Some Considerations on the Selection of Optimum Location, Timing, and Technique, for Diagnostic Tests

R.A. Hartlein, *Senior Member, IEEE*, R.N. Hampton, J. Perkel, *Student Member, IEEE*

***Abstract*—The ageing of the electrical infrastructure is a growing concern for Utilities, Regulators and Customers; and there is no doubt that addressing this problem will become an ever more important priority. Any solution will have to address three basic issues: firstly where is the optimum place and time to start, secondly what is the most appropriate suite of actions that can be taken and finally is the solution going to deliver the expected life. Diagnostic programs play an important part in the first and the third issues. In the first they may be able to guide the identification and prioritization of assets to be addressed; here they operate on the ageing population. The third issue benefits from diagnostics by using them as part of the assurance process that determines that the replacements / repairs have been effective. Addressing the ageing infrastructure is a large, complex and interacting challenge; this paper focuses on the first issue, namely how to select the appropriate locations, timing and technique.**

***Index Terms*—Diagnostics, Partial Discharge, Dielectric Loss, Selection**

Introduction

Utilities the world over, and especially in North America, are facing a significant future challenge to maintain and renew their assets. These ageing assets (for example, >20% of the presently installed underground cables are older than their design lives) are leading to ever increasing annual failures (Fig. 1) whilst, at the same time, the power delivery requirements are increasing. Immediate replacement of these aged assets is not practical – the cost would be enormous and the resources required (manpower and materials) are simply not available. Thus asset management strategies are increasingly being used to help address the issue, such that the replacement of the ageing infrastructure is managed.

A central component of the approach to asset management is the availability of appropriate information on the assets themselves. Such information can be used to predict where the system is heading in terms of reliability (Fig. 1) and to identify which assets are less reliable than others. In one example, it is known that old and unjacketed underground cables are the most prone to failure and yet not every old or unjacketed cable is at *"death's door"*. Thus extra information is needed if a utility is to undertake *"smart maintenance"*, that is, replacement of only those assets that will likely impact the near future reliability. This information is invaluable in helping to determine where maintenance and replacement funds should best be spent. Performance modeling supported by good quality and reliable diagnostic information can be a powerful tool for establishing a) the correct level of resources and b) the most effective way that they may be utilized.

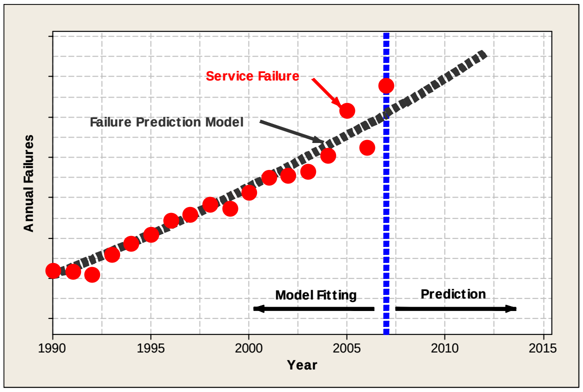

Fig. 1: Increasing utility failure rates and failure prediction.

I. STAGES OF DIAGNOSTIC PROGRAMS

Diagnostic techniques are generally used either to assure the performance of newly installed equipment (commissioning tests) to assess the state / health of older components or systems. This paper concentrates on the issues with assessing the state of the older utility systems. Diagnostics are employed to increase the efficiency of reliability improvement programs; this work contains four basic elements that can be summarized as:

Selection – Choose the assets for testing that will produce a high Diagnostic Yield. Typically this is based on age, failure rate, or other engineering judgment.

Action – What actions will be performed as the result of certain diagnostic outcomes or interpretations? The actions are in two groups (Act or Not Act) and may include replacement,

---

R. A. Hartlein is with Georgia Tech NEETRAC, Forest Park, GA, 30297 USA (e-mail: rick.hartlein@neetrac.gatech.edu).

R. N. Hampton is with Georgia Tech NEETRAC, Forest Park, GA, 30297 USA (e-mail: nigel.hampton@neetrac.gatech.edu).

J. Perkel is with the Department of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30319 USA (e-mail: jperkel@gatech.edu).

