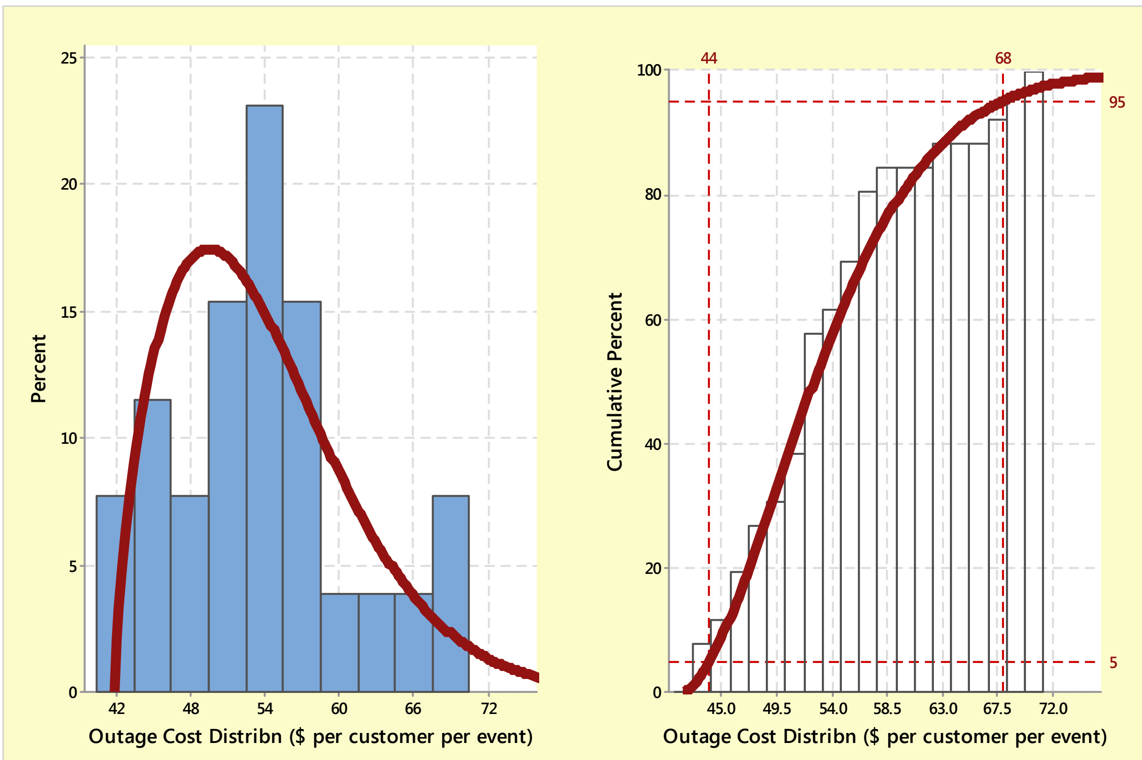

Figure 21: Distribution of Cost/Customer/Event Used to Calculate Outage Cost

Cost of Undertaking Diagnostics

In addition to the Outage Cost, the costs of undertaking diagnostics and the Run to Failure case depend upon other costs for which it is only possible to develop a range of estimates (Table 3). The next analyses have undertaken Monte Carlo Simulations, based upon 20,000 iterations, which have sought to understand the impact of the different uncertainties on the cost estimates for diagnostic testing undertaken by a service provider. These simulations have been carried out using the Outage Cost distribution in Figure 21 and cost distributions based on the ranges in Table 3 (a nomal distribution with suitable means and standard deviations has been used to model each range). 20,000 simulations of the five costs have been used. The Scenario uses the repair / outage data detailed in Table 7 for only replacement of Action Required segments. The diagnostic case has 23 Proactive Replacements and 13 Outages. The Run to Failure case has 0 Proactive Replacements and 19 Outages.

The results for the individual cost elements are shown in Figure 22 as histograms.

