I22: End-Of-Useful Life Assessment of P&C Devices

Report to Main Committee

Final Report – May 2015

Chair: Bob Beresh

Vice Chair: Bruce Mackie

Members: Bob Beresh, Bruce Mackie, Gabriel Benmouyal, Craig Bryant, Ratan Das, Aaron Feathers, Fred Friend, Rick Gamble, J. Gosalia, Gordie Halt, Charlie Henville, Yuchen Lu, Roy Moxley, Anthony Newman, Vajira Pathirana, Mario Ranieri, Sam Sambasivan, Sudhir Thakur, Solveig Ward, Don Ware

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Assignment

Prepare a PSRC report on the criteria for determining the end-of-useful-life for protection, control, and monitoring devices including electromechanical, solid-state and microprocessor-based devices.

Introduction

The end-of-useful life[1] of a device used for protection, control and metering can be defined as a time during the lifecycle of the device when any of the following situations is reached:

1. The device is no longer able to perform as per its design specification when first installed and it is not possible to repair it.
2. The device is no longer under warranty and the cost of repair outweighs the benefits of a newer device.
3. The device is no longer useful and no longer meets present functional requirements.

The expected useful life of a device from the time of its installation date may vary based on the following factors:

1. The device technology (electromechanical, solid state or microprocessor-based).
2. The designed life of the device as defined by the manufacturer.
3. The availability of parts/components/boards for repair and cost of repair in comparison with the benefits offered by newer devices and the mean-time-to-replace.
4. When the device was actually installed, *not* necessarily when the device was purchased or designed/manufactured.
5. There is a significant excursion of operating parameters by the device from set or designed parameters.
6. The environment in which the device is placed has changed (temperature/humidity/EMC/etc.)
7. Regulatory or other requirements have changed the functional requirements.

There are two terms used throughout this document: “end-of-life” and “end-of-useful-life”. End-of-life is what is expected when the device is installed. A device (relay, for example) is purchased and installed and expected to last for 20 or 25 years (for example). This “end-of-life” is the anticipated and planned in-service life of the device. The second term is that which is discussed at length within this document and refers to when the device actually (in real life, not planned originally at design or procurement time) is done/finished serving its purpose *before* the expected end-of-life, that is, it has come to its end-of-*useful*-life. Instead of lasting 20 or 25 years (for example) the device is replaced earlier for some reason that was not initially anticipated. It is the intent of this document to help asset managers, planners, designers and field staff to understand and anticipate the possibility for the early retirement of protection and control devices in order to better prepare for their replacement or perhaps extend their actual useful life.

This document does not address the benefits of upgrading a device but examines:

- The reasons why a device may no longer be useful.
- Possible ways to determine useful life of a device.
- Why knowing the useful life of a device is important.

[1] “Practical life” may also be used as a similar term to “useful life”.

- How to extend the useful life of a device.

Since P&C equipment life, and specifically, useful-life is the focus of this report, it is important to define what is considered the life of a device. There may be many interpretations of this from the age of the device starting from date of manufacture (date code); or the date it was purchased and received by the company (purchase date/shipped date/received date); or the date at which the device was placed in service (in-service date). To further complicate the definition of device life is the fact that the age of a device is not limited to calendar-based longevity but age may be related to the number of operations it has performed (contacts are rated for a finite number of operations, for example) or the number of heat/cold cycles it endures, or the age may be related to how long the device has been sitting un-energized (as with electrolytic capacitors – a major concern in the nuclear industry). Similarly, the age of a device may be related to the life (age) of the most critical or vulnerable component within the device (battery, crystal, capacitor, MOV, etc.).

For the purpose of this document the life, or age, of a device will be considered the length of time from the date the device was placed in-service (in-service date) to the date the device needs to be replaced.

Knowledge of the useful-life of a device will provide valuable input to a number of operational issues for the end user. These will include:

- Staffing needs regarding maintenance and commissioning: Having a better understanding of the end-of-useful life of a device will enable planners and management to better forecast staffing levels, training and resources required to maintain (or replace) their fleet of protection and control equipment.

- Replacement model: With a better understanding of when a device (speaking categorically) will reach its end-of-useful life, financial requirements can be planned and justification made for increases in budget levels. This will help to avoid last minute, un-planned-for responses that can typically occur when a device reaches its end of useful life when it was expected to last for a much longer period of time.

- Spare equipment. A better understanding of the life of device will also assist in providing valuable input to a spares stocking model for devices. A device expected to last for 20 years will have different spare requirements than one that is expected to last for 12.

- Utility experience and information on end-of-useful life shared with the community would enable better decision making to enhance the reliability of the system as well as reduce operating costs in general.

Once end-of-useful life data has been determined this can be used as input to various planning activities as mentioned above, which will ultimately result in the replacement of the device at the predetermined time.

In some cases the end-of-useful life of a device may actually be after the expected or planned end-of-life, such as is the case with many electromechanical relays still in service today.

1) Indicators of End-Of-Useful Life

Technology used in the protection and control industry has changed from electromechanical to solid state to microprocessor-based platforms. This change in technology has also increased the use and sophistication of various communication protocols and media. The need for more device functionality has accelerated because of the following factors:

- More demanding regulatory requirements
- Advances in technology
- Demand for operational data
- Demand for increased performance and reliability

This has resulted in a faster turnover of technology to meet the increasing needs.

As a result, equipment no longer reaches end-of-life simply based on component failure, wear out (age), and lack of spares. End-of-life is increasingly dependent upon the termination of the device's *useful* life – when it can no longer perform as required.

Consider, as an analogy, the many reasons for changing one's car or TV before it fails irreparably. A car may need replacing due to increasing failures, performance issues, functionality, or simply due to aesthetics. A perfectly good television set may need replacing due to government regulation changing analogue broadcast signals to digital. The automobile and the television, in our example, have reached the end of their *useful* life – not their mechanical, electrical, planned, or expected life. Another example is cell phones, which are being upgraded on a routine basis with newer features though the old phones work fine.

The following section enumerates various drivers that can be used as harbingers for determining the end of the useful life of a device.

1.1) Mergers and Acquisitions

In the event that a utility merges with another utility, it may be necessary to upgrade certain devices prior to their end-of-life due to business or technology-related issues. The new entity may require a common platform of devices for purchasing, maintenance, training, and spares. The new entity may be in a position to better leverage lower costs from a new supplier or one partner in the new entity may have had a poor experience with a particular supplier and subsequently chooses to standardize on an alternative platform. A newly formed entity may want a common platform for line protections at each end of the line. There may be many reasons why an amalgamated utility may want to replace devices before their expected end-of-life.

Mergers and acquisitions are not uncommon, especially considering the purchasing of small local municipal (MUNI's) or regional utilities by larger state/provincial entities. It is clear that some conformity to one way or another of doing things will occur and that technology is one area assailable to change.

1.2) Government Funding

Government funding may impact the end-of-life of a device insofar as a having to buy local or indigenous products to receive funding or tax credits or subsidies. For example, government funding may be available for smart grid or synchrophasor initiatives and this might require upgrading existing facilities. Existing, operable devices are replaced with newer devices manufactured within the jurisdiction of the governing body to help stimulate employment. Government funding is typically limited to within a certain time period and usually comes with various conditions associated with it (buy from local state, buy American, buy from job creating companies, buy from approved suppliers, buy from non-restricted countries, buy from green companies, etc.). Utilities may want to take advantage of these initiatives and upgrade their equipment accordingly to enhance performance before devices actually reach their expected/planned end-of–life.

1.3) Technology Trends

Technology related changes will impact existing devices as newer features and greater performance becomes attractive, and even necessary, for the operation of the power system.

End-of-life prior to device failure could be due to a number of technical factors:

1. The existing reporting capabilities of the device are inadequate (sequence of event recording, oscillography, size of memory available for number of records required, etc.).

2. There are missing features which are highly desirable or required:

    a) Logic functionality may be missing, inadequate, or limited in terms of complexity.

    b) Protection function requirements (or setting ranges) may expand beyond current device capabilities due to DG, smart grid, or other requirements.

    c) Multiple settings groups may be required for increased operational flexibility or system performance

    d) Communications functionality may be inadequate, or limited (the device has a serial port but a high speed Ethernet port is required; device has a proprietary/obsolete communications protocol that is not compatible with other devices; etc.)

3. It may be practical to upgrade a device in order to extend the life of other devices (extend life of primary equipment). For example, replacing a transformer relay with one having monitoring capabilities could help extend the life a transformer by providing better diagnostics.

4. Devices cannot be integrated into a complete substation automation solution.

5. Configuration software can no longer operate on newer computers, or older computers used to run old software are broken down and not available. (Will a software interface program used for configuration of a device today run on a Windows computer 15 or 20 years from now – if Windows computers exist as they do now? Will a laptop running XP with settings software today still be working 20 years from now?).

6. In addition to item 5 above, other trends in computing technology such as obsolescence of the CD ROM and the migration towards cloud computing, will have an impact on the end-of-useful life of devices. (Some new computers do not have CD ROMS and the hard drive is being shrunk in size to accommodate cloud computing and solid-state drives.).

1.4) Expediency

A relay may be replaced due to expediency - it just makes sense to do so (even though the device is working satisfactorily). An example would be to replace a breaker controller relay or breaker failure relay during a breaker replacement program.

Many utilities are now installing pre-fabricated protection and control buildings thereby performing wholesale replacement of existing control/relay rooms. Obviously any device in the old facility would be removed (end-of-useful life) and then replaced by newer technology in the pre-fabricated building. Figure 1 is a photograph of a "drop-in" replacement for an existing relay and control room.

Figure 1 - Drop-In Relay/Control Room

1.5) Station-Centric Asset Management

Some utilities are now adopting a station-centric approach to asset management whereby assets (protection and control devices included) are replaced, not across the fleet as they age, but replaced wholesale - one station at a time. This means that existing devices (old and new) are updated on a station-by-station approach. This obviously means that some devices that are fully functional and in good working order, which have not come to their end-of-life, will be replaced (end-of-useful life) during a station-centric upgrade process. The motivation behind the station-centric approach is to optimize staff deployment; minimize outages and outage scheduling; minimize/simplify work program; and minimize travel (reduce road related hazards) [1]. This does, however, imply that devices will be replaced prior to their expected end-of-life, at least for the initial station upgrade process.

1.6) System Reliability

System reliability is an important factor to consider in the early retirement of an existing device. If system performance can be improved by means of a superior product, then it might be prudent to replace the device before its end-of-life. Outage and blackouts also fall into this category of reliability. If the number of outages on a circuit or customer load can be reduced by improving the performance of the protection with a newer or different device then this would certainly be a driver in upgrading/replacing the device prior to its end of life.

For a sample listing of lawsuits against utilities resulting from blackouts, refer to “Liability of Electric Utility in the USA for Outage or Blackout” [2].

System reliability can be improved by various means including: faster protection operating times; by the use of special protection schemes; through the use of redundancy; by means of improved protection schemes; etc. Replacing an existing device for the purpose of improving reliability is a certainly one reason for replacing a device prior to its end of life. The end of its useful-life has arrived due to the benefits that can be achieved by replacing it.

1.7) Product Reliability and Quality

As consumer product lifecycles seem to dwindle in the light of a disposable attitude within the economy, the effects spill over to the industrial sector where product lifecycles have also become shorter requiring earlier replacement of devices. More features, or newer models, or better performance, or higher profits constantly drive sales and marketing to push innovation, change and new product releases. Also the drive for higher profits can increase pressure to save money on manufacturing and material (components) costs.

This pressure can impact quality and therefore end-of-life. Proper manufacturing must enlist the use of quality controls as well as high quality materials to ensure maximal life of a product. Unfortunately, even if a maximal product life is the goal of the manufacturer, component quality is not always easy to monitor and ensure. There is now a problem of used and/or counterfeit components being passed off as new and therefore impacting device performance and life [3]. Certainly, equipment end-of-life would be impacted if it were ascertained that the quality of the components was not as expected either due to inferior components or inferior manufacturing [4],[5].

1.8) Failure Rates, Performance, Change in Failure Rates (Statistical Data)

The IEC describes useful life as "the time interval beginning at a given moment in time, and ending when the failure intensity becomes unacceptable or when the item is considered to be unrepairable as a result of a fault (IEV 191-19-06) [1]." Therefore, according to this definition the end-of-life is when the failure intensity becomes unacceptable or when the [recovery/repair] time is considered to be unacceptable as a result of a fault. Some examples for end of life include the loss of life of capacitors (loss of capacitance because of electrolyte drying and leakage), and loss of semiconductors (mainly ICs) that degrade because of thermal, vibration and humidity. The ability to determine the end-of-life will better prepare the utility for a successful asset management strategy as well as bolstering their rate case application.

One familiar estimate for predicting end-of-life uses the "bathtub curve" which shows the large infant mortality of brand-new relays, the useful life of in-service relays, and finally, the end-of-life obsolescence period where relay failures accumulate rapidly. The key is to predict the length of useful life. The lognormal probability distribution, r(t), indicates that once the relay has one failure, subsequent failures will occur with lesser and lesser time intervals.

Infant Mortality – Consider the left side of the curve of Figure 2. Because of the high initial failure rate it is advantageous for the manufacturer to both minimize that rate and catch those failures before they can leave the factory. These early failures can be caused by component or manufacturing defects. Dielectric tests described in IEEE Std C37.90™-2005 may catch some manufacturing defects (those that would cause an insulation failure)[2]. The most common method of detecting defective components is to perform a high temperature operation of the relay for 24 to 72 hours. This is not required by standards but does perform the function of pushing a component that might be prone to early life failure into a failure condition that is then detected prior to shipment.

In practice, the number of failures during the "useful life" period will not be zero, but will be some small, finite number compared with the failure's during the period of infant mortality and wear-out.

[2] IEEE Std C37.90.1™-2005 states that "Dielectric tests, in accordance with this standard, may be performed once by the user on new relays to determine whether specifications are fulfilled …Additional dielectric tests may be made using 75% of the test voltage determined in accordance with…." See IEEE Std C37.90.1™-2005 for further details.

