Weibull Strength Parameter Requirements for Si_3N_4 Turbine Rotor Reliability

Steve Duffy & Eric Baker
Connecticut Reserve Technologies, LLC

Jim Kesseli
Ingersoll-Rand Energy Systems

Andy Wereszczak
Oak Ridge National Laboratory

Curt Johnson
General Electric Corporate Research & Development

Presented at the Environmental Barrier Coatings Workshop
November 18-19, 2003
Gaylord Opryland Resort & Convention Center
Nashville, Tennessee, USA

Scope

A method to define Weibull distribution metrics for Si_3N_4 vendors, in particular, and ceramic material developers, in general, using component level analysis is presented. This presentation provides an overview of work-in-progress.

The combination of service stress states and a requisite probability of survival for an Ingersoll-Rand microturbine rotor are used to determine Weibull distribution parameters for an arbitrary Si_3N_4 material. Associated pairs of parameters, the Weibull modulus and the Weibull material characteristic strength, are plotted as "material performance curves."

The "material performance curve" is then scaled to standard test coupons (e.g., ORNL button-head).

The "material performance curve" for a generic thin walled pressure vessel subjected to an internal pressure is also presented. Based upon a surface flaw analysis, the material characteristic strengths are scaled to a bend bar specimen.

The number of failed specimens in a data set effects the quality of the parameter estimates. This effect is depicted relative to the material performance curves using likelihood ratio contours in a surface flaw analysis.

Procedural Overview -
Material Performance Curves

Conduct a finite element analysis on a ceramic component.

Establish an acceptable component failure rate.

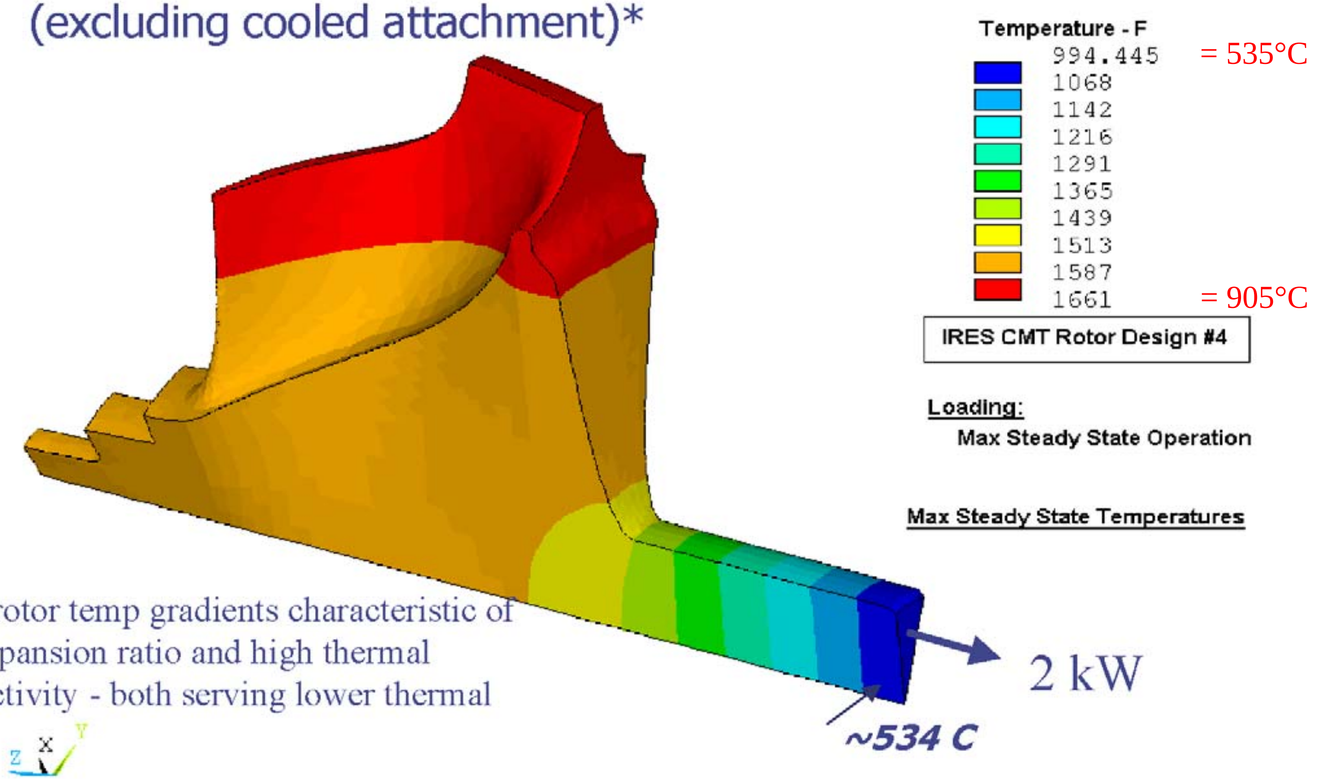
Utilize NASA/CARES to back-calculate Weibull parameter pairs that when applied to the component exhibit the desired failure rate. (Currently this step is executed manually for the examples presented.)