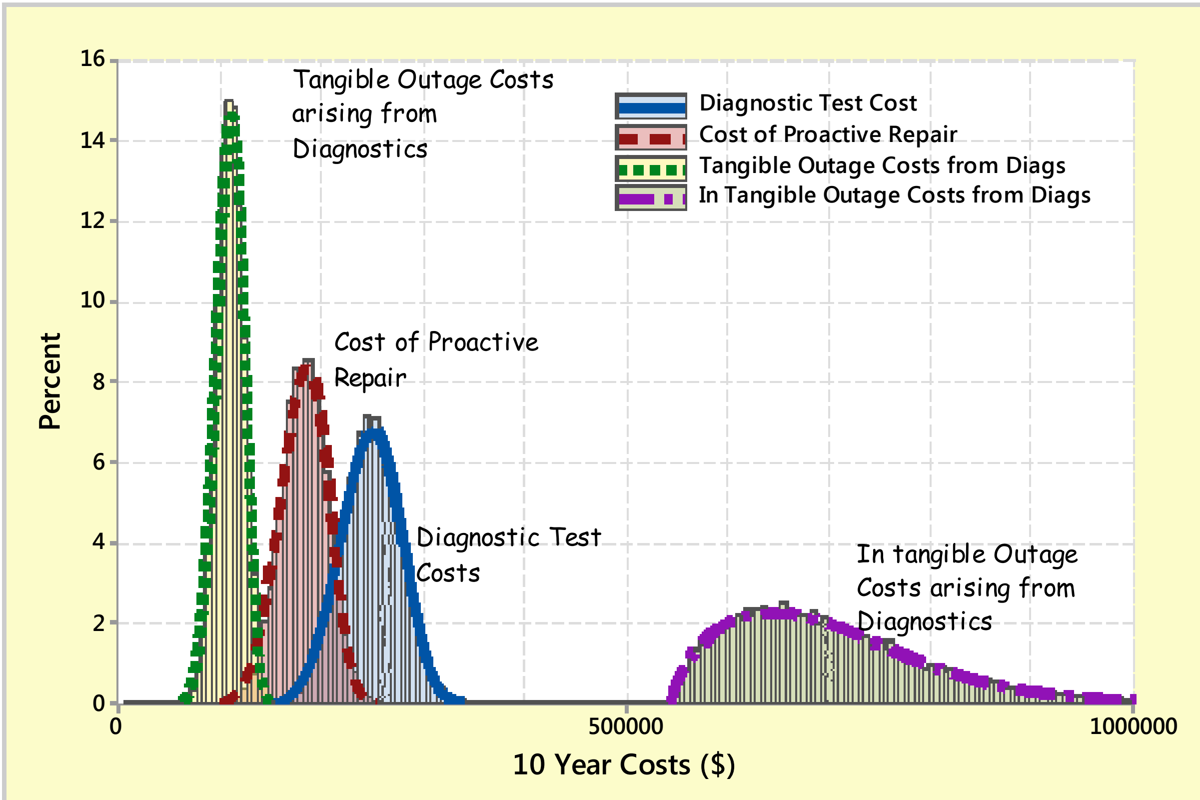

Figure 22: Results of Monte Carlo estimates of Component Costs for Diagnostic Testing conducted by a Service Provider (Table 7)

The four distribution elements in Figure 22 are the component costs that must be summed to derive the total cost (Figure 23).

The large spread in the total cost is essentially derived from the uncertainty in the outage cost per customer per event (rightmost curve of Figure 22). It is also important to understand the uncertainty in any cost and thence as this drives the estimate of the benefit. In this case the best single estimate of cost of the program using diagnostics is $1.24 M over 10 years, yet a reasonable (say 90%) uncertainty in this is +15% and -13% ($1.08 M to $1.42 M from Figure 23). Consequently it is clear that these probabilistic effects need to be considered when undertaking any robust modelling of diagnostic financial benefits. Furthermore this goes a long way to explain the differing cost / value opinions that may be drawn from seemingly the same scenario.

