Reliability Indexing Methods and their Application in Medical Isotope Targetry

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Abstract

Reliability indexing methods provide a means to combine explicit operational data with structural analysis techniques to better assess the ability of a design to undergo specific loading cases. Load variability can be assessed to add additional limits on the stresses components are able to handle, allowing for a more comprehensive estimate of operational life to be made. In design cases, this methodology can be combined with Kriging methods (Gaussian process regression) to minimize the number of Finite Element simulations required to converge on a given feature of a part. To illustrate the effect of combining Kriging methods with Reliability indexing, performance metrics from simulations on solid targets used on the TR30-1/2 and CP42 will be presented, along with the optimized geometry. The method used here is based in [1].

Introduction and Motivation

Estimating the lifetime of operational components used in dynamic environments is often a difficult task, especially in systems where operational variability is not easily measurable. To mitigate the effects of (uncharacterized) variable loading on components, there are a number of design techniques that can be used to ensure the safety of a given part. One means of providing more certainty during part design is to use Reliability Indexing. This method allows the designer to:

1.) Pick a time dependant failure percentage, and compute corresponding safety factors or

2.) Determine failure rate from operational data, and use this as a performance rating of a given part.

Depending on available data, variability in operating conditions can also be inferred from simulations or experiments to add further detail to the model. Using the Solid Target from TR30-1/2 and CP42 as an example, operational conditions may range considerably, especially as the beam cross section on target is not an (explicitly) controlled variable. Analysis of this target from a performance perspective became a critical exercise after 2011, as targets began to fail at a higher rate (later to be linked to material strength deficiency).

As the beam current from TR30-1/2 and CP42 does not fluctuate highly in operation, and there are few beam cycles during the course of an irradiation, material creep failure is the most prevalent failure mode. Data from targets irradiated since 2011 indicates that, on average, a target's risk of failure significantly increases after the 100,000 uA-hr mark, at currents above 300 uA.

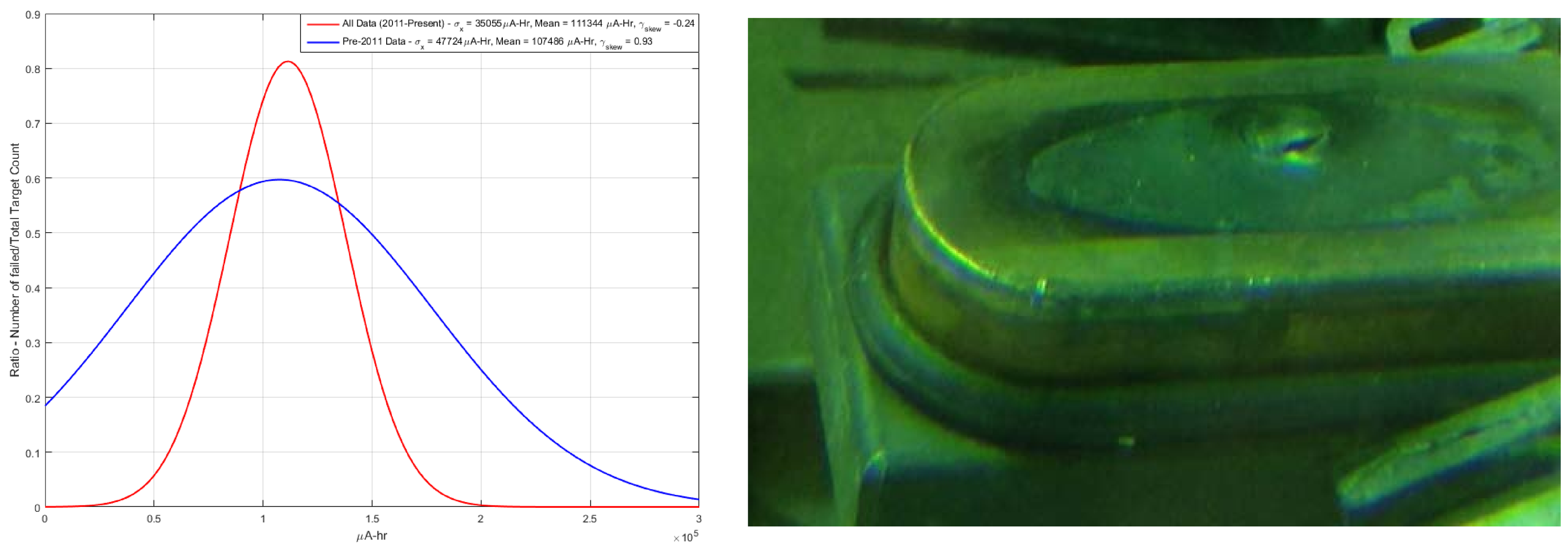


Figure 1: Data collected prior to 2011 illustrated a failure rate <9% year-over-year base on all collected data, whereas post 2011 data indicated failure rates in excess of >20% year-over-year. Note the large spike in the ratio of failed targets after 2011. An example of the target failures typically seen is provided on the right side.