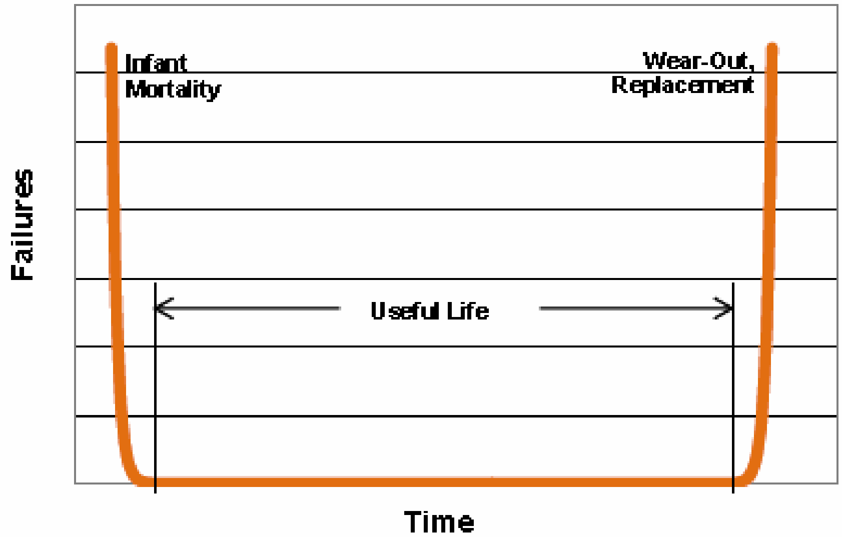

Figure 2 - Relay Failures Over Time

Mean time between failures (MTBF) is another useful parameter that can be calculated for each relay type by evaluating relay failure data in conjunction with the relay asset information for the number of relays installed. This can be broken down by relay class to evaluate relay class performance, or by manufacturer and model to evaluate performance of specific relay types. MTBF is normally calculated for in-service relay failure trends. MTBF can be monitored over time, such as quarterly, to determine positive or negative failure trends.

MTBF = (Total Operating Time) / (Number of Failures) (years)

Relay failures identified during commissioning can be trended to identify quality of relays received out of the box. This may identify manufacturer defects or quality assurance issues. If a negative trend is identified for a particular relay manufacturer or model, then additional relay failure details can be trended to drill down further, such as trending by component failure type or by firmware version or hardware vintage or manufacture date. Always consider whether some system design feature or installation or test procedure is damaging products that seemed to be defective out of the box.

Relay failures can be analyzed based on the age of the relays when a failure occurs. This can be useful to determine at what age relay failures begin to increase significantly and therefore to determine an appropriate and practical relay life. The utility can use this practical life of a relay to be proactive and replace relays prior to end of life failure and avoid possible unplanned outages, loss of customers or damaged equipment. Reliability modeling allows the utility to examine trends occurring in the operation of existing devices [6].

Examining end-of-life based on performance requires diligent recording and analysis of in-service data, failure data, and repair data.

1.9) Incompatibilities/non-interoperability with other Technologies

As new technologies evolve and older technologies become obsolete, it will not only become harder to replace existing devices but also harder to integrate new devices with the old. Newer technologies heavily depend upon communication interfaces using fiber optic cables, for instance.

Even in the modern generation of digital protective devices (numerical, solid state, and microprocessor relays), communication protocol standards for interfacing with the relay have evolved. For example, some devices may only have serial port interfaces while others have options such as USB and Ethernet. However, serial ports are rarely available on laptop computers used to connect to a relay, so consideration must be made as to what interfacing is desired and will survive for the life of the device.

Similarly, digital relays over the past generation have had increased options for input and output interfaces. Early digital relays had discrete set of inputs and outputs, rated at similar speeds and with similar operating values (L/R, ac/dc breaking currents, etc.). Modern relays typically have fully configurable input and output cards, including: options on the number of input and outputs, high speed electronic and standard mechanical outputs, contact Form (A, B, C, etc.), and various current and voltage ratings. Design teams should take into account what inputs and outputs are desired to prevent the need for adding additional devices (such as auxiliary relays) taking up rack space.

Additionally, microprocessor-based relays require software to run on a computer for making logic and setting changes. At some point in a protective device's life, that software will be made obsolete by the manufacturer due to new product lines being introduced, or by operating system software moving to a different generation without backwards compatibility (such as 16-bit to 64-bit). As the cost of maintaining the software to program a relay increases, the cost of maintaining the relay itself increases.

Another issue is connecting electromechanical relays with a limited number of contacts to external devices, such as digital fault recorders and power quality monitoring equipment. As higher visibility and data requirements become a greater priority, the end-of-useful life of these devices becomes more apparent. The cost of retrofitting transducers and auxiliary relays to these devices could outweigh the cost of replacing the device with a modern equivalent.

1.10) Self-monitoring Capability

Self-monitoring is now a key requirement for extending maintenance intervals. The use of self-monitoring, or self-diagnostic capabilities, can significantly extend the maintenance interval requirements for a device as specified in NERC Standard PRC-005-2. This has advantages in reducing labor costs as well as reducing the possibility of misoperations/false trips due to human error.

Self-monitoring features can include such capabilities as outlined in Figure 3. Note that self-monitoring typically does not check the condition of the output contacts.

The availability and attractiveness of self-monitoring can justify the replacement of a device prior to its end-of-life. That is, it may be better to replace an existing fully functional device with one that has self-monitoring capabilities in order to reduce labor requirements and costs as well as to reduce the possibility of human error during maintenance. The device would therefore be replaced at its end-of-useful life because a better solution (self-monitoring) became available prior to the device's expected, or planned, end-of-life.

Component Failure	Monitoring Capability	Detail
RAM Failure	Yes	Static RAM read/write error
ROM Failure	Yes	EPROM program memory checksum error
Analog to Digital Failure	Yes	Analog to digital converter error
DSP System Failure	Yes	The watch-dog repeatedly attempts to re-start the DSP for diagnostic purposes.
µP Failure	Yes	Microprocessor exception or self-test error
Watchdog Failure	Yes	Microprocessor watchdog circuit timed out
Default Setting Loaded	Yes	Relay using default setting.
Password access Lost	Yes	Password access lost. No changes
Group Override	Yes	Setting group override in effect
Settings Change	Yes	Setting change made by a user
Active Setting Group Change	Yes	Active setting group changed
Self-Test	Yes	The most comprehensive self testing of the relay is performed during a power-up. During both startup and normal operation, the CPU polls all plug-in modules and checks that every one answers the poll.
Critical Failure Alarm	Yes	The relay has form-C contacts and is energized under normal operating conditions. The critical failure alarm will become de-energized if the relay self test algorithms detect a critical failure.
Output Override	Yes	One or more output contacts have logic override condition
Output contact Monitoring - Active Voltage Monitor Circuit	Yes	This circuit is connected across form-A contacts. The voltage monitor circuit limits the trickle current through the output circuit. The state of the operands can be used as indicators of the integrity of the circuits in which form-A contacts are inserted.
Clock Error	Yes	Real-time clock not set

Figure 3 - Self Monitoring Capabilities (Courtesy of EPRI)

1.11) Lack of Support, Spares or Parts by Vendors

Devices have a finite life cycle in terms of product support. It is difficult for vendors to support a product for the entire physical life of a device which might be upwards of 25 or 30 years. Vendors may offer a lengthy warranty but will replace a failed device with a newer one if it is not feasible to replace the failed device with an identical one (either at the device or component level). The warranty period is typically less than the actual expected life of the device and does not ensure or guarantee a like-for-like replacement in the event of a failure.

Because manufacturers cannot always control the availability of parts necessary to maintain a device in production, there is typically an “end-of-life” process to support the application, design and installation of products in the field after production has ceased. A process of implementing and communicating this “end-of-life” to customers consists of several steps. The first step is a “Discontinuation Notice” to advise the community that a particular product will become unsupported in some upcoming time frame, typically one or two years. During that time customers can issue “last time buys” of the product with normal lead times and standard warranties. Following the time specified in the “Discontinuation Notice” will be the actual “Cancellation” of the product. At the time of cancellation the product is no longer available for standard purchase - although individual units may be available if required to complete a station or support a complete replacement. For an extended time after the cancellation these individual units and repair support is typically available along with application and documentation support. The time following cancellation that this support is available is typically the warranty period or ten years, whichever comes last. Finally, after this extended support time the unit is no longer supported in an official capacity. Documentation is archived and information will be difficult to obtain.

A utility may not wish to continue the use of a particular device after it is no longer supported or parts/replacements are no longer available. It is conceivable, therefore, that a device can reach its end-of-useful life, long before the expected end-of-life, based on the level of support available from the manufacturer. Spare devices may not be available from the vendor, internal inventory, or are incompatible with recently installed devices. Also there may be a lack of spare parts/components for repairs (for example, cards/modules become obsolete or unavailable, specific components are no longer produced, etc.)

Ensuring the availability of spares is a serious matter to consider in terms of optimizing expense, storage space, availability, system reliability, cost of upgrading if spare not available, etc. A spare supply policy can have a significant impact on what devices are kept running and what devices are replaced at an early point in their life.

1.12) Firmware Changes

A volume of protection and control related devices may reach their end-of-useful life sooner than their expected life if firmware changes and upgrades are considered. Many utilities specify a certain version of a device and perform tests on that device and subsequently order a volume of those exact same devices. The utility may consider that a firmware upgrade constitutes a change in the device performance or operating characteristics. Does a device reach its end-of-useful life due to firmware changes? If firmware changes become frequent in nature or they begin to require massive integration efforts, then the device may have reached its end-of-useful life due to firmware changes. IEEE Std C37.231™-2006 provides some useful techniques for monitoring firmware changes which can be helpful in tracking performance [7].

There may also be a lack of interoperability between various devices due to firmware incompatibilities, vendor related issues, communications issues, device vintage, etc. Replacing existing (operable) devices could allow for more seamless integration and inter-communication rather that upgrading firmware.

In addition, firmware changes may require extensive testing, outages, and commissioning and therefore the incremental cost of installing new devices may be more attractive than maintaining the existing devices[3].

1.13) Cost of Maintenance, Repair, and Operation Compared with Replacement.

A clear indicator of the end-of the useful life of a device is an increase in maintenance costs. This is similar to any repairable consumer product. At some point in time a device needs to be replaced due to an excessive need for repairs. The excessive need for repair could be on only one unit out of a batch of units but could cause sufficient concern to warrant the complete replacement of all units and hence, an end-of-useful life.

In addition to the frequency of repair, the cost of repair is also a serious factor to consider. Increasing repair costs due to lack of qualified personnel, long turnover times, and lack of parts may contribute to an accelerated end of life.

The cost of operating a device is a third factor in determining the end-of-useful life. Some older devices, for example, may require manual resetting of targets (thereby requiring operators to visit, record, and reset targets);

[3] For an example of firmware design and its impact in the automotive industry, refer to http://www.edn.com/design/automotive/4423428/Toyota-s-killer-firmware--Bad-design-and-its-consequences

replacement of batteries; and of course, excessive maintenance. These may contribute to a decision to replace existing (functionally operative) devices for newer devices requiring less operating costs. This is a common consumer decision with regards to appliances and automobiles. Do we continue to repair a device over and over again, or do we replace it? Does the cost of replacement outweigh the cost of maintenance and repair? This type of analysis is called a "cost-benefit analysis" in the business world[4]. Replacing a device and accepting an early end-of-useful life may save money and time in the long run. Unfortunately this is often the case with many mass-produced consumer goods, where it is easier to replace a device (end-of-useful-life) than to repair it [8].

1.14) Documentation and Loss of Knowledge Base

Another reason why a device may have reached its end-of-useful life is that the utility personnel no longer have the expertise to maintain or repair the device and that documentation may no longer exist (or the documentation associated with a particular firmware version does not exist). This may become more of a problem in the future as maintenance cycles become extended and documentation becomes increasingly digitized. Information[5] and skills will actually be harder to retain.

Compound this with staff attrition and job changes; utility acquisitions and mergers; internal downsizing and reduction of storage space; GREEN initiatives to reduce paper; and the changing technology from paper to floppy discs to CD ROMs to USB and hard drives and now to cloud storage; etc. How does the utility cope with maintaining critical information on equipment for 20 years or more to prevent loss of knowledge and expertise on device operation, parts, maintenance and performance? These issues will undoubtedly result in, or at least contribute to, the premature expiration of device usefulness in some situations.

In addition, the increasing use of contract personnel and outsourcing of internal design and construction responsibilities can accelerate the shortening of useful life due to the fact that the contractor, outsourced, temporary personnel simply do not have the historical background, data and documentation to inform them why something was done the way it was; and when things went into service; and the device performance history. It is easier for an outsider to package a design and replace a system, or number of components, than to try to maintain or extend the life or specific devices - especially from an external perspective from the utility.

1.15) Hazard Reduction

Requirements continuously change in order to reduce hazards in the workplace. As a result there may be circumstances that arise after a device is placed into service which require the device to be changed out (shorten its useful life).

Hazardous issues which may provide impetus for replacing a device prior to its expected end-of-life include:

- Lack of sufficient barriers or interlocks when performing maintenance.
- The presence of hidden and dangerous energy sources, such as energized capacitors and springs.
- The presence of toxic materials (PCB's, asbestos, mercury, lead, benzene, etc.).
- Lack of proper clearing times needed for arc flash protection.
- Lack of ability to change setting groups to allow faster clearing times when linemen are working on or near energized power lines.
- Lack of high impedance fault detection for energized lines lying on the ground.

[4] Refer to the wiki page at https://en.wikipedia.org/wiki/Cost%E2%80%93benefit_analysis for a starting point to learn about cost-benefit analysis.

[5] Consider for example the demise of the 5 1/4 or 3 1/2 inch floppy disk. Older devices came with paper copies of manuals which are frequently purged during documentation down-sizing operations.

- The device(s) may be located in hazardous areas with such dangers as: exposure to moving parts; exposure to possible steam leaks; unacceptable noise levels; elevated heights; confined space; unacceptable temperatures; radiation exposure; etc.