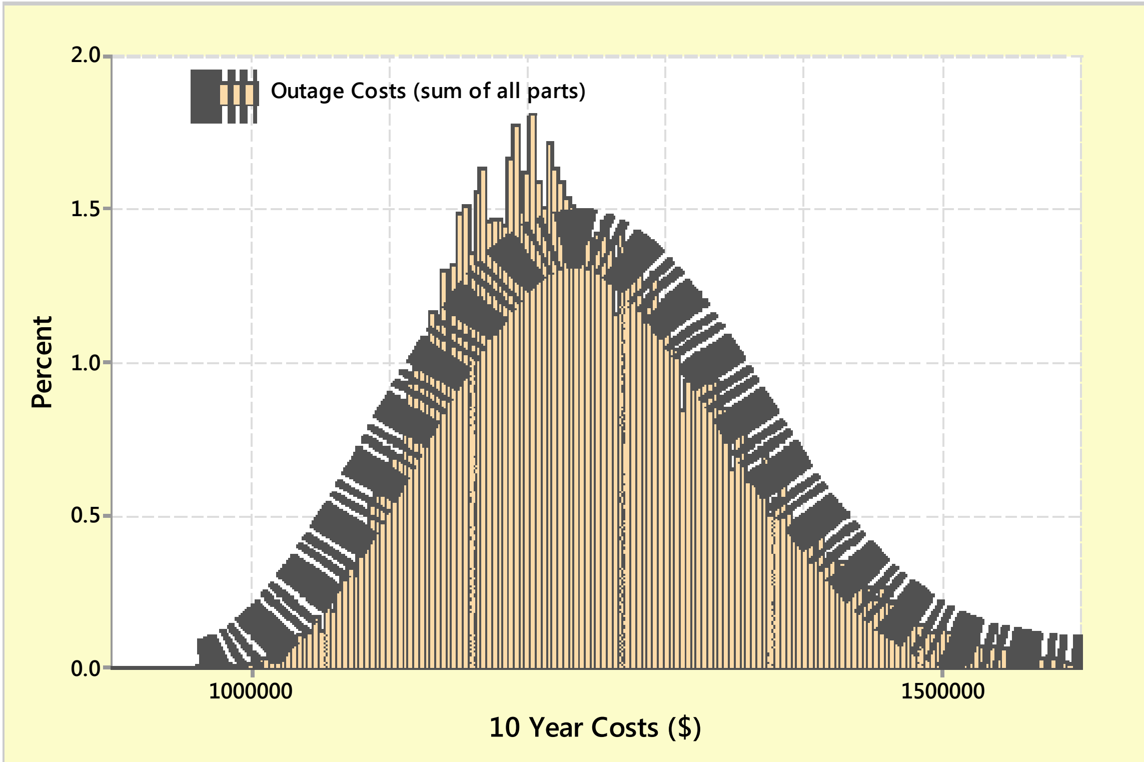

Figure 23: Summation of separate Monte Carlo estimates (Figure 22) to giveTotal Cost of Diagnostic Testing by a Service Provider (Table 7)

Cost of Undertaking Different Diagnostic and Remediation Scenarios

The analysis represented in Figure 23 represents that costs over 10 years of reliability when a diagnostic test is carried out by a service provider and the utility undertakes proactive replacement of the components identified as Action Required (AR). Clearly there are other scenarios that may be calculated in the same manner (estimate the component costs (Figure 22) and then sum them (Figure 23)).

Many alternate scenarios can be concieved; however the ones considered here are identified in Table 8

Table 8: Diagnostic and Rehabilitation Scenarios Considered for Monte Carlo Simulations

Description	Diagnostic Implemented by	Rehabilitation by
Diagnostics Provider AR	Service Provider	Proactive Replacement of AR
Diagnostics Utility AR	Utility	
Diagnostics Provider AR&FS	Service Provider	Proactive Replacement of AR & FS
Diagnostics Utility AR&FS	Utility	
Replace All	None	Complete Replacement
Run To Failure		Replacement upon Failure in Service

Two approaches to proactive replacement are considered a) only replace Action Required (23 Proactive Replacements) and b) replace both Action Required and Further Study (65 Proactive Replacements).