Methodology

For the TR30-1/2 and CP42 solid target design, the process followed for evaluating the safety of the current design, and coming up with safety limits for improvements to the assembly was based around material creep failure. The steps followed and key equations are as shown below [1].

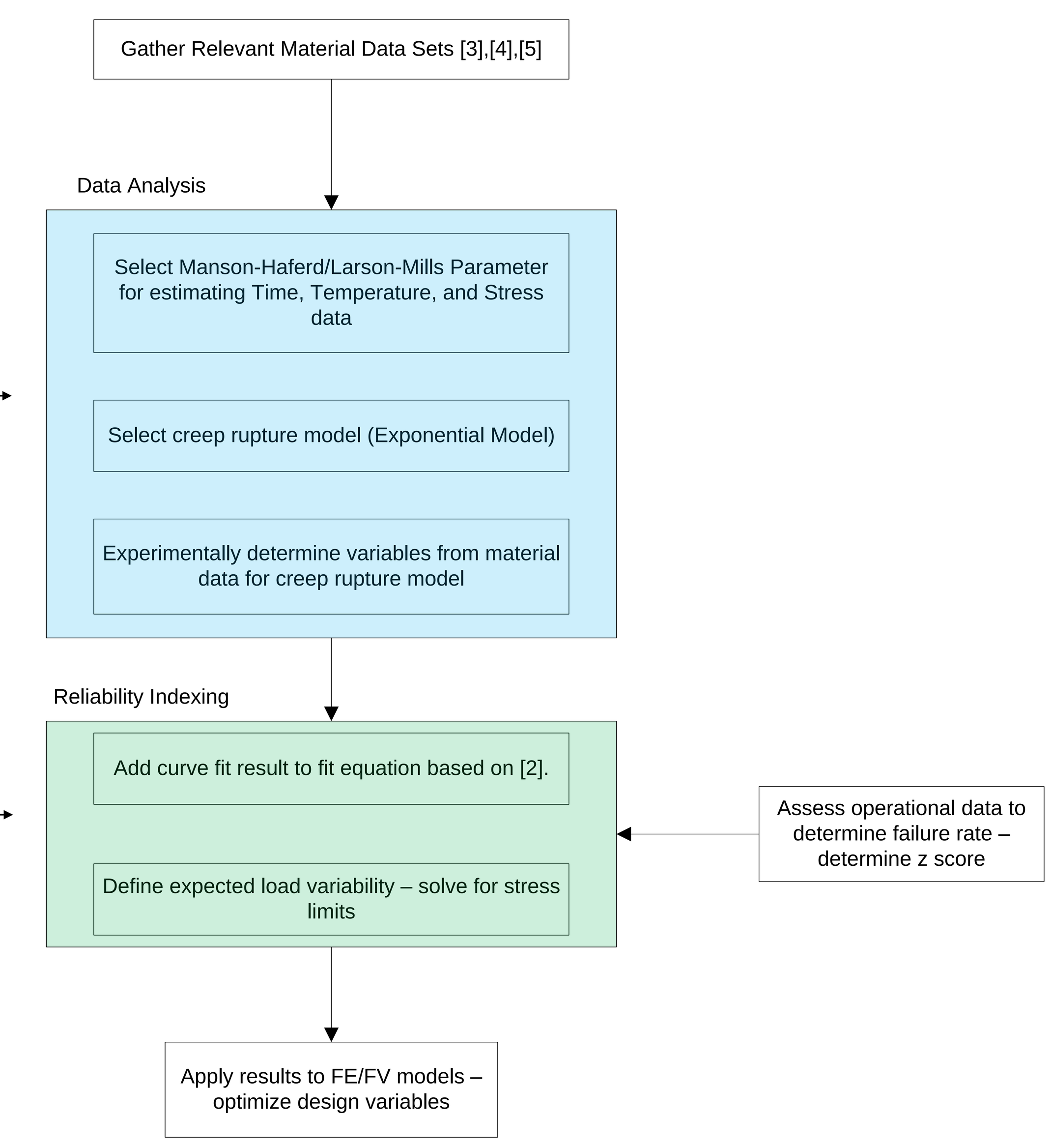
Choose one:

$$P_{LM} = (T + 460)(\log_{10} t + C)$$

$$P_{MH} = \frac{T - T_a}{\log_{10} t - \log_{10} t_a}$$

$$\log_{10} R = A + B {P_{LM/MH}}^m$$

$$\beta = \frac{\ln\left(\frac{\widetilde{R_a}}{\tilde{S}}\right)}{\sqrt{\ln\left((1 + C_s^2)(1 + C_{R_a})\right)}}$$



Stress Limits

Following the steps outlined in the process diagram for reliability indexing allowed for an estimate of the current target's expected performance to be made. Adjusting the failure probability was also completed to obtain the design limits for a new target.