A device may need to be replaced prior to the end of its end-of-life due to these and other concerns. Each utility and state/province/federal government will have its own measure of what is considered to be hazardous in the work place, but it usually involves some level of actual or perceived potential injury to personnel. Power system relays are generally not considered to be hazardous if used according to manufacture specifications but a couple of examples below are instances where they could be:

1) Some electromechanical relays were built with capacitors, wire or other components that contained Polychlorinated Biphenyl, PCB, and insulating fluids. These components have been known to leak and/or off gas PCBs at significant levels and potentially expose employees to this carcinogenic and mutagenic compound. The environmental issues associated with PCBs have resulted in many of these older relays being systematically removed from power systems and being retired.

2) Spurious assertion of trip outputs during non-fault conditions or not tripping for a fault condition may be considered a hazard at some utilities. One utility had a condition where a family of new relays was needlessly asserting breaker failure outputs that resulted in clearing the bus at critical stations. This situation was viewed as a hazard, and the relays were removed from the system.

3) Although not a relay issue, the test switches built into some digital relays have created concerns with their usage. Some test switches do not automatically short circuit incoming current transformer, CT, circuits when the test plug is inserted into the test block. These test blocks require the maintenance personnel to install a number of “test jumpers” in the test plug to continue the shorting function after the plug is inserted in the block. Some utilities have had CTs become open circuited when the test plug was not configured properly and then inserted into the test block. This has led to burned blocks and damaged relays and as a result, some utilities have viewed these types of test blocks as a hazard to personnel. This has led to the early retirement of relays containing these particular test blocks.

4) Maintenance may require access to the proximity of hazardous ac or dc voltages and currents. Also, Maintenance can expose workers to danger from possible high voltages or currents during fault conditions. Maintenance sometimes requires access to rear panel terminals and/or possible hazardous practices of removing connections to facilitate testing. Some older relays, for instance, require that the front cover be removed to access settings and test points while the device is energized.

It is possible that, in extreme circumstances, a manufacturer may recall a device due to possible hazardous concerns such as occurs in the automotive industry from time-to-time. This is of great concern not only from an operational point of view but also from a publicity and litigation perspective as well.

The diligent consideration of hazardous issues may result in a device reaching its end-of-useful life well before its expected end-of-life.

1.16) Operational Issues

Operational issues related to the functionality of a device can lead to a lower life expectancy if, for example:

1. The device does not have operator control or functionality required for the application (distributed generation or interface to local municipal utility, for example). Perhaps with emerging smart grid applications or increased DG penetration there may be operational (control and metering) features that are now required but not previously available. These issues could lead to the device being replaced prior to its end of life.

2. In addition to control and metering information, the device may lack certain capabilities necessary to provide for operator and control data. Financial information, asset management information may be required but not available (consider 61850 and CIM[6] and how data can be used for non-technical purposes as well as technical). Smart meters, though not a protection and control device per se, are an example where an existing device is replaced (before its end-of-life) with another device having data capabilities for operational information.

3. It is possible that device functionality no longer aligns with corporate policies (reliability, connectivity with neighboring utilities, performance, etc.) and therefore must be replaced.

4. Reorganization from a regional-based operation to a centralized operation may require replacing equipment due to the need for remote access, control and data accessibility.

1.17) Reduce Outage Scheduling and Customer Outages

Utilities are now trying to work smarter and reduce the number of outages taken on power equipment in order to reduce customer interruptions, scheduling issues and reduced system security. This is becoming more important recently with the increasing number of generators being added to the transmission system. With their mandate and objective to generate power and maximum revenue, taking equipment out of service multiple times due to uncoordinated outage requests (one for P&C, one for lines, one for this, one for that, etc.) is no longer practical. It therefore makes sense to schedule the maximum amount of work - from all disciplines - during each and every outage and reduce equipment outages to a bare minimum.

This pressure to reduce outages impacts the scheduling of work programs but also has an impact on equipment end-of-life. If a protection or control upgrade is scheduled for a certain date but the power equipment it protects (or controls) is coming out of service prior to that date, it makes much more practical sense to do the P&C work when the power equipment is already out of service. This reduces the number of outages, scheduling requests and trip tests. It may also reduce the amount of time spend traveling (reducing travel hazards) for operators (less switching) and facilitate multidiscipline interaction.

Obviously this requirement by some utilities to reduce outages can impact end-of useful life as devices may be replaced sooner than expected. This will have to be taken into consideration during the planning stages for the P&C equipment end-of-useful-life assessment [9].

1.18) Cyber Security Implications

A device may be replaced due to lack of cyber security features. Even though it may be adequate for the function for which it is intended, the lack of sufficient security features may warrant replacement of the device. This may also be an example of a change (useful life less than design life) due to regulatory requirements.

Even if the device has sufficient cyber security features the usefulness of those features may be an issue as well. Consider the need to update/change passwords on an annual basis. Some utilities are using a user-based account system to update device passwords. Without this remote access capability the operating/maintenance cost of the device may be a factor in upgrading to a newer version to provide such capability to meet the need of securing local/remote access.

A further cyber security concern that may have an impact on the useful life of a device is that of its software vulnerability. Does the device have a back-door vulnerability that may allow unauthorized access? Does the user software require remote access for a license key or help files? Does the software perform routine Internet checks

[6] Common Information Model

for new versions, upgrades, or patches (consider Windows updates)? These issues may warrant the replacement of a device due to security concerns.

Security concerns leading to an end-of-useful life may also arise from lack of conformance to NERC CIP requirements which includes many other concerns aside from those listed above.

1.19) Environmental Implications

A device may have reached its end-of-useful life due to environmental issues. For example, the utility may have a policy against PCBs, asbestos, or lead solder. Some devices may contain these substances and the corporation, due to environmental concerns, policy or public pressure, may need to eradicate these from its system. In older stations, for example, the presence of ebony-asbestos relay panels may be considered a motivation for replacing the panel and equipment - even if the equipment is functioning properly and reliably.

Humidity, seismic activity, and temperature are also factors that may contribute to a less-than-ideal life for protection and control devices. Environmental issues need to be carefully examined, as a bulk order for protection or control devices may be allocated to different sites. Devices installed in air conditioned control buildings would not likely be limited to the same life expectancy as those installed in the basement of a 60 year old substation or in a breaker mechanism box. The end-of-useful life of the devices in the breaker mechanism box certainly would be shorter than those in the air conditioned control room (due to: vibration; dust; temperature swings; humidity swings; greater potential for EMC; and possible UV exposure, for example). These factors need to be considered in determining the useful life of a device. Not all locations can be considered the same

Figure 4 - Ebony-Asbestos Relay Panel

Environmental issues can lead to reduced expected life expectancy, that is, cause an end-of-life that is lower than that for which it was expected to achieve. Factors such as: cycling (on/off/on); air flow; and the normal state of the device (energized/de-energized) are normal operating environmental conditions, however when not taken in to consideration during the design or implementation stage of the application can lead to an end-of-useful life significantly shorter than that for which device was expected.

The Arrhenius equation for aging is shown below, where AF = aging factor; E_a is the "activation energy" of the component being aged; and k is Boltzmann's constant.

$$AF = e^{-\frac{E_a}{k}\times\left(\frac{1}{T_1}-\frac{1}{T_0}\right)}$$

This equation shows the relationship between an elevation in *temperature* and the impact on life expectancy. A device ages, by the aging factor (AF), when it is exposed to higher than designed for temperature. It therefore reaches an end-of-life sooner than what it was originally intended or designed for. Electrolytic capacitors, for example, "typically double their stress and failure rate for every 10°C increase in operating temperature" [10].

A further development on the Arrhenius equation is that of the Hallberg Peck relationship which also shows the impact of *humidity*.

$$AF = \left[\frac{RH_0}{RH_1}\right]^3 e^{-\frac{E_a}{k}\times\left(\frac{1}{T_1}-\frac{1}{T_0}\right)}$$

This equation shows that there is a cubic relationship between an elevation in humidity and the impact on life expectancy. A device ages, by the aging factor (AF) when it is exposed to higher than designed-for temperature and/or humidity. It is not the intent of this report to go into the details of specific aging factors, but to point it out to make the reader aware of these issues.

With the extreme weather conditions, some utilities have experienced flooding and high levels of humidity. Unfortunately, the impact of high levels of humidity on the performance and longevity of protection devices is not well known, or generally even considered. Nevertheless, humidity does impact the age of a device and must be factored into a consideration of the device's useful life.

1.19.1 Storage Considerations

Storage is important factor to consider in terms of: how the device was handled; how long has it been in storage; and under what conditions was it stored? Many of the issues related to temperature and humidity may impact the useful life a device during storage. Most manufacturers carefully package their devices to protect them until the time of installation; nevertheless, storage is an important consideration when determining the end-of-useful life.

Storage is also an important consideration with respect to the aging of electronic components. Aluminum electrolytic capacitors age when they are not subject to energization. The aging process is due to breakdown of the dielectric which occurs when the capacitor is unenergized. When an electrolytic capacitor is energized the dielectric is healed ("reformed") and restored. Degradation in the dielectric leads to an increase in leakage current. Therefore, the longer capacitors remain in storage without being energized or "reformed" the leakage current, when they are energized, can become greater than the rated value. This may lead to failure when the device is eventually energized. Texas Utilities Comanche Peak Steam Electric Station states that the shelf life of electrolytic capacitors is 16 years with appropriate re-forming, otherwise only 5 years without appropriate re-forming [11, 12].

One manufacturer clearly states that "To avoid deterioration of electrolytic capacitors, power up units that are stored in a de-energized state once per year, for one hour continuously" [13].

The leakage current of a capacitor is essentially the presence of parallel resistor across the capacitor as shown inFigure 5. This resistor is ideally and normally extremely high but due to the degradation of the dielectric can become much smaller thereby leading to an increased current flow and possible damage.

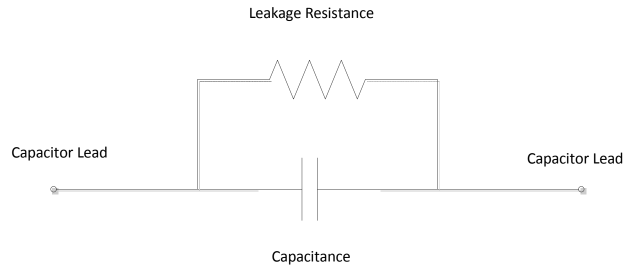

Figure 5 - Simplified Capacitor Model

Storage time and operating temperature can accelerate the dielectric degradation process and create a shorter useful life for the device.

1.19.2 Silver Migration

An environmental issue faced by some older devices is that of *silver migration* (electromigration of silver). Silver migration is the diffusion of metal alloys from one location (typically a terminal post) across a surface to another location (terminal). It is not clearly understood what causes this but is conjectured to be a result of ultraviolet radiation as it occurs somewhat more predominately near sunlit surfaces. Figure 6 shows silver migrating from one terminal to another terminal. Silver migration is a serious issue and has resulted in the need to replace entire relay cases. Silver migration is an example of how an environmental issue can lead to an end-of-useful life that is less than desirable. Proper conformal coatings are required to help prevent this from occurring. Silver migration has also been identified as a problem in the railroad and telephone industries [14,15]

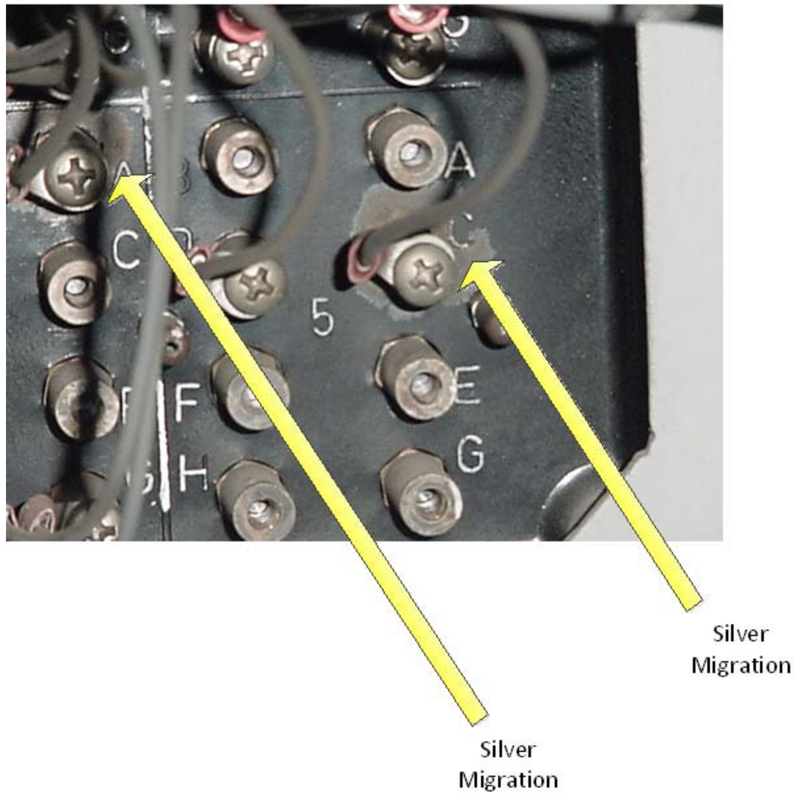

Figure 6 - Example of Silver Migration

1.19.3 Tin Whiskers

Another environmental issue leading to a reduced end-of-life is that of *tin whiskers*. Tin whiskers are small filaments of tin (or alloys) that can grow to be millimeters in length and bridge between traces on a circuit board, pins on a sub connector, relay contacts, and various other metallic surfaces[7]. Tin whiskers have also played a role in the failure of other devices such as GPS receivers [16]. For more information on tin whiskers with graphics, details on their formation, and damage caused as a result of their presence, refer to [17 and 18]. A downloadable spreadsheet providing a "Tin Whisker Risk Assessment" is available from the URL link provided in the References [19].

Figure 7 shows a tin whisker growing between two pins on a 14 pin DIP package IC. In this case the whisker actually grew long enough to short the two pins of the IC. The pins on this IC were tin plated with a spacing of 0.1". Figure 8 shows a whisker (possibly zinc in this case) growing between a relay base and relay coil.