This material is based upon work supported by the Department of Energy under Award No DE-FC02-04CH1237 and the Utility and Manufacturing participants of the Cable Diagnostics Focused Initiative (CDFI).

defer action, rejuvenation, and/or multiple levels of repair. These actions are chosen based on those that are most suitable for the system topology and most prevalent failure mechanisms (local or global defects).
Generation – Diagnostic tests generate data that are well fitted to the type of maintenance actions and prevalent failure mechanisms.
Evaluation – Are the methods employed for Selection, Action, and Generation, giving the expected results: lower rates of failure and increased times between failures? Can the diagnostic elements be improved?

Fig. 2 illustrates how the four components function together over time to produce (if implemented properly) a reduction in the anticipated failure rate. It is useful to note that this benefit is not seen immediately nor does it cease once the program has ended: there is a lag and persistence. Furthermore, failure rates do not begin to change until the program is well into completing the actions directed by the diagnostic testing (Generation). Selection, Generation, and Action, are each defined stages in time while the Evaluation component is ongoing throughout the entire test program and beyond.

Although each of the elements are separate they operate very interactively; for example the action that will be taken will have a profound impact on the choice of the appropriate diagnostic in the data Generation phase.

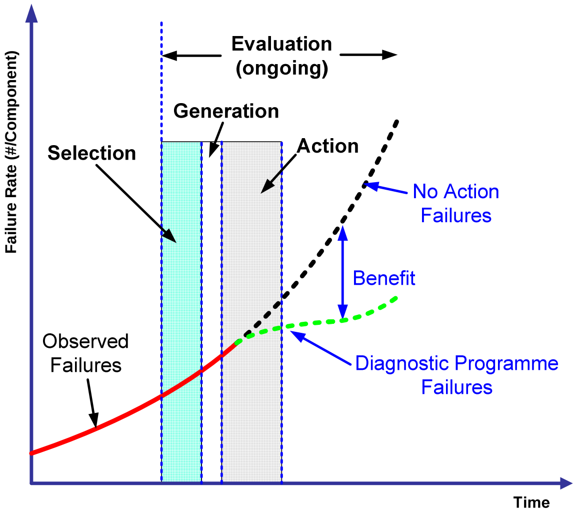

Fig. 2: Failure performance of Diagnostic Program following proper Selection, Generation, and Action, as compared to the "No Action" Program.

Selection is the first, and probably most important, portion of the program as it encompasses so many issues. These issues include:

- Timing – selection of the optimum times to start the program.
- Location – selection of the appropriate test location which will be a subset of the whole utility network.
- Technique – selection of the Diagnostic that best matches the type of defects / failures that occur within the selected location.

II. TIMING

The issue of when to initiate a diagnostic program is of tremendous importance to the ultimate performance in terms of benefits for the utility. The timing of the program determines the number and types of maintenance actions (including, perhaps, replacement) that will be required to produce the desired reduction in failure rate. If the program begins too early (i.e. too low failure rate), then very few service failures will be avoided through maintenance in the population. In other words, the population is too "Good" to produce a benefit. On the other hand, starting the program too late (i.e. too high failure rate) will leave few components in the population that do not require maintenance. In this case, there are no "Good" components to save and, therefore, the diagnostic does not provide useful information since the utility could simply have replaced all the components in the population from the beginning. The diagnostic then simply becomes an extra cost.

The question then is how to determine the proper time to begin the diagnostic program such that there are enough "Bad" components to remove that will produce a large enough improvement in reliability but not so many that the whole population needs to be replaced. There are two possible approaches: (1) Weibull analysis and (2) historical failure prediction

A. *Weibull Analysis*

It is well established that the failure rates of electrical components follow the familiar bathtub curve, which has three defined regions: Burn-In or Infant Mortality, Reliable Operation or Random Failures (the failures rates are at their lowest) and Ageing (failure rates are increasing and the time between failures decreases).