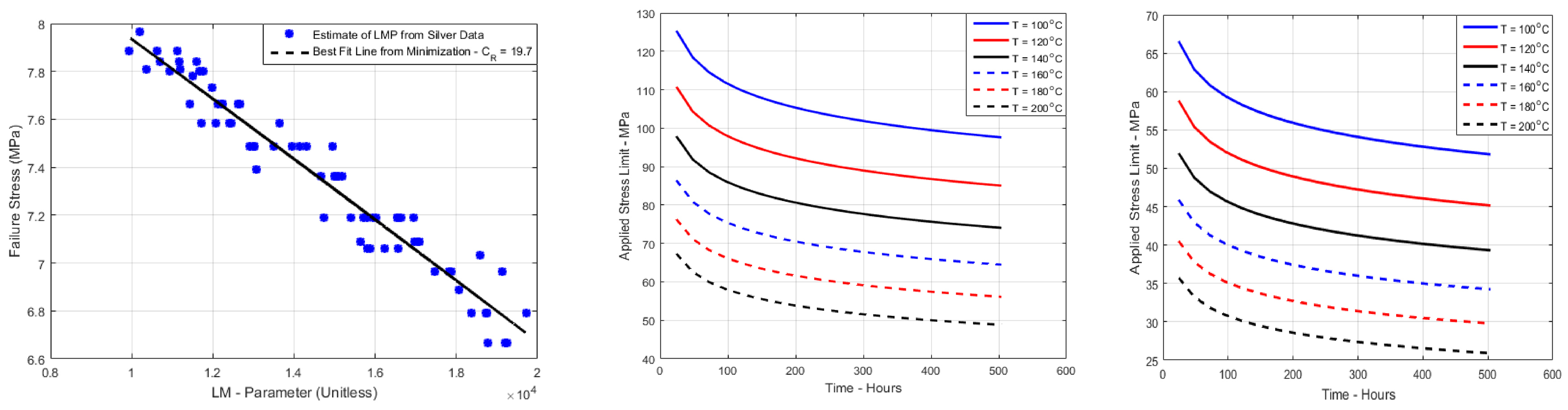


Figure 2: Reliability Data output. The graph on the left is the plot of the P_{LM}(Larson Mills Parameter) for Silver from [2],[3], and [4]. The middle graph represents the allowable stresses for a target reliability of 70% year-over-year reliability, where as the graph on the right represents the stress limits for target reliability of 95% year-over-year.

Design Optimization

Using the stress curves from reliability analysis, along with a series of solutions from simulations analyzing different cooling channel options for a given beam profile, a more optimal design can be developed. To reduce the number of simulations required, a kriging method was used to minimize the number of iterations required to converge on a more optimal design

