# A New Design Process Paradigm: Sustainable System Design

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**Abstract** – A new design process paradigm that explicitly considers maintenance is described. The paradigm is ideally suited for planning and design of sustainable systems, systems designed to last indefinitely. To explicitly consider maintenance the engineer must be aware of materials deterioration, damage modes, and inspection technology constraints and capabilities. Problems with existing nuclear power plants, legacy aircraft, bridges, and water distribution systems are used to illustrate the need for this new paradigm. Engineer educational institutions are urged to teach this new design paradigm along with the supporting coursework.

*Keywords: Design Process, Sustainable, Maintenance*

## INTRODUCTION

Traditionally the planning and design process taught to engineering students and practiced for the most part by industry ignores maintenance. As such maintenance is considered an activity that is to be undertaken long after commissioning and operation is underway. However, for many of our most important systems, transportation vehicles, water distribution systems, power plants, and bridge structures failure to include maintenance as part of the initial planning and design limits the approaches that can be used to maintain such systems. This is especially problematic when it is decided to "extended-the-life" of such systems. Even sophisticated reliability-centered maintenance schemes cannot overcome designs that ignore maintenance.

It might be assumed that a simple remedy would be to include "consider maintenance" on the design consideration checklist. However, most engineering design for mechanical performance is limited by a strength value or limit on the number of stress cycles and offers no insight into how deterioration develops prior to these limit points. Consequently consideration of maintenance requires at least a modest awareness of how materials degrade due to the service environment which might involve thermal, chemical, and mechanical factors. Furthermore, the capabilities to assess the condition of the deteriorated components to support the maintenance actions must also be understood.

This paper will overview a planning and design process paradigm for sustainable systems. Here "sustainable system" is used to suggest a system that will operate indefinitely. Since all systems begin to deteriorate as soon as they are placed into service, maintaining a system indefinitely that is both reliable and highly available requires a new design paradigm. It is therefore imperative that such a new design paradigm be the basis for engineering education with regard to design.

## HISTORICAL NOTE

"The great and highly advanced Roman waterway system known as the Aqueducts, are among the greatest achievements in the ancient world. The running water, indoor plumbing and sewer system carrying away disease from the population within the Empire wasn't surpassed in capability until very modern times. The Aqueducts, being the most visible and glorious piece of the ancient water system, stand as a testament to Roman engineering. Some of these ancient structures are still in use today in various capacities."

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“Maintenance of the water system was a continuous task, and the Romans assigned a Curator Aquarum to oversee this undertaking. Paid laborers, slaves and the legions all had parts in building parts of the water system. The Curator Aquarum maintained the aqueducts of Rome, while similar curators oversaw those in the provinces. The legions however, when building new colonies or forts, were responsible for providing their own water supply. Just as they were the great road builders of the Empire, they most assuredly took part in the aqueduct construction of outlying areas.” [1]

Fig. 1 Section of the Roman Aqueduct that is still standing for approximately 2000 years.[1]

The Curator Aquarum was involved in the planning, design and construction of new sections of aqueduct to assure that these additions could be maintained.

## TYPICAL DESIGN PROCESS

The traditional planning and design process uses the following steps:

- Define Functional Requirements
- Formulate Initial Concept
- Assess with respect to Service Requirements
    - Derive requirements for materials
    - Determine subcomponents
- Revise Initial Concept
    - Reassess with respect to Service Requirements
        - Refine materials selection
- Real or Virtual Prototype Trials
- Refine Concept
- Develop Manufacturing Process(es)
- Refine Concept & Manufacturing
- Begin Production

Of course within these various steps discussion with so-called discipline experts may occur e.g., to determine “loads” which can in turn be used to size components or to make appropriate materials selection. The prevailing rationale is then to “properly design” the system and insure that it is “properly fabricated” and if this is done the system will function reliably if used according to specifications for its service life. Often considerable effort is devoted to assuring that the system is built in accordance with the original design, including nondestructive inspection of various manufacturing processes to assure that no manufacturing defects are present. At times, but less so with computer-aided design tools, a redesign may be needed to facilitate fabrication, perhaps because limited access might for example make it impossible to properly weld components together.

More to the point here is that the process being used is the process we have and continue to teach our engineering undergraduate students. If we want industry to change, we must change the way we teach our future engineers.