If suitable failure and system (number of components and age data) records are available then the whole curve can be constructed and it is relatively straightforward to monitor progress (Fig. 3). A significant practical problem is that utilities have imperfect records which limit the straightforward approach of monitoring the bathtub curve. These imperfections take many forms but the most common ones that we have encountered are:

- Failure data are not collected at the component level
- Data collection was discontinued

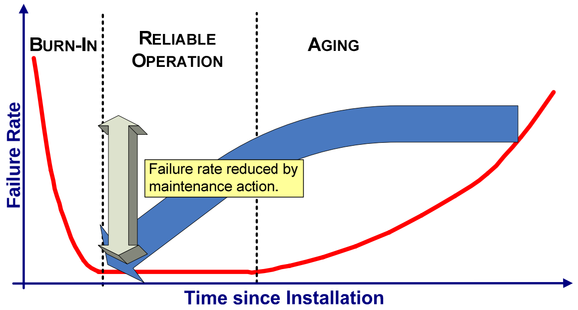

Fig. 3: Effect of diagnostic program when program was implemented at the correct time and sufficient actions can be deployed.

One practical approach is not to dwell on these issues and to to start to collect data as soon as possible. This means that the whole curve cannot be constructed, however, within a reasonable amount of time it should be possible, using Weibull Analysis, to determine where the aged population lies on the bathtub curve and whether any failures due to the remedial actions are in the Burn-In area. Equation (1) shows the Weibull probability distribution function with the two parameters, α_t and β [1].

$$P_f = 1 - \exp\left(\frac{t}{\alpha_t}\right)^{\beta} \qquad (1)$$

Where

P_f = Probability of failure

α_τ = Weibull Scale Parameter for the time to failure of 63% of the population

β = Weibull Shape Parameter.

In the Burn-In region the Weibull Shape Parameter is less than 1, whereas the Weibull Shape in the aging region is > 1. Furthermore the Weibull Shape in the aging region will increase as aging proceeds. Fig. 4 shows an example of such an approach for a population of components that have yet to be selected for diagnostic testing. Note that time to failure data in this figure was computed using only an arbitrarily chosen start date and the actual failure dates.

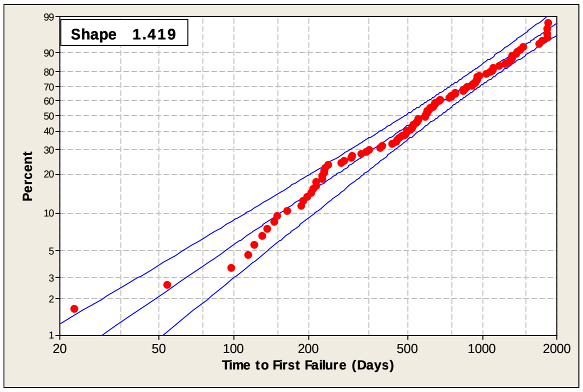

Fig. 4: Sample population with shape parameter in aging region of bathtub curve.

Using information such as that shown in Fig. 4, one can define the goal of the diagnostic program in terms of the bathtub curve. Fig. 3 shows the ideal case where the program is started at the correct time such that the actions bring the components back to the start of the reliable portion. Engineers will recognize that this difficult in practice as it is important that the action does not introduce too many Burn-In failures. The Evaluation stage of the diagnostic program is intended to monitor whether the actions / diagnostics introduce too much Burn-In (Fig. 5) and whether the actions bring the performance back into the reliable operation area. If the process is started too late then it may not be possible to deploy sufficient actions to bring the failure rates back into the reliable operation area as shown in Fig. 6.

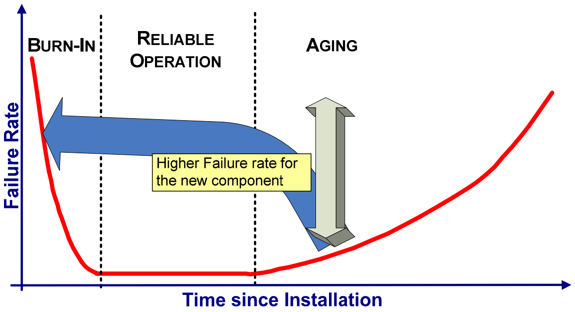

Fig. 5: Example of actions / diagnostics that produce too many Burn-In failures.