[7] For videos showing whisker growth see: http://www.engin.brown.edu/faculty/Chason/research/whisker.html

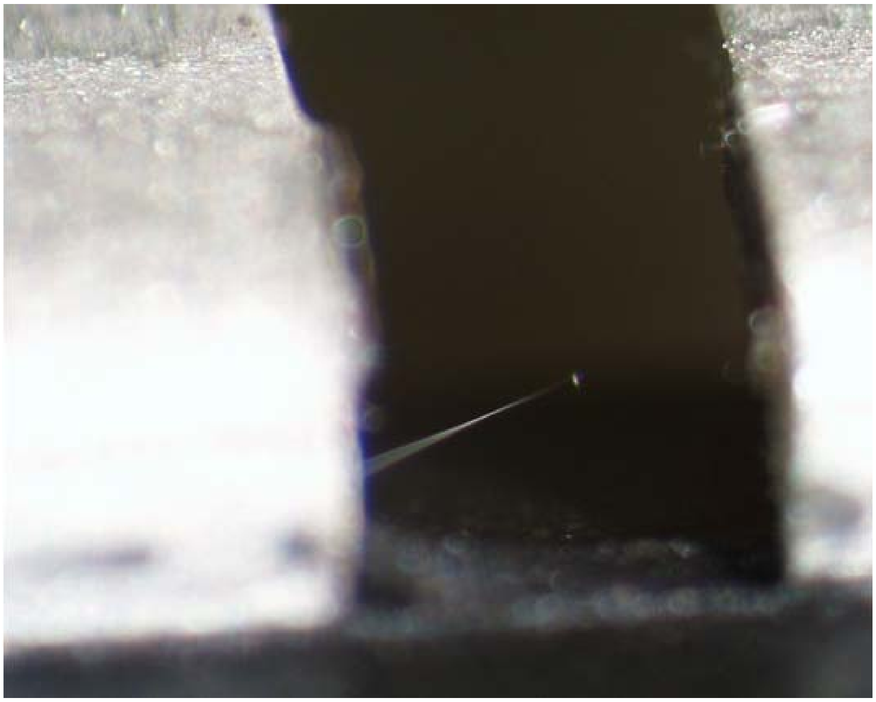

Figure 7 – Whisker Growing between Two Pins of 14 Pin DIP IC (Photo Courtesy of Kinectrics Inc.)

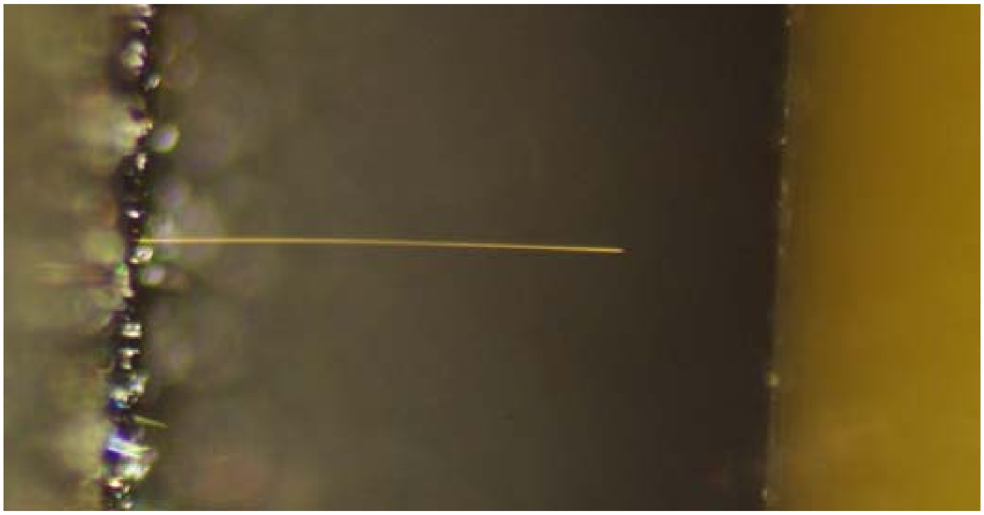

Figure 8 – Whisker Growing between Relay Base (left) and Coil (right) (Photo courtesy of Kinectrics Inc.)

1.19.4 Other Environmental Issues

Other environmental issues that could lead to a shorter useful life - if the device is not suitably qualified include:

- Vibration, which can be caused by seismic activity, road traffic, blasting, and lead to lead to "wire chafing, loosening of fastener, intermittent contact closure/opening, seal deformation of enclosed components component failure, optical misalignment and cracking [20].
- UV radiation from the sun.

- EMI (surge withstand, dielectrics, fast transient, etc.)
- Moisture (rain, snow, frost) in outdoor locations
- Humidity from damp control room basements with cable entrances and sump pumps.
- Dust ingress
- RF radiation

Some very old devices are susceptible to vibration, dust, moisture, contact contamination, as well as other contaminants hostile to electronic or electromechanical equipment.

1.20) Improper Application

To an extent, improper application has been covered indirectly in other discussions in this report; however it is important to realize that improper application can result in a less than ideal life expectancy. If the application design and product selection were not properly identified then the device may require replacing in advance of its end-of-life due to improper application – the wrong device for the application.

Possible improper application issues include:

1. Output contact ratings are not correct for the application.
2. Humidity, temperature, vibration, altitude rating, or EMC ratings are not appropriate for the application or installation location. For instance, the wear and tear example of an electromechanical plunger type relay described in Section 1.23 could be considered an incorrect application.
3. Potential for smoke damage to equipment/contacts in areas susceptible to forest fires.
4. Setting ranges are not adequate for the application.
5. Performance requirements or networking capabilities not sufficient.
6. Using an overly complex device for a simple role. This may not appear to be a problem but in terms of replacing the device it makes it more complicated. Also, maintenance, settings documentation, procedures, functionality may be overly excessive for the specific application.

Any number of the above issues, and more, are sufficient to render the device unsuitable for future use. The issue comes down to proper planning to a great extent. This highlights the need for proper design and device selection at the start of a project in order to help avoid end-of-useful life issues in the future.

The NERC Misoperations Report (April 1, 2013) provides the following suggestions for helping to avoid possible trouble arising out the improper application of devices [21]:

> "Applications requiring coordination of functionally different relay elements should be avoided. If these applications cannot be avoided, the coordination should be studied and tested thoroughly. This type of coordination is virtually always problematic, and is the cause of numerous misoperations reported in the study period. Some examples to avoid include:
>
> - Mixture, in the same scheme, of distance elements and overcurrent elements
> - Distance and directional overcurrent elements at opposite line terminals that use different directional polarization methods, particularly in the same pilot scheme
> - Overcurrent elements that use different measurement methods, such as phase vs. residual ground vs. negative-sequence current measurement"

Proper application of a device is critical.

1.21) Application beyond Design Parameters

Akin to improper application, it is also possible that the device may be applied in conditions that exceed its design parameters and therefore could lead to an earlier end-of-useful life. Manufacturers typically give extensive operating parameters for their devices including: voltage, humidity, temperature, EMC levels, altitude, shock/vibration, dust, etc. If a device is operated outside of these ranges, it could degrade the life expectancy, similar to when a transformer is operated above its rating for extended periods of time.
An example of a protection and control device applied beyond it design limits could be:

- The operation of the device in a humid environment or located above a heater, or near a window.
- The device could be installed at a site whose elevation exceeds the device's rating.
- The device is used with a battery charger that has an excessively high float level.
- The device operates more times than it is designed to operate.

The device operates a load that exceeds its contact ratings.

1.22) Early Adoption

Early technology adoption (trendsetting) may be a driver for a shortened end-of-useful life. Technologies may be deployed before they have been fully tested or "proofed". The Rogers's Bell (Figure 9) curve is a Gaussian-based distribution showing the demographics of technology adopters over time [22]. Care (type testing/pilots/environmental testing/etc.) should be taken when adopting new technologies.

Early adopters, also called "Lighthouse Customers" by the industry[8], may face near-term issues with products from software, firmware, and hardware-related teething pains. This may necessitate early retirement of the device due to performance issues.

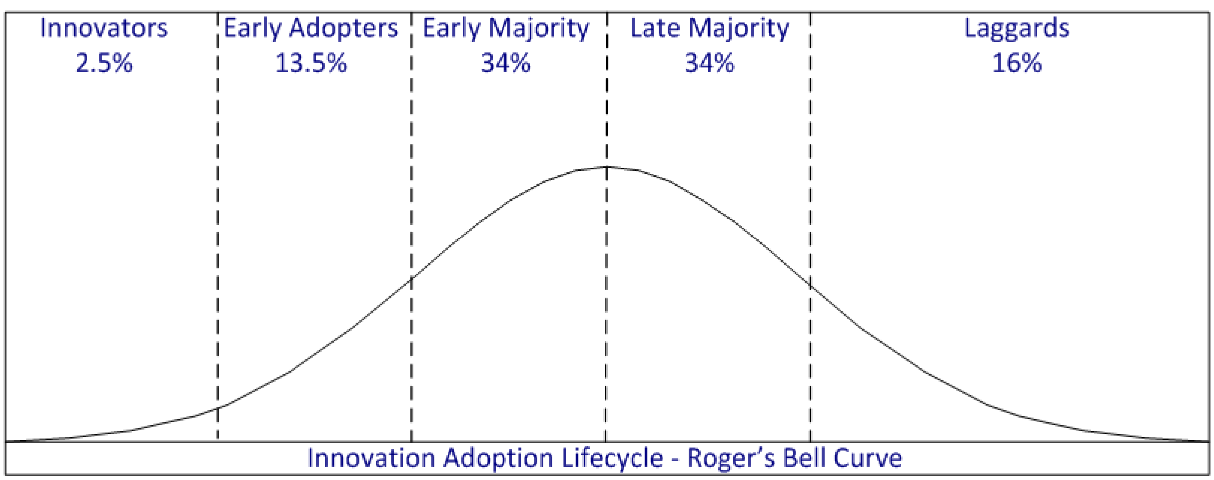

Figure 9 - Innovation Adoption Life Cycle

Early adoption of new technology may have associated risks as well as the touted benefits. The Gartner Hype Cycle depicts a graph, similar to a damped wave with overshoot, illustrated in Figure 10. On the "y" axis is the visibility of a new product and the abscissa shows product maturity. When a new product is deployed, there is a "trigger" that pushes the new product out in to market place. As the product is promoted, the expectations begin to increase

[8] Presumably so called as they provide a warning to later adopters?

and eventually peak. The product then may fail to realize some of the promised benefits and the then enters the "trough of disillusionment". This trough then gradually reverses as the product matures and the adopters begin to see the promoted benefits and rewards. Eventually the product matures and becomes accepted by the mainstream [23]. This illustrates that new products may come with inflated expectations until there finally comes user maturation with greater acceptance. During this development cycle the product evolves and performance stabilizes.

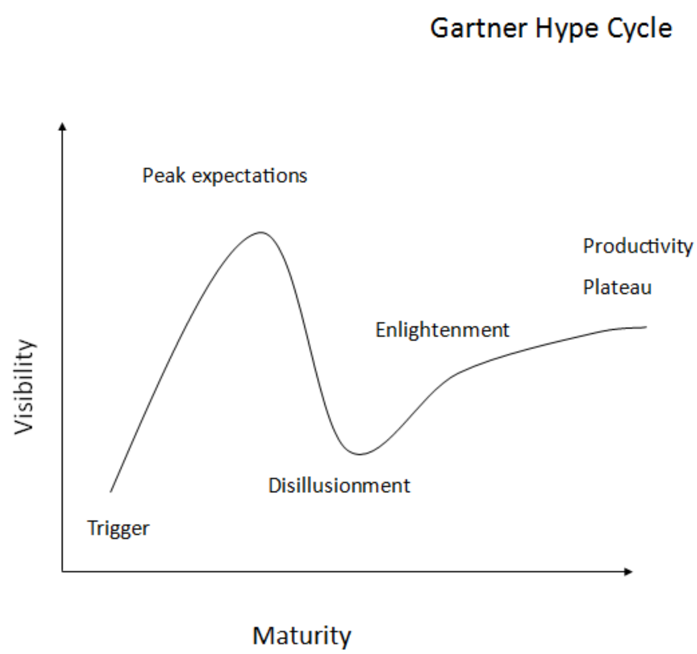

Figure 10 - Gartner Hype Cycle

Early adopters of new products, or technologies, must be aware of the inherent potential for life-cycle impact including possible shorter life issues. This is a well-known, common and industry wide phenomenon.

1.23) Wear and Tear and Mechanical Failure

As mentioned in the introduction of this report, the manufacturer-based rating for the number of operations is a possible indicator of actual end-of-life. This is related to wear and tear and operational life due to mechanical/electrical failure characteristics (no device will last forever).

An example of a failure that led to the early end-of-life of a device is given below and illustrated in Figure 11:

> One utility experienced a problem with a plunger type relay used in under voltage applications that were not designed for continuous AC energization operation. The mechanical wear as a result of this continuous operation caused fretting and sticking of the device. The resulting increase in maintenance and other alternatives do not resolve the problem and the device had to be replaced [24,25].