## DEGRADATION DURING SERVICE

Essentially all engineering materials are imperfect. Often these imperfections are microscopic, although at other times the imperfections may be visible. However, if the imperfection does not negatively affect the serviceability of the component such an imperfection might be considered “cosmetic.” Thus the engineer does not seek to make a perfect structure or system, but rather one where the imperfections do not affect serviceability during the service-life of the system. Unfortunately, as soon as a structure or system is placed into service the loads, temperatures, and environment cause the components to begin to deteriorate. One strategy to achieve the desired service-life is for every component of the system to function acceptably throughout the service-life. Another strategy is to have some components replaced periodically, because they may not be durable enough to last for the full service life. Obviously if the latter strategy is used, then the planning and design process would have provided for a means of removing and replacing these components efficiently without damaging other components. However, to be truly efficient these components would not be replaced until just before they have degraded to a point that would compromise their performance.

Unfortunately, two factors complicate determining the exact time when a component will degrade to an unacceptable condition. One factor is that service-use may vary even within the specified service limits, or these service limits might at times be exceeded. The other factor is that even components with seemingly identical conditions may endure the same service experience for considerably different lengths of time. To overcome this material variability, components might be replaced using a worse-case scenario, so that the chance of failure during that service interval is highly unlike, perhaps 1of 1000; this design approach is inherently safe and is referred to a “safe-life design” but it is imperative that the service-use be accurately logged so that replacement is done before a problem occurs. Because of material variability, presumably 999 of 1000 components could have endured more service-use; so insuring safety comes with a price.

In other cases the degradation of the component might proceed to a point that the degraded condition, such as a crack or loss of material due to corrosion or erosion, might become detectable and this component could be replaced. If this were expected to occur before the service-life of the system, the design of such components would be referred to as “damage-tolerant” because the component could tolerate damage and still perform adequately. Of course in this situation an effort would need to be made to inspect the component to detect this degradation. Since the time-frame for such degradation to become detectable is often as variable as the material durability, inspection is often performed periodically to be sure to detect such degradation before a component fails. The fact of the matter is that because of material variability, and service-use variability, designs intended to perform without the need to replace components may turn out otherwise. Unless the system is designed so that all of the components to be inspected are easily accessible, it might be necessary to spend considerable time removing the system from service, disassembling it, inspecting it, reassembling, and returning it to service. In some cases, disassembly is not possible, so extraordinary measures are required to perform inspection and maintenance. Almost always in these situations the inspection is more expensive and less reliable than if the critical component is accessible.

Furthermore, because of resource limitations, systems that perform adequately until the end of their service-life tempt asset managers (power plant owners, airline operators, departments of transportation, city managers regarding water distribution systems) to continue to use these systems rather than replace them.

Except for the safe-life design situations, which tend to only be used for high performance military aircraft, a serious maintenance effort is needed to maximize availability and reliability. However, maintenance is not explicitly considered as part of the planning and design process taught in undergraduate engineering programs. In situations where minimal maintenance is expected to be needed during the service-life, the designers perhaps can be forgiven, unless the norm is for the service-life of the system to be extended. Of course if these designers were never educated to consider maintenance the engineering educators are to blame. Extending the service-life has happened with nuclear power plants, numerous models of aircraft, most interstate highway bridges, nearly all water distribution systems in major metropolitan areas, the NASA space shuttle orbiter, and on and on. As a consequence, planning and design must assume that the system being developed is to be sustained indefinitely and our engineering education with regard to design must explicitly incorporate these elements.

## SUSTAINABLE SYSTEM DESIGN AND PLANNING

It bears repeating that essentially all engineering materials are imperfect and the structures and systems made from them begin to deteriorate as soon as they are placed into service. Traditional design is directed at avoiding failure by avoiding the development of significant damage. This is done by limiting stress cycles and reducing stresses below limit values established through materials testing for an anticipated service regime and service-life. However, when this service regime is violated, or the designed for service-life has been expended the designer is generally uncertain what will happen. Since these situations are for all intents and purposes essentially inevitable engineers must be taught to design sustainable systems as a default.