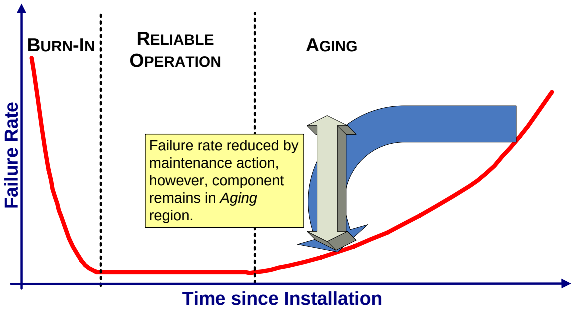

Fig. 6: Diagnostic program's effect on failure rate when actions are insufficient to attain reliable operation or the program has been started too late

B. Historical Failure Prediction (Reliability Growth Model)

An alternative method of analyzing failure rates is through the Reliability Growth Model or Crow-AMSAA [2]. This graphical method identifies changes in failure rates through alterations in the slope of cumulative failures versus time (log-log scale) plot. Such information can be used to identify whether a system of components is improving, staying the same, or worsening, in terms of the historical failure rates. Once a chosen threshold for the failure rate is reached, a diagnostic program may be initiated. This threshold would be selected based on the number of components in a potential target population and the estimation of the percentage of "Good" and "Bad" components within that population. The latter is based on both the size of the population and failure rate for that population.

This method is also useful for showing improvements in reliability from a diagnostic program. Fig. 7 shows the relative failure rates (gradients from a Crow-AMSAA plot) for each year of a diagnostic program employed on cable systems. It is interesting to note that the failure rate does not begin to decrease until the diagnostic program has reached a critical level in terms of completed actions. Prior to *Year 3* in Fig. 7 the failure rate continued to increase even with the diagnostic program in place. However, at *Year 3* the program completed enough actions so as to begin to bring the failure rate back down. At *Year 6* the failure rate was approximately 60 % of that experienced at the start of the program.

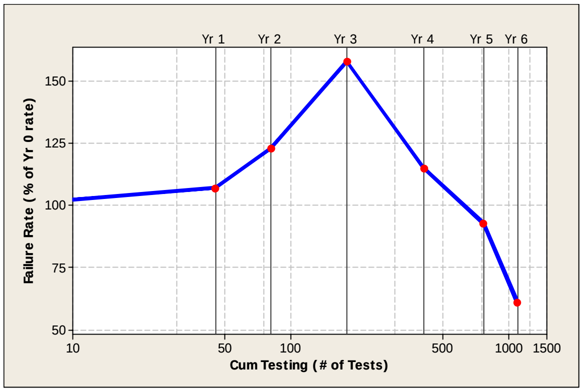

Fig. 7: Failure rate versus cumulative tests for an overall Testing and Action program.

The diagnostic program depicted in Fig. 7 shows that such programs (Selection, Action, Generation, and Evaluation) require the deployment of considerable resources. To complete work on an entire system requires enormous financial resources and time (several tens of years). As a result, diagnostic programs are typically conducted on subsets of the full population. Thus when considering the choice of time to start the testing this should be made based on the data for the potential target populations rather than on the whole population. As a result, decisions regarding the timing of the start of testing and precise location are highly dependent on one another.

III. LOCATION

Since diagnostic programs are conducted on subsets of the full population another important issue is that of determining which subset of components to include in the target population. This segregation also turns is to be critical to the performance of the diagnostic program. Generally, utility systems are on the average highly reliable, however, there are typically portions that are less reliable (in the aging region of the bathtub curve) and are as a result responsible for a large portion of the recent service failures as seen in Fig. 8. This figure shows that several portions of the system have failure rates that are above the system average represented by the 100 % line. These groups of components should be the focus of the diagnostic and replacement programs. However, as noted previously, some of these populations may be better candidates for wholesale replacement as they may be too “Bad” for the diagnostic program to produce a benefit.

Unfortunately, the number of components within these groups may be too large to complete the diagnostic testing within either a reasonable time or budget. Therefore, it is also necessary to consider the relative importance of each group. The importance could be a function of a number of parameters including the number of customers, customer types, or even the subject of current reliability complaints either from customers or the utility’s regulator. The specific details of the criteria will likely vary from utility to utility; however, it is clear that certain groups of components will have greater importance than others.