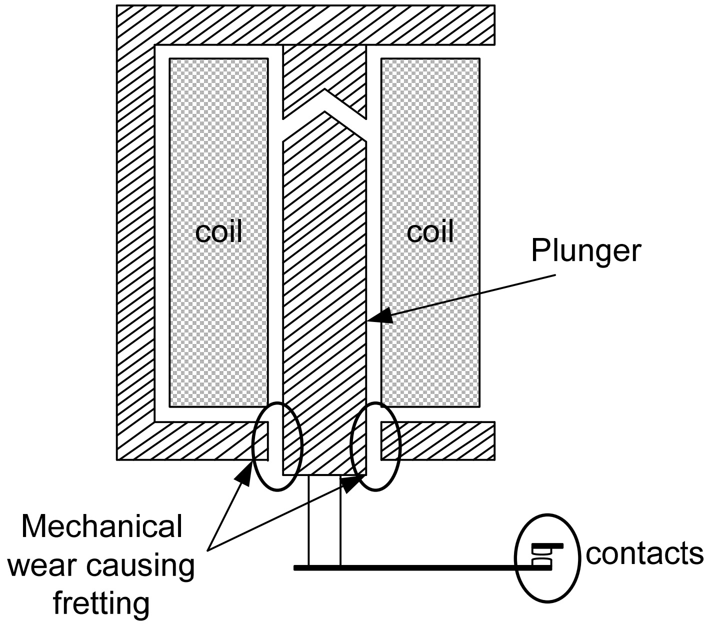

Figure 11 - Illustration of Mechanical Wear Which Resulted in End-of-Useful Life [24]

Typical concerns with electromechanical contacts are their ratings. Manufacturers specify the rating of their device contact by means of voltage, current making (or breaking) and L/R ratings. Switching devices may fail due to: overheating; overcurrent; overvoltage; excessive *di/dt;* or excessive *dv/dt* [26]. Contact arcing through time, or misapplication, can result in degradation of contact resistance and/or welding of contacts. This may necessitate the repair or replacement of a device. This is an example of where proper design and application would ensure the longevity of a device by possibly installing contact protection (snubber circuit) or increasing the rating of a device (over specify). For example, the inclusion of a simple snubber circuit during the design of an application can help prevent contact damage due to arcing, reduce possibility of EMI, and subsequently help extend the useful life of a device. Snubber circuits can be a simple RC circuit, diode, or varistor to mention only a few [27, 28].

1.24) Human Factors

Although this may be a minor issue, human factors may also contribute to the early demise of a device in respect to its end-of-useful life. There may be occasions when accessibility and usability may be factors in the usefulness of a device and therefore its longevity. Consider for example:

- Ease-of-use – Does the device have mechanical interfaces (knobs/dials/terminals/etc.) and are they easily (and safely) accessible? Does the device require the use of specialized tools for accessing it (physically, or via software, or via communications ports)? Is the documentation easy to read, understand, and is it well organized? Are the on-panel indicators and displays clear? Are the controls/interfaces confusing? A bad design or poor documentation can lead to operator error or create a personnel hazard which could impact the life of the device if performance is impacted.
- Software usability – is the software such that it makes the life of the user easier? Is it intuitive to use? Does the way it is designed help reduce the possibly of errors? Does it allow for the self-checking and verification of data? Does the software conform to company policies? (Perhaps the software accesses remote servers for help files, software updates or license validation – in contradiction to NERC CIP or company policy requirements. Obviously this could lead to a shortened life if the equipment must be replaced due to internal or external policy violation.

These human factor issues should be addressed at the design and purchasing stage, nevertheless, circumstances sometimes arise where these issues must be considered retroactively.

1.25) Disposal

It may be prudent to retire a device prior to its end-of-life due to pending legislative changes such as those requiring increased diligence, cost and procedures with respect to disposal (for example, lead solder or NERC CIP requirements for disposing of critical cyber assets). However, as a good corporate citizen, utilities will want to dispose of equipment properly regardless of pending legislative changes. Devices containing the following hazardous materials are strictly controlled with respect to their disposal [29]:

- Lead paint, lead solder
- PCBs (found in some capacitors)
- Asbestos insulation
- Mercury (relays, LCD displays, batteries, etc.)
- Phosphorus displays
- Flame retardant materials
- Cadmium in batteries
- Beryllium (printed circuit boards, monitors, relays)

However, disposal is no longer simply limited to hazardous materials. Now one must also consider devices containing critical cyber asset information or data and dispose of this equipment in a controlled manner. This ensures that confidential information stored in the device is not left for non–authorized personnel to view and exploit, The following excerpt is from NERC CIP-007-3a Section R7 [30].

> R7. Disposal or Redeployment — The Responsible Entity shall establish and implement formal methods, processes, and procedures for disposal or redeployment of Cyber Assets within the Electronic Security Perimeter(s) as identified and documented in Standard CIP-005-3.
>
> R7.1. Prior to the disposal of such assets, the Responsible Entity shall destroy or erase the data storage media to prevent unauthorized retrieval of sensitive cyber security or reliability data.
>
> R7.2. Prior to redeployment of such assets, the Responsible Entity shall, at a minimum, erase the data storage media to prevent unauthorized retrieval of sensitive cyber security or reliability data.
>
> R7.3. The Responsible Entity shall maintain records that such assets were disposed of or redeployed in accordance with documented procedures.

The disposal of devices is an important consideration in determining the useful end-of-life of a device in so far as how long the process may take and what is required as well as the cost in time and labor. Device disposal cost and considerations should be examined at the time of evaluation, design and purchase. It is hoped that with the awareness from documents such as this one, including the list of things to remember found in the appendix, that obscure items like “disposal” will also be considered in the product life cycle.

2) Motivation for Determining End-of-life

The following are a number of issues that provide motivation for determining the actual end-of-life of devices.

2.1) Impact of End-of-Life on Reliability and Redundancy

Redundancy is designed into many protection schemes to provide adequate protection coverage in case of component failure. This redundancy plays a large role in the reliability of the scheme. The system dependability is maintained as long as confidence in the viability of the installed equipment remains high. As this equipment approaches end-of-life, the loss of a component effectively removes the redundancy and its inherent reliability. This in turn creates a higher level of uncertainty for the health of the remaining equipment. Improvements in the predictability and management of the end-of-life help maintain a high level of reliability and dependability of the protective system. It might also be noted that this impact can vary depending on whether the affected relay is a single-function device such as an electromechanical relay or a multifunction device such as a microprocessor relay. Older electromechanical schemes may rely on partial redundancy from a collection of relays. For example, the loss of a ground relay is covered by the protection provided by the phase relays. Other schemes may consist of two multifunction relays or a combination of mixed multifunction and single-function relays. The impact of losing a component in each scheme on redundancy will vary but the impact on the overall reliability will remain the same.

2.2) End-of-Useful-Life Needed for Asset Management

Asset managers require a thorough knowledge of the characteristics of their assets in order to schedule changes/upgrades and also to determine the economic impact of a change. If scheduling and equipment/resource forecasts are predicted based on the end-of-physical life (wear out as per bathtub curve) then rate cases, labor and reliability issues can become a significant issue to contend with.

Of course it is impossible to determine when new functional requirements regarding device performance may be necessary to comply with some technical or regulatory directive, nevertheless, it is prudent in the planning stages to consider that a device may reach its end-of-useful life significantly sooner than its expected end-of-life.

Asset management requires a comprehensive understanding of the life of equipment – sometimes referred to as a “health index”. It is not necessary for the sake of this document to enter into the details of asset condition assessment, however it is enough to say that end-of-life features prominently in any asset management strategy and taking the end-of-life to mean the end of a device’s physical life is not necessarily the most prudent course of action to take.

As an example, microprocessor based devices have an expected life of 20 years or less due to technical obsolescence. The primary equipment they protect often has a life of 40 years or more. Therefore asset managers may wish to plan for replacement of protection and control equipment based on the life of a primary asset.

2.3) Impact of End-of-Life on Regulatory Compliance

It is difficult to know if technology drives the regulatory bodies to draft new policies or if the system operating requirements drive the technology. Regardless, due to the need for a highly reliable system regulatory requirements will continue to impose themselves upon the industry. These requirements will also drive the need for newer technologies. We currently see this already with requirements for DG integration, energy storage, smart grids and smart metering. Technology will continue to play an important role as conservation, hazard reduction, and environmental considerations are addressed by legislators.

NERC standards either requiring or influencing the end-of-life of older generations of relay manufacturing technologies include PRC-023 Transmission Relay Loadability Standard, NERC PRC-005-02 Relay Maintenance Standard, and NERC CIP 7. NERC PRC-023 was created to address relay loadability which has been cited as a factor in major system disturbances since 1965 including the 2003 blackout. The standard improvements are intended to be permanent and enforceable [31]. Some relay technologies including electromechanical distance relays cannot be set to meet this standard for all applications particularly those providing protection of long transmission lines where the zone coverage required drops below the rating of the circuit. Newer distance relays with load encroachment blinders often can be applied to meet the NERC PRC–023 standards. PRC–005-02 the relay maintenance standard requires that electromechanical relays to be tested more frequently than common micro-processor relays because they do not have self-monitoring capabilities. NERC CIP 7 requires the use of strong passwords for micro-processor relays when possible. Utilities prioritizing on cyber security would be motivated to replace early versions of micro-processor relays that do not support strong passwords.

2.4) Technological Advances

The current focus on technology and what it can do for the power system will inevitably drive the industry to earlier adoption and deployment of innovative solutions resulting in more end-of-useful life considerations. Consider the impact of blackouts and terrorist attacks and how this has driven the industry to adopt synchrophasors and disturbance records and cyber security considerations. These have led to advances in technological requirements and the need to either replace or integrate new devices far ahead of existing, planned replacement cycles.

Of course none of this is predictable and one cannot enter these societal issues into an end-of-life equation, but nevertheless they significantly impact the useful life of protection and control equipment. It would be prudent for each utility to at least be aware of, if not involved in, the regulatory processes that impact the operation of their industry as this will impact equipment end-of-life.

2.5) Performance (Need for Calibration)

One possible indicator of a device nearing its end-of-useful life is its performance with respect to routine maintenance. If the set points or calibration response is drifting, or not consistent from one maintenance interval to the next, this may be an indicator the device is ending its useful life. Components in the device could be aging or becoming more susceptible to environmental issues. Obviously to determine if the device is behaving inconsistently, the need for accurate record keeping and the ability to track performance is essential.

This metric of monitoring performance may become more difficult to evaluate and interpret as maintenance intervals become extended (due to less maintenance data), nevertheless, it is a sure indicator that there may be issues with the device and that the device may need to be retired[9].

3) Determining End-of-Useful Life

In order to develop an effective end-of-useful life assessment for a device, proactive studies need to be undertaken. Each device type should be studied regarding the issues summarized in this report and evaluated in terms of what the end-of-useful life could be. Anecdotal evidence using internal data and experience would be highly valued.

Up to this point the report has discussed many of the issues that may contribute to a shorter useful life - compared with an expected design or device life. Now the report shall attempt to provide some tools to evaluate quantitatively the impact of these factors (*F*). Specific factors include:

[9] Tracking of performance in light of reduced maintenance intervals may provide an impetus for an industry-wide database on device performance. Even though one particular utility may only maintain their device every 8 years for instance, using a combined force of many dozens of utilities would provide great insight to the performance of specific devices and help all utilities in their end-of-useful-life assessment.

1. *F(manufacturer)* - What are the end-of-life factors that are impacted by the manufacturer?

    a. Viability of manufacturer. What is the likelihood the manufacturer will be around for the next 10 years? How long have they been in existence? How long have they been making protection and/or control devices?

    b. Past performance experience of manufacturer. Has the manufacturer been responsive to issues? How has their quality control been? What is the turnaround time for repairs? Do they charge for repairs?

    c. Support: Is support available? What is the quality of support? What is the timeliness of support?

    d. Spares: Are spares available? Do they have the correct firmware? Is the appropriate configuration software available and functional and will it run on present generation computers?

    e. Firmware upgrades: How frequently is the firmware updated? How severe are the firmware changes? How difficult is it to upgrade the firmware?

    f. Hardware issues: Have there been any hardware issues? How severe have they been? Do they require a return to the manufacturer? Does the relay need to be removed? How long does service take?

    g. Recent experience with other products from same manufacturer. Use experience with other products as a baseline or indication of what to expect. Is the device a mature product?

    h. Are there possible issues arising from early adoption?

    i. Are there quality related issues with the manufacture or components used in the manufacture of the device?

2. *F(performance)* - What has been the performance of the device?

    a. Past history of reliability of device based on own experience (MTBF determined by vendor or utility?)

    b. Past history of reliability based on the utility's own experience with similar devices. Many devices have similar characteristics and performance can be generalized in the event of a lack of specific information.

    c. Actual performance (as observed during routine testing/as-found information) can be used as input to developing an accurate end-of-useful life model for a particular device.

    d. Number of false operations and unscheduled maintenance can be a motivation to replace a device before its design life. Similarly, self-reporting indications of internal problems (memory checksum, power supply etc.) may also be indicators of that useful life may not be equal to design life.

3. *F(company)* - What are the company (utility) factors impacting end-of-useful life?

    a. Fiscal outlook of the utility and likelihood of possible rate increases may impact device end-of-useful life. If a utility is constrained by financial resources they may implement changes in their design and maintenance programs to accommodate financial policies.

b. Future direction of the company in terms of replacement/upgrades in other areas (RTUs replacement, breaker replacements, control through IED, etc.) may cause a device to have a shorter life. If a utility has a fleet of a certain type of breaker and they wish to upgrade short circuit rating, they may replace the associated protection and control equipment the same time, even though such equipment is still perfectly functional.

c. Does the company (utility) have staff and resources to support the products in the field?

d. Operating requirements to reduce the number of outages

4. *F(industry) - What industry factors impact end-of-useful life?*

   a. Utility industry experience

   b. Other/Comparative industry experience (NASA/GM/AT&T/etc.) – The utility industry is not the only one using networking equipment for example.

   c. Anticipated standards under development can influence the end-of-useful life of a device and shorten it from its anticipated design specification. Standards are constantly being developed and revised. The impact of a change, especially a regulatory one, can have a significant effect on the end-of-useful life of a device.

   d. Trends in other areas of the industry will have repercussions on the expected, or planned, device longevity. For example: the growth of Ethernet speed may render some devices obsolete before their expected end-of life; the typical manufacturing life of electronic components may shorten the design life of a product; global acceptance of 61850 is making great inroads in the utility industry and may be a reason for replacing some devices before their actual end-of life; etc.

   e. Monitor performance. The use of an industry-wide database containing historical information regarding the performance of protection and control devices would be of great use to the industry

5. *F(device) - What are the non-performance-based factors impacting end-of-useful life?*

   a. Risk assessment (could include redundancy)

   b. Determining the life of vulnerable component(s) such as electrolytic capacitors can help determine useful life, as in routinely done in the nuclear industry.

   c. Disposal related issues: Are there special requirements (or pending requirements) for disposing of the device (hazardous waste, NERC CIP, time necessary to remove, special tools needed, etc.)

   d. Ergonomic issues, human factors: what are the ergonomic issues surrounding the device?

   e. Wear and tear and mechanical factors – are there mechanical issues arising from operation movement that can impact-end-of useful life?

   f. Environment (Hot vs. moderate, humid vs. dry) can lead to shorter life expectancy. Empirical data exists showing how life expectancy is depleted due to elevated temperature or humidity. This can be factored into an expected useful-life analysis

   g. Does the device impact system reliability?