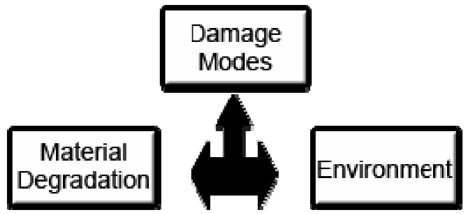


Fig.2 Schematic diagram depicting the synergistic interplay of material degradation, damage modes, and environment [Piascik, 2]

Designing a structure or system that can be sustained indefinitely requires understanding how the components deteriorate through the synergistic interaction of the material degradation, the damage modes, and the service environment, fig.2. Only then can the design properly support the maintenance function that will inspect, and repair or replace the necessary components. Appropriate consideration during the planning and design stages of maintenance will make it possible to incorporate monitoring technology, which often is not needed during the early life of a new system, but pays back many fold the initial investment once the system has been operating for a number of years. Failure to properly consider maintenance during design often eliminates consideration of monitoring-maintenance strategies that can maximize system availability through scheduled maintenance and reduced disassembly to access critical components that have not degraded to a point where they require attention.

### Reliability-Centered Maintenance

Maintenance of complex systems has become very sophisticated, beginning basically when Boeing recognized that the 747 airplane required a different approach from the so-called preventive maintenance approach used previously. A document referred to as MSG-1 for Maintenance Steering Group was the precursor to the present day reliability-centered maintenance (RCM) approach used by the airline companies and nuclear power plant operators. Nowlan and Heap introduced this approach in 1978 [Nowlan, 3]. Building on considerable maintenance history at United Airlines they established that different components of a complex system, including structural, electrical, electronic, and engine components might exhibit different age related failure probabilities. The United Airlines study was conducted in 1968 and subsequent studies in Sweden in 1973 and by the US Navy in 1982 confirmed these findings, fig.3 [4]. Consequently the approach for maintenance needs to consider this reality.

The various types of age related failures tend to be typical of different types of components:

- Type A- typical of reciprocating engine cylinders and brake pads
- Type B- typical of electronic components
- Type E- (the so-called "bathtub curve" is characteristic of a small percentage of components) typical of tires and structural components
- Type F- typical of aircraft turbine engines

However, it is clear by examining the steps in the RCM approach that consideration of many of these steps during the initial planning and design stage better facilitates the objective of high reliability and high availability.

- Functions and performance standards of the asset?
- What ways does it fail to fulfill function(s)?
- What causes each functional failure?
- What happens when each failure occurs?

- What is the consequence of a failure?
- What can be done to predict or prevent each failure?
- What should be done if there is no proactive task?

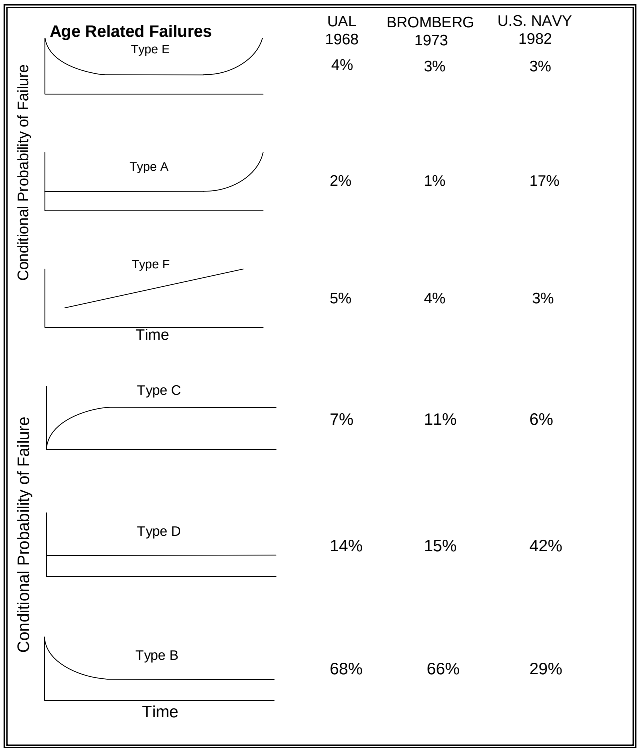


Fig.3 Conditional probability curves for six different types of age-related failure showing the percentage of components of complex systems studied by United Airlines (1968), Bromberg in Sweden (1973) and the US Navy (1982).[4]

It must also be noted that the RCM approach was originated to address maintenance of multiple copy systems, where knowledge obtained from other members of a fleet, or cohort, can be used to avoid some ineffective inspection. However, this notion can be suggested to be analogous to monitoring of unique systems. Effective utilization of monitoring is a result of careful initial planning to facilitate installation of these technologies and to establish initial and periodically updated performance baselines.