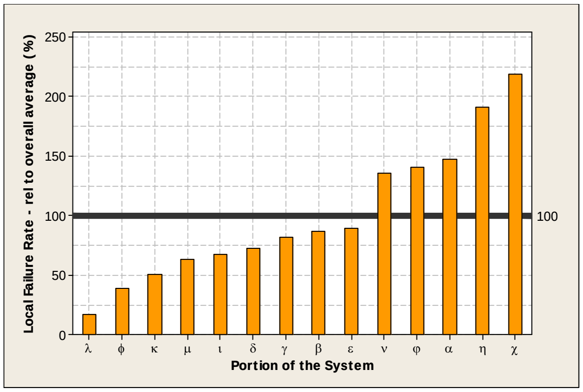

Fig. 8: Failure rates for different portions of a utility system.

Once the criteria have been established, the utility can use them to rate the relative importance of each group. This allows the utility to prioritize the diagnostic testing if needed. Fig. 9 shows a prioritization based on the importance of the system for the groups depicted above in Fig. 8. Yet another common way to accomplish this would be the number of customers that would be affected by any outage. It is interesting to note that the group with the highest failure rate in Fig. 8 actually represents a portion of the system with relatively low importance. The utility could then choose to include those components with both above average failure rate and high importance in the diagnostic program.

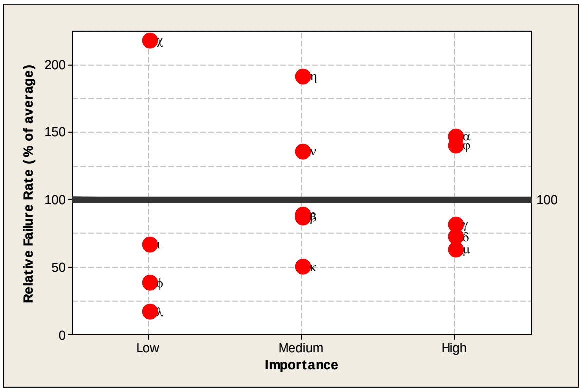

Fig. 9: Relative importance of system sections to the utility.

The location also impacts the value and benefits that can accrue from the diagnostic program. At its simplest level this is essentially the mixture of “Good” and “Bad” components in the target population. Of course in reality there are also “Not so Good” and “Not So Bad” components, but the simple two-level case is sufficient to illustrate the issues. If the chosen location has a high level of “Good” components then it is much harder to find the “Bad” components on which to act. However if there are too many ”Bad” components then finding them is not a problem, however, such a population will require action on almost all the components and this may exhaust the available resources. Plus effort would have been expended and lost on the testing element when there was little on the system to save.

This issue is most commonly encountered in the early stages of the diagnostic program. It is very common that in these early stages and in pilot studies that the locations are chosen very timidly and as such there are too many “Good” components.

components. The subsequent analyses then struggle to show value and benefit. In these cases it is not the diagnostic or action that are at fault, but the inappropriate selection of the target population.

The selection of location also interacts very strongly with the selection of Diagnostic Technique and its required accuracy. Fig. 10 shows the influence of local failure rate and diagnostic technique accuracy on the percentage of avoided service failures. As the failure rate increases, less accuracy is needed from the diagnostic to correctly identify the same percentage of "Bad" components that would have failed in service. A specific example is to consider the 50% level of failure identification. Fig 10 shows that at a failure rate of 0.1 only an accuracy of 60% is required, however an accuracy of 95% is required to achieve the same impact when the failure rate falls to 0.01. Therefore, in a system that is in poor condition, the diagnostic does not need to be very accurate for that utility to be able to avoid a large number of future service failures. On the other hand, for a system that is in very "Good" condition, the diagnostic must be very accurate for the utility to derive benefit in terms of reliability.