The above factors can be integrated into a checklist for scoring purposes; however, it is difficult to quantify certain things or to place a weight upon them. For example, vendor support may be good, fair or poor; however, vendor support may not be as critical as the actual performance of the device. If the device functions well with little trouble, then vendor support may be of little consequence. In addition, the evaluation of the parameters above *must* be made by someone who is aware of the issues. It would be of little value to have somebody in purchasing describe the efficacy of customer support, or device performance, and assign some numeric scale value to that, for example.

Nevertheless, there are ways of quantifying subjective information and it may be possible to derive an algorithm using the above factors, with suitable weighting, to determine an effective end-of-useful life.

Expected end-of-life can be defined by the MTBF or warranty period as specified by the manufacturer. Some manufacturers state that their devices have a certain MTBF, or provide a warranty for a certain duration or explicitly state that their device will last and/or be supported for a certain number of years. However, in terms of end-of-useful life it would be beneficial to define a heuristic by which the utility itself can estimate the useful life of a device for their planning budgeting, forecasting and staffing purposes.

Possible ways to determine a numerical end-of-useful life estimate might include:

- Examine subjectively/objectively the concerns and issues and assign some weighting factors.
- Scaling the issues and concerns and issues from 0-10, for example.
- Use a live-to-fail policy based on performance trends and historical data.
- Determine a percent of end-of-useful life metric based on various factors.

Examining the above life-factors elucidated in this document, one may come up with a very simple equation based on a totally subjective analysis. The following equation is presented as one option: a de-rating factor which is proportional the sum of the above factors, each of which factors is weighted according the intrinsic value placed it by the utility.

$$F(derating) = \delta\,[\alpha_1 F(performace) + F\alpha_2(company) + \alpha_3 F(industry) + \alpha_4 F(device) + \alpha_5 F(manufacturer)]$$

Where:

F(derating) is the end-of-useful life de-rating factor (this is what we are interested in)

δ = Overall importance of determining end-of-useful life (value from 0 to 1). For example, if useful life is of only modest interest to the utility, then a factor of 0.1 may be appropriate for δ.

For the sake of illustration, consider an individual or team has examined each of the above life factors for a particular device and determined the following:

Table 1 – Example of Rating Factors for Illustration Purposes

	Factor	From 0-10	Comment
1	*F(performance)*	9	The device has performed well (or a similar device that we have experience with has been a solid performer).
2	*F(company)*	10	Company is doing well with clear direction and solid management and staff.
3	*F(industry)*	8	There are some trends in the industry that may impact how we do business down the road.
4	*F(device)*	9	There are no or few non-performance based issues with this device.
5	*F(manufacturer)*	9	The manufacturer has a good reputation and provided timely and consistent support.
	Total	45 (out of 50)	This value is normalized in the analysis by dividing the total by 50.

Table 2 – Example of Weighting Factors for Illustration Purposes

	Factor	Co-eff	Weight	Comment
1	*F(performance)*	a_1	0.9	The impact of past performance is considered critical
2	*F(company)*	a_2	0.6	The impact of company-related factors is considered to be modest
3	*F(industry)*	a_3	0.75	The impact of industry factors is considered important
4	*F(device)*	a_4	0.9	The impact of the device factors is critical
5	*F(manufacturer)*	a_5	0.8	The impact of manufacturer performance is important

Then, for this hypothetical example:

$$F(derating) = 0.1 * \left[\frac{0.9 * 9 + \ 0.6 * 10 + 0.75 * 8 + 0.9 * 9 + 0.8 * 9}{50}\right]$$

or, a de-rating factor of 0.0885. Therefore, if at design time the expected life of the device was given as 30 years, then using a de-rating factor, as derived above, an estimate for the useful life would be 30*(1-0.0885) or 27.345 years. (Recall that the “50” in the denominator is for normalizing the Rating Factors in Table 1.)

If the useful life is an important consideration and a factor 0.4 is used instead of 0.1 for δ, then the de-rating factor would be 0.2832 and the estimated useful life would be 21.5 years. This number (21.5 years) could then be used (instead of 30 years) in the planning process for capital replacement, staffing levels, and rate case support.

The above analysis and equations are not scientifically determined but provide one way of quantifying end-of-useful life. Of course if the end-of-useful life is being determined at the beginning of the product life cycle then factors such as performance and industry experience would not be available and may have to be removed from Table 1and Table 2 though the manufacturer's stated MTBF or utility experience with similar products could be used as a basis for the performance factor in this case). The factors can be adjusted to develop unique or comparative models.

Also, it is important to keep in mind that the expected life (30 years, as used in this example) is often of questionable origin in actuality. Expected life is used as the basis for financial planning as well as equipment replacement (without consideration of useful-life). Expected life (*not* useful life) can be based on:

a. The design expectations for the device or application.
b. The financial deprecation life of the device.
c. Life, or mortality, tables, such as used in the insurance industry.
d. Maximum support period provided by the manufacturer (a new product will have a finite production and support life).
e. Maximum warranty periods provided by the manufacturer.
f. Expected operational life (rated number of operations divided by expected number of operations per year, for example).
g. Past experience with other similar devices.
h. Past experience with a previous generation of devices (perhaps expecting the life of a microprocessor device to be the same as that of an electromechanical device).
i. Expected life based on other equipment associated with the protection (for example, expecting a transformer protection to last the same length of time as the transformer itself).
j. Industry guidelines
k. Other user defined parameters.

This **expected** life of a device (not to be confused with its **useful** life) is important to establish, regardless of what method is chosen. It is assumed that most users would already have some idea of the expected life of a device. It is the intent of this report, as has been discussed, to make this expected life more realistic in terms of the issues and factors that have been discussed to this point and determine a reasonable and realistic end-of-useful life for the device[10].

4) Other Methods of Determining End-of-Useful Life

4.1) Sample Testing

The nuclear industry is currently faced with the challenge to extend the life of their existing and aging fleet of plants. The initial design life is being extended however it is critical to assess the reliability of existing devices. In this case one approach taken has been to perform sample testing on specific devices. This approach enables the planner to determine if specific equipment can function past its deigned life. Stress testing, including environmental and electrical effects, can be used to determine if a device will continue to function for some additional to-be-determined period of time.

[10] For an interesting perspective on life and death and life after death as related to lead acid batteries, please see "The Meaning of Life" at http://www.mpoweruk.com/reliability.htm.

A similar approach can be used to determine the useful life of a device for typical utility applications. A sample of existing devices (if available) can be tested to determine their expected-end-of life (which may be shorter or longer than their designed life). These tests are typically environmental-type test using heat and or humidity to perform an Arrhenius type of analysis.

4.2) Probabilistic Risk Assessment

Another approach can be the use of probabilistic risk assessment that has been used to determine the expected life of the International Space Station (ISS) [32]. Figure 12 is the index item from the NASA technical reports server describing a paper using PRA for the end-of-life assessment on the International Space Station [33].

1. International Space Station End-of-Life Probabilistic Risk Assessment

Document ID: 20140004798

NTRS Full-Text: Click to View [PDF Size: 343 KB]

Author: Duncan, Gary

Abstract: Although there are ongoing efforts to extend the ISS life cycle through 2028, the International ▼
Space Station (ISS) end-of-life (EOL) cycle is currently scheduled for 2020. The EOL for the ISS will require de-orbiting the ISS. This will be the largest manmade object ever to be de-orbited, therefore safely de-orbiting the station will be a very complex problem. This process is being planned by NASA and its international partners. Numerous factors will need to be considered to accomplish this such as target corridors, orbits, altitude, drag, maneuvering capabilities, debris mapping etc. The ISS EOL Probabilistic Risk Assessment (PRA) will play a part in this process by estimating the reliability of the hardware supplying the maneuvering capabilities. The PRA will model the probability of failure of the systems supplying and controlling the thrust needed to aid in the de-orbit maneuvering.

Publication Year: 2014

Document Type: Conference Paper

Report/Patent Number: JSC-CN-30995

Date Acquired: May 08, 2014

Figure 12 – Document Search Index Item on PRA on EOL re ISS from NASA

It is not within the scope of this document to explain the details of PRA, but many useful resources can be found on the Internet. The NASA Technical Reports Server[11] has many useful tutorials and papers on PRA as do many other worthy sites.

4.3) Economic Analysis

An economic analysis may be a viable approach to help determine whether a device should be replaced before its end-of-life or not. An economic analysis considers such things as alternatives, stakeholders, costs and of course, benefits.

The following is an excerpt from DoD Instruction Number 7041.3 [34]

> *E3.1… Economic analysis is a systematic approach to the problem of choosing the best method of allocating scarce resources to achieve a given objective. A sound economic analysis recognizes that there are alternative ways to meet a given objective and that each alternative requires certain resources and produces certain results. To achieve a systematic evaluation, the economic analysis process employs the following two principles:*
>
> - *E3.1.1. Each feasible alternative for meeting an objective must be considered, and its life-cycle costs and benefits evaluated.*
> - *E3.1.2. All costs and benefits are adjusted to "present value" by using discount factors to account for the time value of money. Both the size and the timing of costs and benefits are important.*

[11] http://ntrs.nasa.gov/search.jsp

Economic analysis is another tool that can be used to help to make the decision whether to replace a device before its end-of-life or not. For a tutorial on Economic Analysis, reference [35] provides an introduction including a non-technical example.

4.4) Failure Analysis

By performing a failure analysis, the root cause of the failure can be determined and perhaps mitigated in other devices, thereby extending their useful life. One device failure can help prevent other failures as well as extending the life of the remaining fleet. It is important for the user to examine and understand why a device fails.

As an example, failure analysis was used to estimate the end-of-useful life of a particular relay having trouble with "jaws" used to connect the current and voltage signals from the case to the relay - the "jaws" were fatiguing and cracking with age.

The utility underwent an extensive program to replace the jaws on vulnerable devices. The data obtained from this replacement process was analyzed by means of a Weibull analysis to determine if the failures were a random process or indication of early wear-out.

In this case, the Weibull analysis, Figure 13, provided a good fit to a straight line which indicates a single-mode failure in this case. The slope of the line (Beta) reveals if the failures are due to infant mortality, random failures, or wear-out. In this case the slope (2.766) indicates wear out. The intercept at 63.2% indicates the characteristic life of the device, that is, 63.2% of the jaws are expected to fail by this time, which in this case is 3232.75 days or about 8.85 years. The points shown in the graph represent the individual samples used in the analysis. Weibull analysis is particularly suited for cases with low sample sizes.

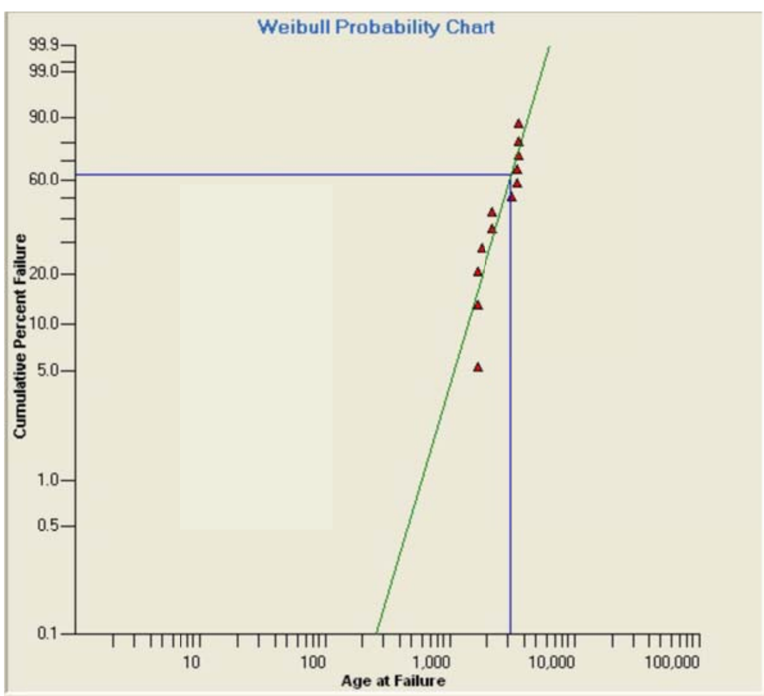

Figure 13 - Weibull Analysis of Jaw Failures

In this analysis, the data is somewhat questionable because exact in-service dates were not available and the out-of-service data used was not necessarily when the jaws failed (cracked) but when the failure or fatigued state was discovered (this uncertainty in the dates is also made evident by the undulation/curve in the plotted data points on the graph).

The Weibull plot can be used to determine the number of failures expected at certain levels. For example, with 10% failure, what is the expected life of these devices? By using the graph it can be seen that 10% of the jaws will fail before 2000 days, or 5.5 years from in-service.

The advantage of Weibull analysis is that a good prediction can be made with a small sample set. By randomly eliminating all but 5 samples from the above analysis, the same conclusion was reached, however the characteristic life was a bit longer.

> *"The primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely small samples. Solutions are possible at the earliest indications of a problem…" [36].*

Weibull analysis is one tool that can be used for determining end-of-useful life based on a failure analysis using actual data. In this example, the failure of the jaws was repairable, however, in many cases failures are not as easy to resolve and the device may have to be replaced (earlier than planned).

5) Life Extension

How can the end-of-useful life of a device be extended? There are several methods explained below, however, one can infer various solutions by examining the issues *causing* a shortening of useful life and then ameliorate those causes where possible.

5.1) Replace Aging Components

One method for extending the useful life of a device is to replace aging/aged components, for example in nuclear industry [37].