**Examples not to follow**

At this point in the history of our constructed facilities we can identify a number of examples not to follow for the future. Although highway bridges are periodically inspected, the period is often every two years and the method used is typically visual inspection. However, to facilitate this form of inspection it is often necessary to disrupt traffic flow in order to allow for access of the inspector to the various parts of the structure. In major metropolitan areas this incurs significant costs for the traffic control personnel and equipment, as well as wasted fuel due to traffic congestion, or detours. In situations where problematic deterioration occurs that is not severe enough to warrant closing the bridge for immediate repair, subsequent inspections are conducted more frequently and with this added costs; much of which might have been avoided had provisions for monitoring technology been incorporated with the original design.

Similarly all nuclear power plants are inspected every 18 months. Inspection services companies have whole divisions that design and fabricate specialized inspection systems to overcome limited access in these nuclear power plants in order to inspect critical components. It is an absolute certainty that had these facilities been design to afford access these inspections could be done far more reliably at much less cost. Of course the cost for the inspection is added into the cost of operation and the utility customers pay higher rates as a result. A number of other examples that space does not allow discussion have resulted from unexpected deterioration so of course no provision was made to provide access for inspection of these components. However, since deterioration will occur with time had the designers considered this inevitable reality and planned to accommodate inspection and maintenance much less cost would be occurred when the deterioration reached a critical level.

Water distribution systems through out the US are seriously deteriorated [5]. Recently a small town in southwest Virginia reported to the local news media that their system was losing water and they didn't know why and asked all of their customers to look for leaks. With increasing frequency in older cities natural gas explosions are occurring most likely as a result of degraded cast iron piping. While replacing such distribution systems with better material choices is expected, it is critical that the planning and design anticipate how these new materials deteriorate and plan for appropriate maintenance, perhaps not for the current generation but for their children and grandchildren.

## CONCLUSIONS

Many if not all major systems, due to complexity and cost, should be designed to be sustained indefinitely. The way we teach design as part of the undergraduate engineering education must use a new sustainable systems design paradigm. Sustainable design, as described here, recognizes that components will need to be repaired or replaced to achieve this goal. As a consequence maintenance is explicitly considered as part of the initial planning and design to maximize reliable operation with high availability of the system. This alters the planning and design paradigm:

- Define Functional Requirements
- Formulate Initial Concept
- Assess with respect to Service Requirements
    - Derive requirements for materials
        - *Identify the chemical, thermal, and mechanical environment*
        - *Establish how the materials will degrade*
    - Determine subcomponents
        - *Identify damage modes that should be expected for these materials under these environmental conditions*
        - *Provide accommodation, where appropriate, for monitoring technology*
    - *Determine that maintenance and associated inspection can be accomplished reliably and cost-effectively*
- Revise Initial Concept
    - Reassess with respect to Service Requirements
        - Refine materials selection
- Real or Virtual Prototype Trials
- Refine Concept
- Develop Manufacturing Process(es)
- Refine Concept & Manufacturing
    - *Assure that design changes to facilitate manufacturing do not negatively impact maintenance and associated inspection*
- Begin Production

It is perhaps worth considering that the project manager leading the planning and design team transition into the system manager responsible for operations and maintenance.

To enable our future engineers to be able to design using the new paradigm suggested they must have coursework that:

- Informs them about how materials degrade in different service environments
- Enables them to identify critical damage modes in system components operating in various service environments
- Provides them an awareness of what inspection and maintenance capabilities are and how to avoid restricting them by appropriate design details

While some engineering programs offer courses in manufacturing processes and perhaps mention the possible associated defects this is not adequate as regard service induced degradation from cyclic loads, corrosion or erosive environments, high fluence materials aging and degradation, or materials property changes at high temperatures. Few if any programs provide any coursework that describes the capabilities of nondestructive inspection or the limitations on reliability caused by designs that ignored inspection and maintenance.

This is not to suggest that all engineers need to be experts in these areas, but it is essential that they have a basic knowledge in order to seek and properly weigh the input from discipline experts during planning and design.

As the US stands on the precipice of renewing the nation's infrastructure, for what some estimates set at $1.6 trillion, we must replace our existing infrastructure with one that can be sustained indefinitely or at least 2000 years. In that much of the infrastructure is public we would all be wise to heed "caveat emptor," let the buyer beware and remembering the example of the Curator Aquarum demand that these new facilities be designed so that they can be maintained long into the future.

Colleges of engineering are urged to adopt this new planning and design paradigm and include at least some course work that informs engineering students about materials deterioration, damage modes, and inspection capabilities.

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