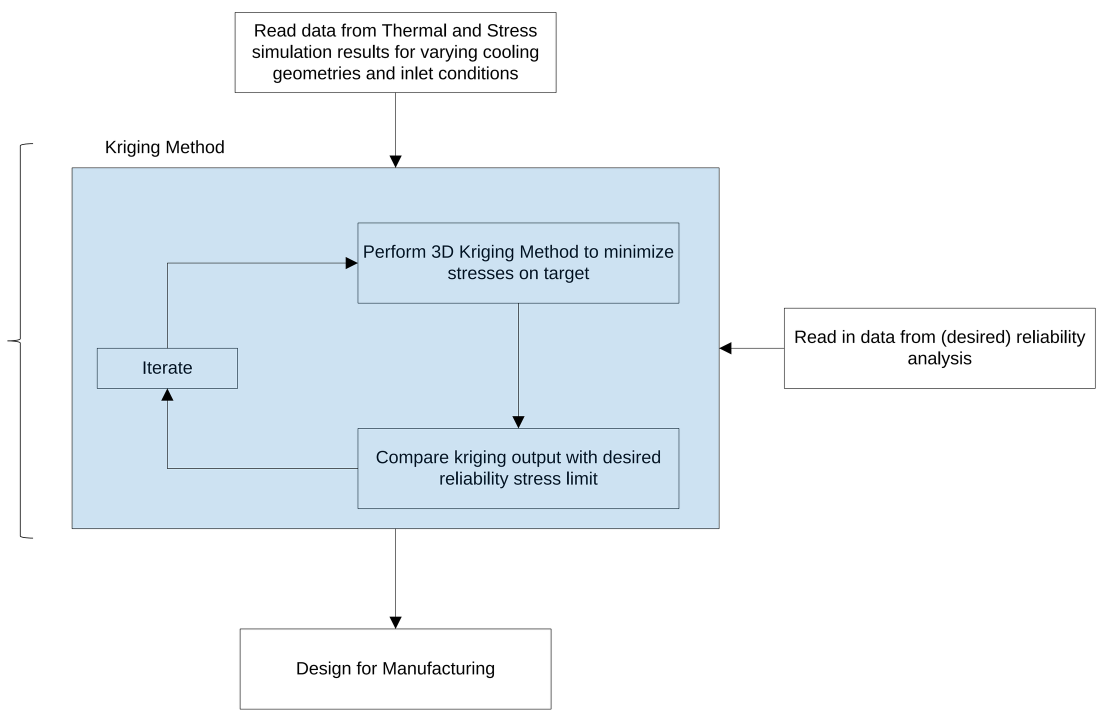
Kriging is a method which uses assumptions on prior covariances to optimize the trajectory between known data points. Each interpolated point is assigned a weight based on its distance from a known locations to spatially step between defined points [5].

$$\sigma_k = E\{|Z_n - Z_k|^2\} = \mu_k - \sum\lambda_i \bar{C}(v_i, V)$$

Where

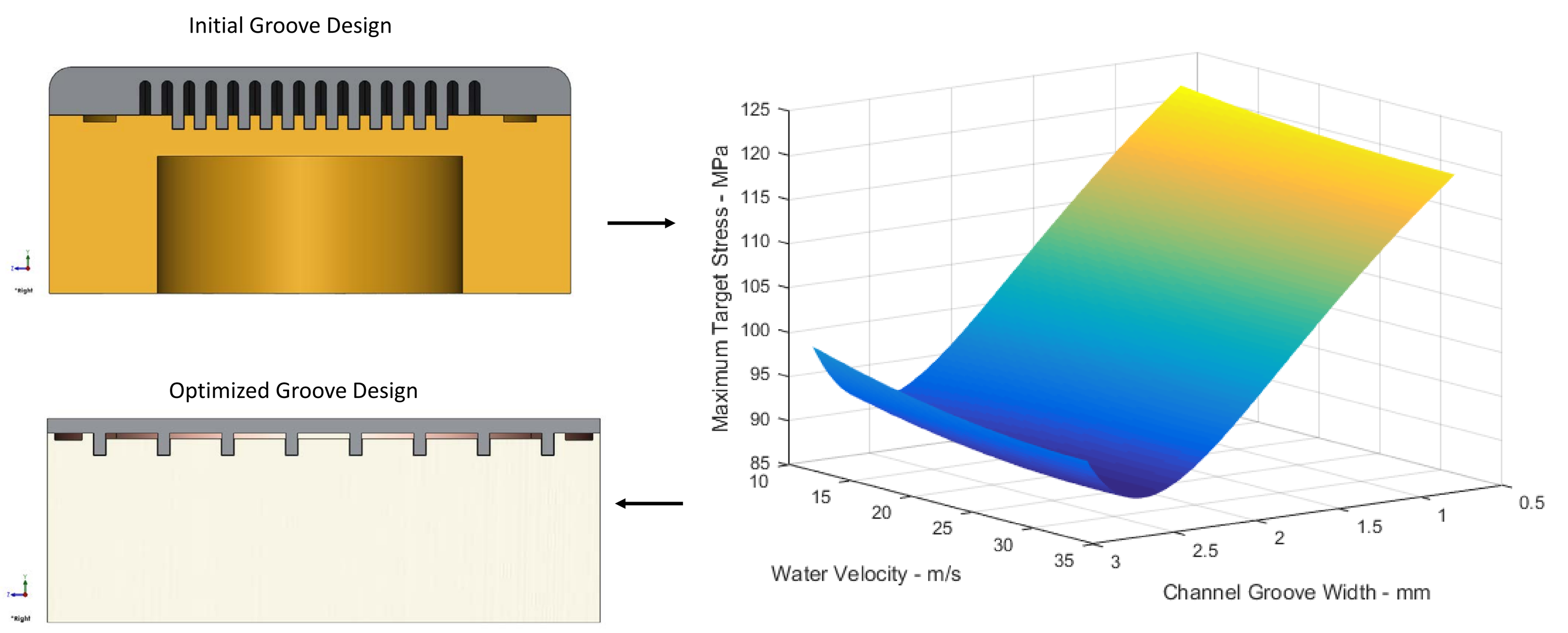
$$Z_k = \sum\lambda_i Z_i;\ Z_i = Variable\ of\ interest, \lambda_i = Weight\ value$$