> "Capacitors also may exhibit tendencies to leak, drift, or make electronic noise, as a result of varying environmental conditions (e.g., shifts in temperature, humidity levels, or both). Extreme temperature conditions can be problematic for capacitors that contain aluminum electrolytes. At lower temperatures, capacitance falls off rapidly. At higher temperatures, the electrolyte may be lost through evaporation, thereby accelerating leakage. This may result in premature circuit damage or malfunction."
>
> "Capacitors are energy storage devices that are widely used in electronic and electrical power circuits. Operating experience has shown that capacitors have finite lifetimes. Placing these capacitors in a periodic preventative maintenance program that accounts for both time in storage and time in service can address the adverse effects of aging capacitors in equipment circuitry and prevent equipment failures."

Of course a precursor to replace aging components is to know which components are most vulnerable to aging in the first place. This may be a difficult task without the use of laboratory testing or extensive data on past performance of similar devices. Nevertheless, it is not an impossible task and there are components that age faster than others. Component activation energy, used in aging analysis, is one indicator that can be used to rate devices in terms of vulnerability to aging. Activation energy tables are readily available and provide a quick overview of what components age faster than others. Refer to MIL HDBK 217 for one source of activation energies related to electronic components [38].

5.2) Like-for-Like

A like-for-like replacement of an existing device involves finding a similar product to replace the existing end-of-useful life device. This has the advantage of simplifying the replacement process but it may be difficult to find a device that has the same characteristics years after the device under consideration has been in-service

5.3) Reverse Engineer

Reverse engineering of a device is a possible solution to replacing or upgrading an existing device that has come to its end-of-useful life. This option is often used in the nuclear industry due to the volumes of paper work and approvals necessary to qualify a new product that is not identical in form fit and function to the original device. Reverse engineering is typically a very expensive proposition but is certainly one that can be considered to extend the life of existing devices.

5.4) Keep Better Records

In order to better understand and track the performance of devices, and even for the sake of simple reliability indicators, good record keeping must be implemented to record in-service dates; out-of-service dates and repair times. In addition to better date records, better recording capabilities in terms of why a device was taken out of service; what was done to it; and what changes were made to the device would go a long way towards understanding device performance and thereby being better able to monitor and predict device failures as well as longevity. With modern technology it is trivial to track devices using bar codes, RFID, QRC codes. Bluetooth, or many other technologies commonly used in the retail industry.

Many documents already exist describing reliability and performance monitoring which also provide detailed information for record keeping.

5.5) Implement Servicing as per Manufacturer Service Bulletins

Manufacturer service bulletins are intended to address specific issues pertaining to devices. It is understood that by following these bulletins that the life of the device will be either maintained at its original predicted longevity or will be extended past its original design life.

Some manufacturer will state that their device MTBF is contingent up application of all manufacturer service bulletins. If manufacturer service bulletins are not being implemented (or only on a limited scale) the expected useful life of the device may be reduced. It is prudent to consider this important factor in maintaining the optimal useful life.

In order to ensure that the end user is aware of any impact on useful life, one option would be to state in the purchase order that the manufacturer is required to inform the utility on the impact of expected life, or MTBF, if the manufacturer’s service bulletins are not implemented.

5.6) Device Self-Monitoring

Self-monitoring is the ability of a device to examine its own performance and to determine if there are any abnormal conditions in its hardware or software. Self-monitoring is widely used in most modern microprocessor devices, however, the implementation and what is being monitored is not well defined or specified. Simple self-monitoring can be the verification of checksums in a memory chip.

The advantage of self-monitoring is that failures or anomalies in performance can be detected immediately and some action taken. This action can be an alarm, event record, self-healing or going into a safe operating (or non-operating) mode. Note that self-monitoring typically does not address the condition of the output contacts.

Self-monitoring can extend the useful life of a device as corrective action can be taken as soon as the anomaly is detected rather than waiting for a misoperation or failure to operate or the next routine maintenance cycle to detect the problem. Issues can be resolved and the equipment performance restored to normal. In some cases the device is also able to heal itself by performing a self-reset, reboot, re-calibrations, or reloading of data, for example.

5.7) Involve Multi-party Teams

Many players are involved in the process of specifying, purchasing, designing, installing and maintaining a particular device. On top of that there is the industry involvement/awareness, standards development (internal and industry), P&C, IT, fault analysis, failure reporting, firmware updates, manufacturer interface, and settings etc. involved with a particular device. It is very difficult for one person to have a handle on all the aspects of a specific device and therefore a team approach is highly recommended for determining the end-of-useful life for a device. This will ensure that all aspects are covered and provide a greater sense of certitude regarding the expected life of a device.

5.8) Be Proactive

In regards to extending useful life, it is vital to plan ahead and consider what conditions could occur that tend towards reducing the life of a device and then consider what to do in the event that any of these conditions do occur. One obvious issue mentioned is the impact of storage/shelf life on unenergized devices. It is a known that the life of electrolytic capacitors degrade the longer they remain unenergized. Therefore, knowing this fact and the fact that manufacturers recommend energizing devices in storage for one hour per year is a simple and obvious way to be proactive in extending device longevity (a greater end-of-useful life).

Having a specifically appointed and responsible person or team with the authority to investigate, evaluate and make recommendations is a good step in ensuring a greater life for P&C devices. An overall analysis of what the issues are is a proactive process. This cannot be optimized by leaving things until the issues causing short life expectancy become critical or imminent.

5.9) Documentation

Documentation (manuals) and document of activities plays a vital role in the process of ensuring an optimal end-of-life for P&C devices. In-service date, failures, device history, rationale, issues must be recorded and made available.

Keep user manuals and equipment documentation available and in formats that provide for easy access. Document activities related to each device with as much detail as possible. This will help in providing the necessary data for failure and life analysis.

5.10) Inter-Utility Cooperation

A common database of utility experience would go a long way towards ensuring device longevity. Not only could typical problems, issues and experience be listed but remediation and recommendations also could be provided to contributing utilities. Of course this could be contentious and open various legal issues, but such a solution could be implemented given proper care and coordination. Such forums exist already to a limited extent: in NERC with respect to compliance issues and reporting [39] also in the North American Transmission Forum [40] and nuclear users groups etc. However, specific utility related P&C issues are not centrally available or coordinated at this time.

5.11) Components

There can be little guarantee against the possibility that somewhere in the production cycle of electronic devices that a counterfeit or used component was purchased inadvertently, however, tendering specifications can explicitly state that only new components can be used in the manufacture of devices. Also, inspections can be made by the utility or manufacturer whenever a new or different supplier is used for a specific component [3].

5.12) Provide Feedback to Manufacturer based on End-of-Useful Life.

By providing feedback to manufacturers on their device performance, the manufacturer may be in a better position to provide effective end-of-life information to their clients. Overall trends may be better understood in the context of the entire manufactured population of devices rather than a smaller subset purchased by an individual utility. Also, manufacturers have the experience and incentive to optimize the performance of their devices. Often utilities do not have the resources to investigate issues and trends in specific devices.

Feedback to manufacturers should include specific details of device performance and failure(s) as well as dates associated with commissioning, maintenance and removal from service. Serial numbers, model numbers of both the main devices and associated modules (if any) as well as firmware version would be helpful in their analyses.

5.13) Equipment Coordination

Consider the impact of coordinating multiple activities on the useful life of a device. If a relay, RTU and breaker are going to be replaced at some time, then consider the benefit of replacing all associated equipment at the same time. This can be done on a scheme basis, such as breaker/relay, or on a station-centric approach where the entire station is upgraded at the same time.

By coordinating the work of replacing multiple devices, then the life of the P&C equipment, in the context of the station, is maximized. This obviously depends on the definition given to end-of-life and what is expected from a piece of equipment, however if the entire station is said to be expected to operate for a given number of years and all the equipment in the station is upgraded at the same time (station centric) then, any one device can be said to have reached its maximum life in the context of the station replacement program.

5.14) Redefine the Problem or Change the Parameters

One way to extend the life a device with respect to its expected life is to redefine what is meant by expected life and lower the expectations. If a device is expected to function for 30 years and it is replaced after 20 (its end-of-useful life) for any one or more of the reasons mentioned in this document, the device seems to have failed and come short of its expected performance. However, if the device was initially only given a 20 year life due to foresight; planning; basing life on the number of operations; or the life of operating system; or the expected support from the vendor; or by means of some equation similar to the one presented in this document, then the device would have fulfilled its duty and the application of the device would have been a success.

It may, therefore, benefit the prudent asset manager/planner to carefully consider how to specify the actual life of a device. In an environment where new products are constantly being introduced and older products obsoleted, a re-definition of expected device age may be beneficial and more practical than simply applying an arbitrary, historical, or book value, of expected life. Firmware support, for example, may on average be no longer than 16-20 years and so a life expectancy based on expected firmware support that may be appropriate. Similarly, the operating system used to access the device and configure settings may have a finite life and the life of a device may be closely tied with that system. Basing the life expectancy of device on accounting principles or historical values may no longer be the wisest or most appropriate benchmark to use. It may be that with the use of internal self-monitoring capabilities and the extension of maintenance periods (NERC PRC-005-002) that a device's life may be considered to be from its initial installation to the time at which it first requires re-calibration (if calibration periods are on the order of 12 years, a device will likely not last long enough to be calibrated a second time anyways).

Another issue to consider is the way in which a replacement program will be carried out. It may be unlikely that a utility would go around to all stations in its operating territory and replace a single type of device at each station because it has met its end-of-useful life. A more likely scenario would be that devices are replaced on a station-by-station basis or in parallel with other work programs, such as breaker replacements.

5.15) Failure Modes and Effects Analysis (FMEA) or Fault Tree Analysis (FTA)

By conducting a FMEA or FTA (or similar failure analysis) it may be possible to determine why a device is failing (or failed) and identify the root cause. Having done so, remediation could help extend the life of the remaining un-failed devices and also provide valuable input into extending the life of other similar devices [41].

FTA, for example, is used to determine the underlying basic events that lead to a specific "top" event. The top event could be "Why has a device reached an early end-of-useful life?"

FTA is a tool used to [42]:

a. Understand the logic leading to a top event – why did this happen?
b. Prioritize contributors leading to the top event – what caused this?
c. Help be proactive in preventing the top event – what can be done to prevent this?
d. Monitor the performance of the system – how are things doing today?
e. Used to minimize and optimize resources – what can we improve upon to better manage this risk?
f. Assist in system design to select best alternatives – what is the best solution for fixing this problem or designing this system?
g. As a diagnostic tool to identify and correct causes of the top event – what caused this to happen?

Failure analysis tools are a valuable means by which to identify early end-of-life issues and therefore a first step in helping to remediate these issues to provide for longer equipment life.

5.16) Cocooning

Cocooning is the process of regulating the environment of a device or component in order to keep it within the manufacturer's specifications during operation – and thereby maximize the life of a device. The following conditions may be required [43]:

1. The device may require a regulated power supply.
2. The device may require a regulated temperature environment.
3. The device may require shock mounting and or vibration isolation.
4. The device may require humidity regulation.
5. The device may require special shielding.

6. Additional manufacturer specifications.

Whatever requirements it takes to make the device continue to function in an environment that is specified by the manufacturer, would be part of the cocooning process. Cocooning has been used to successfully prolong the life of devices in some applications; however the cost can be significant.

6) Other issues

There are two important perspectives: forward looking to determine what end-of-life may be (predictive) and backwards looking to determine what end-of-life is. Examine overall device performance – is the device still functional in spite of reaching end-of-life? Look at positive side as well – maybe device performance is better than expected.

6.1) Device Criticality

The criticality of the application for which the device is intended may be a significant factor in determining its end-of-useful life. In a critical application a device may need to be replaced significantly earlier than if the application was somewhat benign and the failure of the device of little consequence. It is not practical to take a chance to run to end of life a device that is in a critical application, a shorter, end-of-useful life must be considered – replace the device while it is still working rather than when it fails unexpectedly.

How does risk of failure impact relay replacement (end-of-useful life)? One driving factor for criticality may be the impact on customers. The effect of a device failure on customer supply can be quantified and used as a metric to weigh the importance of replacing a device in a priority manner before it reaches its end of actual life. Does the device function in a scheme to protect a critical facility like a hospital or military installation/vessel or research facility? Will a failure of the device result in system instability or possible hazardous issues? Could a failure of the device compromise national security? Will a failure of the device compromise the good will and reputation of the utility?

A criticality score can be derived from various metrics. One such scoring system involves a combination of the importance of the scheme, bus and substation. Other scoring systems can be developed and customized internally by the utility or be based on established industry practices [44].

6.2) Cost of Not Replacing

The need to optimize one’s investment as well to as weigh off the alternative driving factors to replace a device must be balanced. One way to consider the decision to replace a device prior to its actual end of life is to examine the social-economical-technical impact of replacing early (end of useful life) or at the end of its actual life.

The following factors are important in making a decision to replace a device:

- The embarrassment that might occur if a device is not replaced and it fails.
- The impact of doing nothing.
- The time it takes to replace the device or the time taken to deal with issues if the device is not replaced.
- Fines from regulatory bodies (NERC).
- Must do – no choice
- The cost of replacing versus the cost of not replacing:
    - Cost of disposal
    - Cost of type testing

- Cost of design changes
- Cost of training on new devices
- Cost of documentation and procedure changes
- Cost of spares
- Cost of removal and installation
- Impact of outages and reduced security during replacement
- Cost of new test equipment perhaps (think of a migration from electromechanical to IEC 61850)
- Administrative costs of updating systems, going for tenders, tender review, etc.

These issues, among others, should be considered in making a decision to replace a device or to leave it or to find a way to make it last longer.