Graph the Weibull parameter pairs and establish the "Material Performance Curve" relative to the component.

Scale this curve to standard test specimens.

CMT Rotor Steady State Temperatures

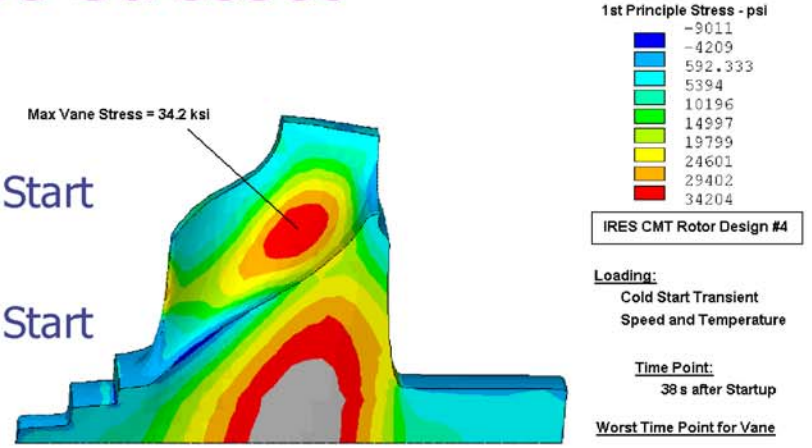
- TIT = 1000 C
- Maximum adiabatic Wall Temperature = 905 C
- Maximum rotor temperature difference = 60 C (excluding cooled attachment)*

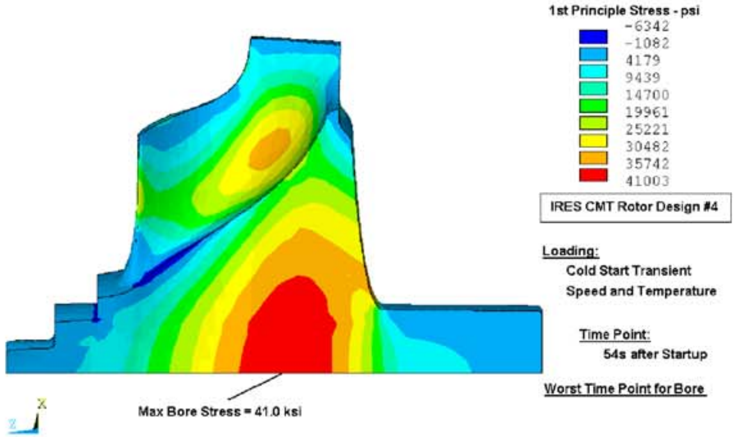


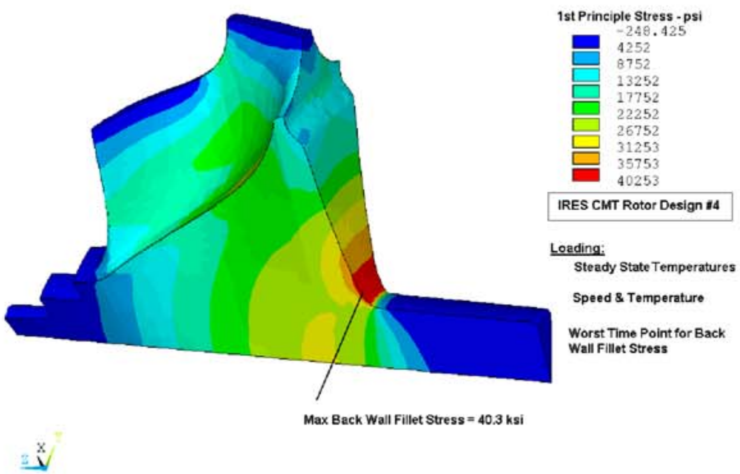
* low rotor temp gradients characteristic of low expansion ratio and high thermal conductivity - both serving lower thermal stress

CMT Rotor Worst Case Stresses

- Worst Cases:
  - Vane
    - 234 MPa @ 38 sec. into Cold Start
  - Bore
    - 282 MPa @ 54 sec. into Cold Start
  - Back Wall
    - 278 MPa @ Steady State