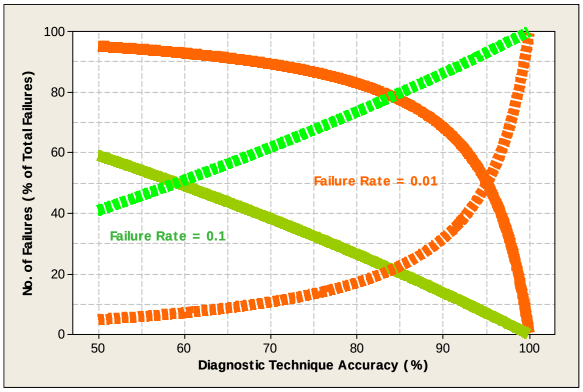

Fig. 10: Percentage of failures that are diagnosed (dashed lines) and undiagnosed (solid lines) versus diagnostic accuracy for failure rates of 0.01 and 0.1 per component per year, for a total population of 100 components.

This sort of analysis can be used to determine how "Bad" the population must be for the diagnostic to yield a desired failure reduction. It may also be used to determine how accurate the diagnostic technique must be to be capable of locating a desired percentage of the "Bad" components. Unfortunately, the diagnostic accuracies are not straightforward to compute and require specialized techniques [3], [4]. They are, nonetheless, vital to the selection of diagnostic techniques as each technique is capable of delivering a certain level of accuracy.

IV. TECHNIQUE

The selection of the appropriate diagnostic technique will depend upon many factors, a selection of which is listed below:

- Accuracy of Technique – How often does the diagnostic provide a correct assessment of the condition of the component (see discussion associated with Fig. 10)?
- Action – What maintenance actions is the utility willing and/or capable of performing?
- Cost (total including utility involvement) of Technique – How much per test does the diagnostic cost? More accurate diagnostics may also be more expensive.
- Difficulty of Deployment – What is involved in actually performing the test? Do the components need to be de-energized or can the diagnostic test be performed online?
- Failure Type / Mechanism – What causes the component to fail? Is there a reasonable chance that the technique is sensitive to the symptoms of this failure mechanism?
- Form of Test – Commissioning of New Equipment / Replacements or Health assessment of aged components to determine a priority of action?
- Risk to Utility Asset – Could the component be damaged by the diagnostic test during testing? Are there lingering effects from the diagnostic test that may cause premature failure?
- Safety – What precautions must be taken in order to safely employ the diagnostic?
- Immediacy of feedback – How long does it take to receive the results from the diagnostic testing? The more immediate the feedback the quicker remedial action can be taken; generally this will mean that the associated costs are lower

The selection of the diagnostic technique usually begins with an assessment of the actions that the utility is able or willing to perform on the components. Different component types can be repaired in various ways ranging from small repairs such as a bad termination on a cable system all the way to replacement with a new component. One example is where the standard Utility action for a component is to replace it with a new version. In this case a technique that has some chance of showing how the unit may be repaired will not be appropriate, as that repair will not be undertaken. Thus the optimal approach would be a technique that treats the unit as a whole and provides a prioritization for replacement. Table I shows an example of how it is possible to compare diagnostic techniques for some of the important elements of the selection process.

TABLE I
COMPARISON OF SOME OF THE IMPORTANT CHARACTERISTICS FOR A SELECTION OF DIAGNOSTIC TECHNIQUES FOR UNDERGROUND CABLE SYSTEMS [5].

Technique	Type of assessment (Global/Local)	Difficulty of Use	Availability of Result
VLF AC Withstand [1, 3]	Local	Low	Immediate
DC Withstand [2]	Local	Low	Immediate
Power Frequency Withstand [3]	Local	High	Immediate
Partial Discharge - Online	Semi-Local	High	Long Wait
Partial Discharge - Offline [3]	Semi-Local	High	Long Wait
Dielectric Loss (Tan δ) [3]	Global	Medium	Short Wait
Time Domain Reflectometry	Semi-Local	Medium	Immediate
Isochronal Relaxation Current	Global	High	Short Wait

Notes on Risk to Asset
[1] No unexpected risk if IEEE 400.2 levels (voltages and times) are used.
[2] Lowest risk to systems fully comprised of paper cables; increased risk on extruded and hybrid systems.
[3] Likelihood of failure depends on test voltages and times employed.

The diagnostic should be capable of detecting the signs or symptoms of the prevalent failure mechanism or mechanisms. A diagnostic technique designed to detect insulation problems is not the best choice for identifying a bad oil seal in transformers. In other words, the diagnostic should be sensitive to the problems that are occurring in the components. The quality of the Utility failure data, at the component level, is critical in ensuring that there is a good fit between technique and the mode of failure.