6.3) What to do if Replacement is Required

If a device comes to its end-of-useful life, then a decision must be made to replace it or try to extend the life - if possible. A process for making this decision could include:

- Prioritize the work to be done – How important is it? When does it need to be done? What resources are needed?
- Estimate the cost of replacing the device. Consider parts, outages, labor, and contingencies.
- Test replacement device(s). Test the replacement device prior to considering a replacement. Does it have the required functionality? Does it fit? Does it have the same power requirements? Does it have the same CT/PT burdens and input ranges? Does it operate the same re outputs/inputs? Is the network compatible? Can the user interface software be supported in the current computer equipment? Is additional training required for this device? Will it function in the same environment? Are there any special requirements that the previous device did not need?
- Work with the manufacturer for the best solution.
- Replace the existing device with additional capabilities and play with it to see and test its capabilities
- Watch for scope creep – it is easy to get sidetracked and do additional work or “nice-to-haves”
- Replace with like-for like? Consider replacing the failed device on a like-for-like basis. What are the implications? Does it matter?

7) Utility and Industry Examples

7.1) Pacific Gas and Electric

The following is a list of several examples from Pacific Gas and Electric (PG&E) where devices were replaced before their actual end-of-life for various reasons [45].

1. Line protection scheme is required to change to line current differential from existing POTT or non-pilot protection in order to adequately protect the line or provide relay coordination. PG&E has a proliferation of new photo-voltaic (PV) interconnections. These new interconnections many times require a new switching station, bisecting an existing line and creating a short line section requiring line current differential protection for coordination. Existing relays at the remote terminals will require replacement to match the new line current differential relays at the new switching station, regardless of the age of the relays. Since the PV interconnections are third party driven projects, they may be unforeseen and relays recently replaced by the utility may be impacted by a third party interconnection forcing replacement of relays prior to end of useful life. PG&E is in the process of updating its protection design standards to use the same relay type for all applications, which will help alleviate this problem. Current PG&E protection design standards use different relay models for POTT and line current differential protection.

2. Installation of a drop in place control building which replaces all protection and control at one substation with latest design standards. Relays at remote line terminals will have to match for line current differential protection, requiring replacement of relays at remote terminals. For other pilot schemes, such as POTT or Blocking, relays may be replaced depending on policy/tolerance for mixing different relay manufacturers/models in a pilot scheme. For PG&E mixing relay types is not recommended on the two ends of pilot protection scheme. It may be tolerated with different microprocessor relay type at the remote terminal as an exception, but not with electromechanical relays.

3. Bus configuration is changed at a substation. For example, converting from Double-Bus Single Breaker (DBSB) to a breaker-and-a-half (BAAH) bus configuration for increased reliability. For PG&E a bus configuration change will require installation of a new drop in place control building. All of the existing relays in the old control building will be retired. Some of those existing relays being retired may have been fairly new and installed due to other capacity, reliability or third party driven work that could not wait for the BAAH project. PG&E also installs new drop in place control buildings for SCADA automation purposes, and for those jobs all of the existing relays in the old control building will be retired similar to the BAAH projects.

4. Unacceptable relay performance – excessively high failure and misoperation rates. This problem is typically associated with relays near end of useful life; however in one instance PG&E specified a new standard relay type that was determined to have unacceptable performance within one year of application. Approximately 40 relays were installed before PG&E stopped purchasing the poor performing relay type due to excessively high failure rates and misoperations. The continued high failure and misoperation rates for those devices already installed caused them to be nominated for replacement prior to the end of their useful life. Manufacturer support for the relay type in question was limited due to a plant closure where the relay was manufactured as a result of a merger/buy-out with another relay manufacturer.

7.2) Bonneville Power Administration

The following is a list of several examples from Bonneville Power Administration (BPA) where devices were replaced before their actual end-of-life for various reasons.

1) A station upgrade from a ring bus configuration to a full breaker and one half scheme was undertaken. New breakers were added as well as a bus protection, new control panels and the replacement of line relays. The new line protection relays were mounted on new panels installed in a new location and put into service incrementally as each HV bay position was cut over and put into service. The relays were replaced to keep them as up-to-date as possible with internal standards. Other relays were also replaced, such as the breaker failure, to make them current with latest standards and make their behavior consistent with other devices in other bays of that particular substation - even though the particular relays were not necessarily at end of their useful life. This philosophy was also used in the case of the line-oriented lockout relays. These relay replacements ensured that consistent behavior existed throughout the substation. Similarly, reclosing relays were replaced where previously existing reclosing relays were breaker oriented but the new standard specified lead-breaker/follow-breaker reclosing - which is quite different. Again, the same reasoning was used in the replacement of the reclosing relays, that is, to obtain consistent performance and ensure that performance conformed to the current standards.

2) Identical relays with identical schemes protecting each end of a transmission line are often required. Although it might be possible to have different schemes at each end of a line, this can be confusing for field staff and for the proper functioning of the scheme. Line terminal protections are often updated to meet a new standard at one end of the line. They might also be updated to conform to what one utility is using at the end of a particular line - despite the relays not being at end of their useful life.

3) Another reason why devices may be upgraded prior to their end-of-useful life is in the case where a new control HMI is updated that requires reading the active file of a relay to obtain status information. Newer relays with downloadable data files might be needed and therefore older, yet still functional, devices must be replaced.

4) Obsolete TDM communications of leased telephone circuits are being removed by the telephone companies and new technologies are required for communication. This may require the early end-of-life of a device in order to replace it with one having newer telecommunication capabilities.

5) There is an integral relationship between breakers, relays and SCADA alarms. They are each closely interrelated and interdependent when in service. BPA has many substations where it is unlikely that the useful life of these three types of devices is the same or are in sync with each another. If one device needs to be replaced now then possibly 5 years later a different device may need replacing because it is at its expected end-of-life. Replacing devices individually and incrementally was found to be expensive partly due to the need to replace wiring that was just previously installed a few years ago. The new direction is to now integrate multiple replacements, and replace breakers, relays and sometimes SCADA systems at the same time when feasible. This is more efficient but clearly involved replacing some devices prior to the end of their expected life – thus their end-of-useful life is shorter than expected.

Obviously, good planning can go a long ways to optimizing the life of a device. Many utilities, such as BPA, are now using smarter approaches to asset (P&C) replacements to minimize outage time; reduce personnel and material costs as well as the potential for mistakes.

7.3) National Aeronautics and Space Administration

The value of performing a failure analysis is clearly stated in the following extract from a National Aeronautics and Space Administration (NASA) report.

> "FAILURE analysis at the Kennedy Space Center (KSC) is performed on both flight hardware and ground support equipment for all of the programs that operate at the center…The fundamental goal of the analysis is to determine the root cause of the failure in order to prevent future failures. The majority of failures can typically be attributed to one or more of the following causes: failure due to fabrication problems; failure due to environmental problems; failure due to maintenance and processing problems; and failure due to design problems. The proper fabrication of hardware is of fundamental importance to the success of the component. Several failures have been analyzed where a part has received an inadequate heat treatment, improper coating, or unauthorized material substitution. The failures that occur due to fabrication problems typically become evident early in the materials evaluation. Whereas many problems can be prevented through a quality assurance program, some problems are not apparent until failure occurs under service conditions." [46]

For the sake of emphasis, "The majority of failures can typically be attributed to one or more of the following causes: failure due to fabrication problems; failure due to environmental problems; failure due to maintenance and processing problems; and failure due to design problems." It is obvious that if we can learn from mistakes in terms of a less-than-ideal life expectancy of devices in the area of protection and control, as in the space industry, that life expectancy can be understood and lengthened by taking proper care:

1. In the fabrication – that is, site acceptance testing perhaps, proper adherence to environmental testing at the factory,
2. Environmental problems – understanding what the specific location and environmental conditions for the application are (that is, do not assume all site locations for the equipment are the same).
3. Failure due to maintenance and processing problems.
4. Failure due to design.

8) Additional Suggestions for Manufacturers and Utilities

The following are some suggestions for extending the useful life of P&C equipment.

8.1) Ideas from the Aerospace Industry

The following are suggestions to help extend useful life from the aerospace industry, but find application in the protection and control world as well [47]. Many of these apply specifically to manufacturers.

1) Optimize use of devices – can one device be used for multiple applications?
2) Can a modular design be used?
3) Can one device with multifunction capabilities be provided?
4) Can the use of toxic materials be reduced or eliminated?
5) Can the product design be such that future replacement be considered (future proof the design)?
6) Can the maintenance requirements be minimized?
7) Ensure high quality assurance.
8) Ensure that inferior or counterfeit parts are not used.
9) Extend product lifetime.
10) Consider environmental impact of materials used.
11) Consider how easy/hard it would be to replace devices.
12) Consider ability to upgrade.

Other considerations in addition to the above could be:

1) Engage customer feedback on performance and maintenance and needs
2) Consider bulk purchase of parts
3) Consider an integrated supply chain where parts are obtained from a minimum of suppliers
4) Consider the possibility to self-manufacture critical components.
5) Simplify the design to reduce parts and complexity.
6) Provide portable software to different hardware platforms.
7) Provide modularity in design to facilitate partial replacement.
8) Keep firmware versions the same in all similar devices and don't change unless absolutely necessary.
9) Pool resources (such as spare parts) with other manufacturers..

8.2) Ideas from the Federal Aviation Administration

The following is an excerpt of suggestions from a Federal Aviation Administration (FAA) Software Engineering Resource Center paper that deals with software intensive COTS (Commercial Off The Shelf) devices (compare with microprocessor relays). This checklist can be used to help extend useful life of devices. Many of these items emphasize the need for up-front thinking and planning [48].

- “Do not rely on vendor claims; verify with operational demonstrations.
- Bring the users into the operational demonstrations, not just the vendors.
- Establish a technology watch to track vendors and products.
- Be forward looking…Unanticipated changes in hardware platforms may occur.
- Understand that your leverage occurs before the contract with the vendor is signed.
- Negotiate all prices up front.
- Understand that profits are what motivate vendors. Whether they are cooperative or not depends to a large degree on anticipated profits.
- Distinguish between essential requirements and those that can be negotiated. Successful use of COTS solutions requires the capability to modify requirements.
- Use mature products.
- Skill level and experience are important. This includes people on the acquirer’s side who are determining essential requirements as well as the COTS integrators.
- Expect to spend time in training. In choosing a system integrator, look not only at experience in the application domain but also with COTS integration in general and with the specific products to be integrated. Do they have a mature COTS integration process?”

8.3) Ideas from the Medical Field

The following is an example of end-of-useful life assessment from the Medical field, specifically “Life Cycle Guidance for Medical Imaging Equipment in Canada – 2013” The following recommendations were produced as a result of a recent (2013) study examining life cycle issues surrounding medical imaging equipment. These recommendations focus on the planning process and more details can be obtained by reviewing the original documentation [49]. Although these recommendations and their associated details refer to medical imaging technology, in many respects this can also be useful for the power industry, and specifically, protection and control.

The following are the recommended guidelines for the planning stage of installing medical imaging technology. For the sake of copyright and space limitations, only one section is included in below. Refer to [49] for further details.

1. Establish a formal process
2. Establish criteria for lifecycle planning
3. Considerations for Initial Purchase of Equipment

“During the initial purchase process, it is wise to determine when an original equipment manufacturer (OEM) equipment platform was first established and how long the technology platform will continue to be developed and supported (including upgrading) with regard to hardware, software and service support. It can also be beneficial to understand (a) the hardware / software updates to be provided as part of the original purchase, as well as those involving additional cost; and (b) the hardware / software considered optional, how long these will be available, and at what cost. This knowledge will be helpful when evaluating each device for equipment lifecycle planning.”

1. Considerations for replacing equipment
2. Considerations for upgrading equipment
3. Considerations for adopting new/emerging technologies

Appendix - Checklist

The following checklist is by no means exhaustive, nor can many of the issues discussed in this report be distilled to a simple yes or no type of evaluations. Nevertheless, this will provide some guidance in helping to identify issues that may result in a less-than-ideal end of useful life.

Item	Issue	Comments	Notes	Category Factor Rating
1	Manufacturer	How viable is the manufacturer? Will they be around in 10 years? Is support available? What is the quality of support? What is the timeliness of support? Are spares available? Do they have the correct firmware? Is the appropriate configuration software available and runnable? How frequently is the firmware updated? How severe are the firmware changes? Have there been any hardware issues? How severe have they been? Do they require a return to the manufacturer? Does the relay need to be removed? How long does service take? Recent experience with other products from same manufacturer. Use experience with other products as a baseline or indication of what to expect. Is the device a mature product? Are there any possible issues associated with early adoption?		
2	Human Factors	What human factors issues impact the life of the installed or proposed devices? Are there any ergonomic issues with the device?		
3	Impending Government regulations - NERC	What regulations are now being discussed or balloted that may impact the device life?		
4	Hazards	What hazards are there that may impact the life of the installed or proposed devices?		
5	Security	Does the device meet existing or pending cyber sectary requirements (both internal and industry-based)		
6	Environment	Do the devices require any special disposal procedures? Are there any hazardous products associated with the device?		
7	Common sense	Does the device use specialized parts or software that may become obsolete?		

8	Performance	What is the past history of reliability of device based on own experience (MTBF determined by vendor or utility?) What is the past history of reliability based on the utilities own experience with similar devices? What has been the actual performance (as observed during routine testing/as-found information)? Have there been any false operations or unscheduled maintenance on the device?		
9	Company	What is the fiscal outlook of the utility and likelihood of possible rate increases may impact device end-of-life? What is the future direction of the company in terms of replacement/upgrades in other areas (RTUs replacement, breaker replacements, control through IED, etc.) may cause a device to have a shorter life? Does the company (utility) have staff and resources to support the product(s) in the field?		
10	Industry	Is there any industry experience on this device? Is there any other (comparative) industry experience (NASA/GM/AT&T/etc.)? The utility industry is not the only using networking equipment for example. Are there any anticipated standards under development that can influence the end-of-life of this device? Are there any trends in other areas of the industry will have repercussions on the expected, or planned, device longevity?		
11	Device	Risk assessment (could include redundancy) Are there any vulnerable component(s) such as electrolytic capacitors? Are there special requirements (or pending requirements) for disposing of the device (hazardous waste, NERC CIP, time necessary to remove, special tools needed, etc.)? Are there mechanical issues arising from operation movement that can impact-end-of useful life? Are there environment issues regarding the application of the device (hot vs. moderate, humid vs. dry) which can lead to shorter life expectancy? Does the device impact system reliability?		

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