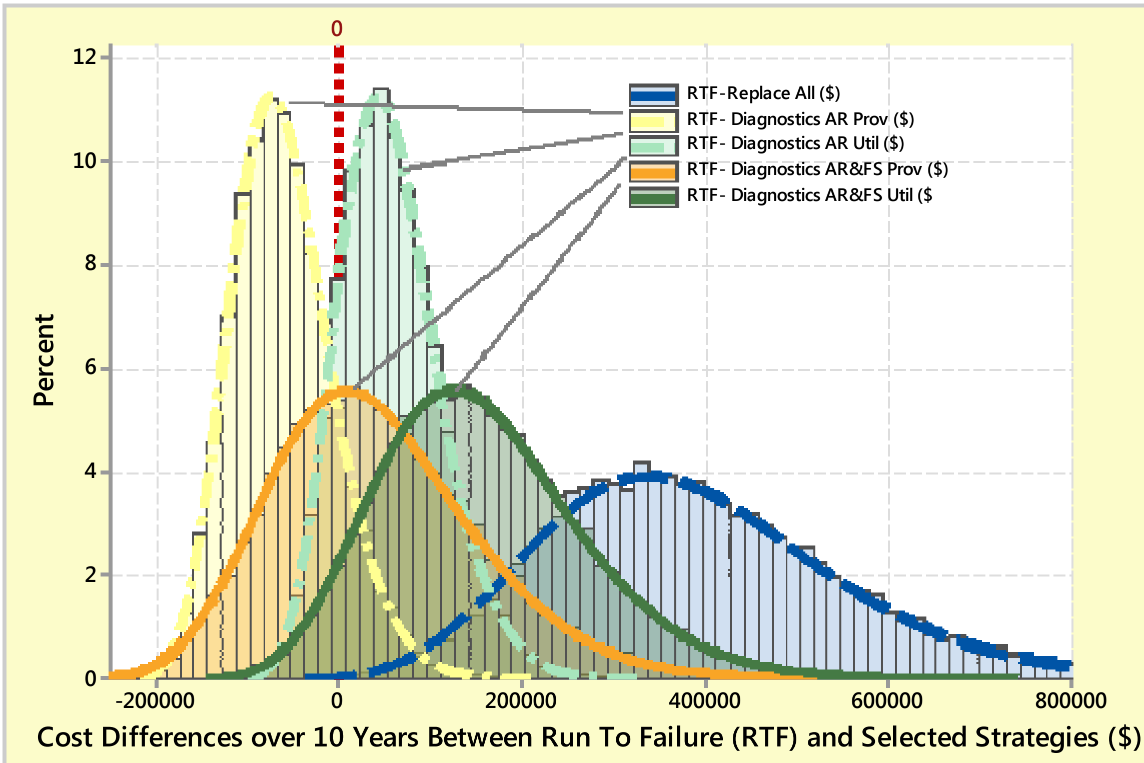

Figure 24: Cost Differences over 10 Years Between Run To Failure (RTF) and Selected Strategies (Table 8)

Figure 24 shows the cost differences over 10 years between Run to Failure (RTF) and Selected Strategies. These differences have ben estimated by taking the Monte Carlo distributions for each scenario and subtracting the distribution for the Run to Failure (RTF) case. The resulting positive numbers show that there is a cost benefit for the scenario, whilst the negative numbers show that there is no cost benefit.

Figure 24 shows:

- There are a range of cost benefits for each scenario – it is difficult to consider a single number
- How the diagnostic is deployed impacts the cost benefit – in most, but not all, cases utility deployment of a diagnostic delivers larger benefits than those from a provider
- The actions taken following the diagnostic impacts the cost benefit – addressing Action Required and Further Study brings larger benefits than addressing Action Required only

Clearly the simulations above are not exhaustive and for expediency some interesting ones have been omitted, such as:

- Rejuvenation of all segments as a remediation strategy – this would need reasonable cost ranges and an estimate for the outage rate post rejuvenation

- Simple Withatsnd as a diagnostic
- Monitored Withstand as a diagnostic
- Mixed replacement and rejuvenation as a remediation strategy (for example Replace AR and Rejuvenate FS)

13.4 Conclusions

Estimating diagnostic program costs is a complicated but survivable ordeal that requires significant knowledge of costs that are difficult to precisely quantify. The most diffciult element is obtaining a good estimate for the true of an outage. The true cost of an outage involves elements beyond the labor and materials needed for restoring service. Customers are impacted by outages and these do affect the utility's bottom line.

Using established tools for estimating the cost of outages, it is possible to show that diagnostic programs can provide financial benefit to a utility when reasonable costs of outages are used. Were these outage costs not to be included then there would be no way to place a financial value on high reliability and so run to failure would always be the default mode of operation. On the other hand, utilities have increased their use of diagnostics since the *CDFI* began in 2004 and so there must be benefit present for them to have adopted and continued these programs.

It is clear that challenges still remain to be studied in this area, and they include:

- It is obviously beneficial not to subject a cable system to a system fault and any subsequent location trauma (thumping). It is intuitively reasonable that these will accelerate ageing in the cable system. Diagnostic testing clearly reduces outages and thus reduces tehse stresses. However it is not clear how to either represent these benefits of place a value on them so that they may be included in the financial estimations.
- Run to Failure and Complete Replacement clearly represent the extremes of the remediation spectrum. However there are a plethora of alternate schemes: Diagnostic Guided Rolling replacement, Rejuvenation, Mixed Replacement & Rejuvenation, Diagnostic Guided Accessory Replacement etc

What is also clear is that diagnostics do not make sense in all situations and so a utility must carefully weigh these issues before embarking on diagnostic programs.

13.5 References

1. D. Johnson, "Risk-based Approach to Justifying Cable Intervention", Presented at the Fall 2014 ICC Meeting in Colorado Springs, CO, in Subcommittee C: Cable Systems, Oct 7, 2014.