The important factor to recognize is that the choice of diagnostic needs to be continually validated as an approach that works for one utility may not work for another. Also as the remedial actions take effect, the make up of the system will change thus the techniques may become less effective. The primary cause is that they are insensitive to the remaining modes of failure for the system. An alternate way to look at this is with Fig. 10; for simplicity we talk about single modes of failure, however there are always mixed modes e.g. 70% with a failure rate of 0.1 and 30% with a failure rate of 0.01. In the early days the 0.1 rate dominates and thus an accuracy of 60% suffices. However as these areas with the high failure rates are addressed the required accuracy moves towards the 95% level. Thus the chosen technique needs to be continually tuned such that the program remains relevant and there may come a point when the technique needs to be changed. It is precisely for this reason that the Evaluation phase is of such critical importance.

V. CONCLUSIONS

Diagnostics are a valuable tool in efforts to reduce current failure trends while maintaining acceptable budgets. Yet to be effective, the diagnostic technique must be selected in conjunction with target populations that are carefully chosen to be the correct mixture of “Good” and “Bad” components. A number of techniques may be employed to identify these populations even if data are scarce. Small amounts of data can be used as a starting point. In fact the amount of data required is much smaller than often thought by utilities.

Once the target population is selected, the diagnostic test can be used to target the maintenance actions to only those components that require them. The diagnostic test must be sensitive to the problems being experienced by the target population. In addition, it should provide results that will allow the utility to perform the maintenance actions they are willing and able to complete.

VI. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the valuable discussions with Jorge Altamirano, Tim Andrews, Miroslav Begovic, Ron Harley, J.C. Hernandez, and Thomas Parker, of the Georgia Institute of Technology and the National Electric Energy Testing Research and Applications Center (NEETRAC).

VII. REFERENCES

[1] Abernethy, R.B., *The New Weibull Handbook*, Robert B. Abernethy, North Palm Beach, FL, 1993.

[2] International Electrotechnical Commission, *Reliability Growth – Statistical Test and Estimation Methods*, IEC 61164, Second Edition 2004-03.

[3] Perkel, J.; Hampton, R.N.; Begovic, M.; Hartlein, R., “Validating ‘Diagnostic Tests’ for Cables in Service,” *7th International Conference on Insulated Power Cables 2007 (JICABLE’07)*, June 2007, pp. 449-454.

[4] Hampton, N.; Perkel, J., “How Accuracy Impacts the Economic Benefit of Cable Diagnostic Programs”, *IEEE PES Insulated Conductors Committee Meeting (ICC), Subcommittee C, Fall Meeting*. Presented November 6, 2007.

[5] J. Densley, “Aging Mechanisms and Diagnostics for Power Cables-An Overview,” *IEEE Electrical Insulation Magazine*, vol. 17, no. 1, pp. 14-22, Jan. /Feb. 2001.

VIII. BIOGRAPHIES

R. A. Hartlein (SM’02) is the Director of the National Electrical Energy Testing Research and Applications Center (NEETRAC) of Georgia Tech in Atlanta, GA, USA. Rick received B.Sc. in Mechanical Engineering from the Georgia Institute of Technology. He actively participates in the development of industry standards and specifications for underground cable systems and has served as Chair of the IEEE Insulated Conductors Committee.

R. N. Hampton is the Program Manager for Reliability work at the National Electrical Energy Testing Research and Applications Center (NEETRAC) of Georgia Tech in Atlanta, GA, USA. Nigel has B.Sc. and Ph.D. degrees in Physics from the University of Bath in the UK and holds an M.Sc. in Polymer Engineering. He has spent more that 15 years working in the power cable arena, holding positions within BICC, Pirelli, Borealis, and NEETRAC.

J. Perkel (S’04) received the B.S. in Electrical Engineering and Computer Science (EECS) from University of California, Berkeley, in 2001, and M.S. in Electrical and Computer Engineering (ECE) from Georgia Institute of Technology in 2005. Josh is currently completing his a PhD research in the area of asset management strategies for power system components and underground cable diagnostics at Georgia Institute of Technology, Atlanta, Georgia, U.S.A.