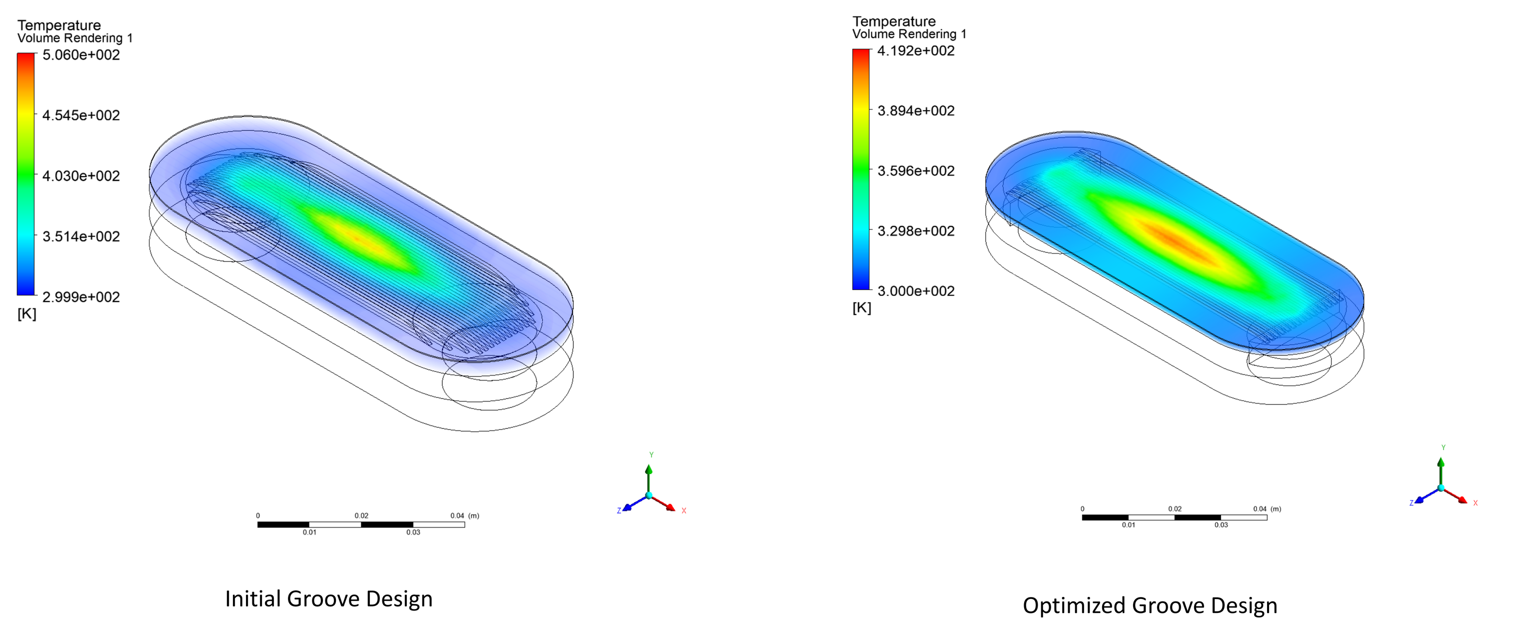
The goal is to minimize $E\{|Z_n - Z_k|^2\}$



Results

Based on the output from the kriging method, a more optimal flow condition based on inlet mass flow and groove dimension was selected. Old style target used a groove with a 0.8mm width, while the new target will use grooves which are 2.5mm in width. The design is undergoing testing in beam; no failures have occurred under nominal operation conditions.





References

[1] Wirsching, A. P.-D. (2018). *Creep-Rupture Reliability Analysis.* Kirkland AFB, New Mexico, USA: NASA.
[2] Price, C. (1966). On The Creep Behaviour of Silver - I The Oxygen Free Metal. *Acta Metallurgica*, 1781-1786.
[3] Price, C. (1966). On The Creep Behaviour of Silver - II Oxygen Effects. *Acta Metallurgica*, 1781-1786.
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[5] Jeong, Shinkyu & Murayama, Mitsuhiro & Yamamoto, Kazuomi. (2005). Efficient Optimization Design Method Using Kriging Model. Journal of Aircraft - J AIRCRAFT. 42. 413-420. 10.2514/1.6386.