Material Performance Curves

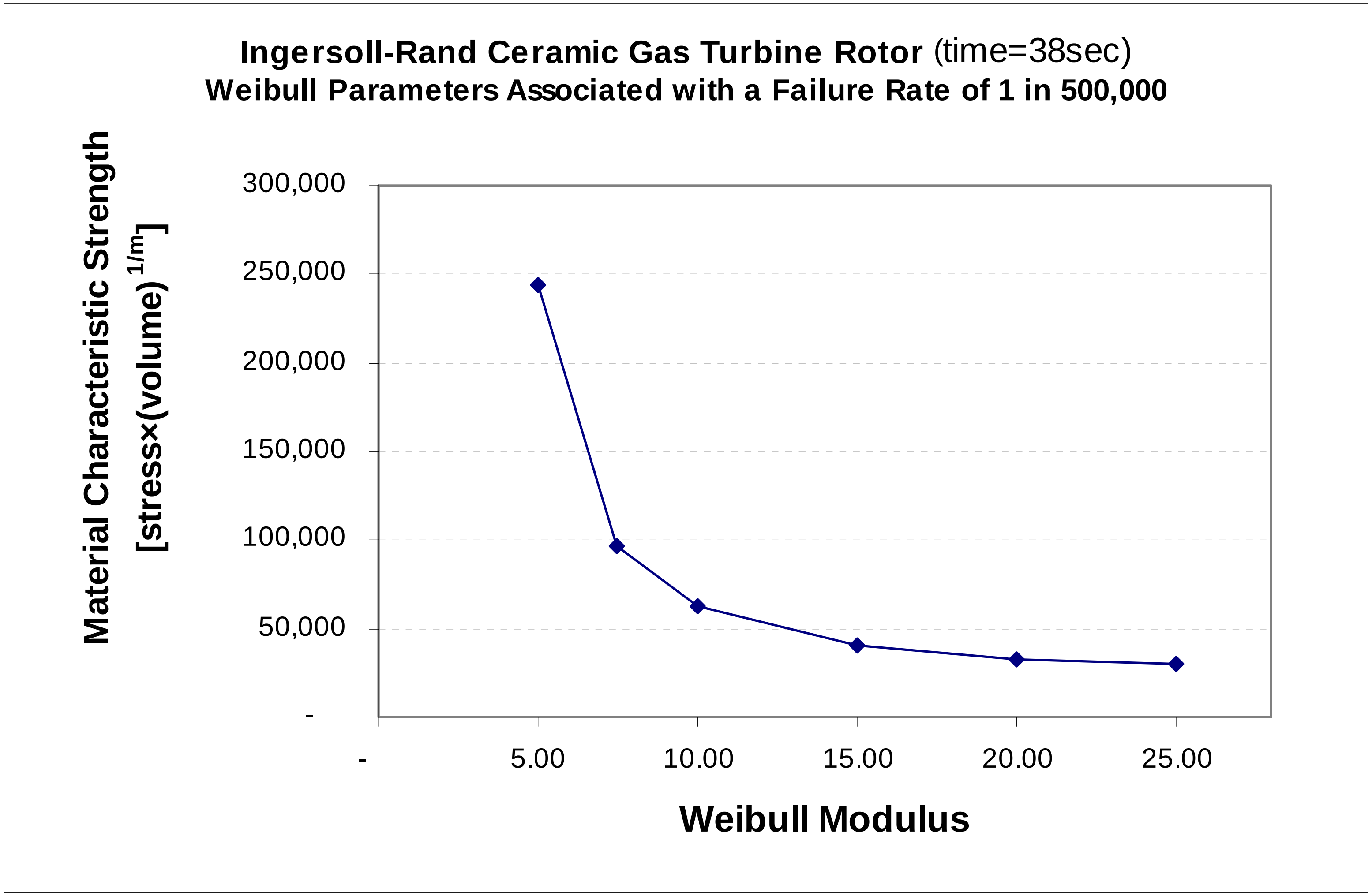
From the finite element analysis of the microturbine rotor the NASA/CARES algorithm was used to establish material performance curves based on the following assumptions:

> *Failure rate must be established a priori. Here a rate of 1 in 500,000 was assumed (Reliability = 0.999998).*
>
> *A single pair of Weibull distribution parameters was used initially for demonstration purposes. This corresponds to using a set of parameters characterized at high temperature for the entire reliability solution. This high temperature assumption would be conservative. The ability to relax this assumption is discussed later.*

Based on the assumptions above Weibull moduli and material characteristic strength pairs were found which satisfy the assumed failure rate as computed through NASA/CARES.

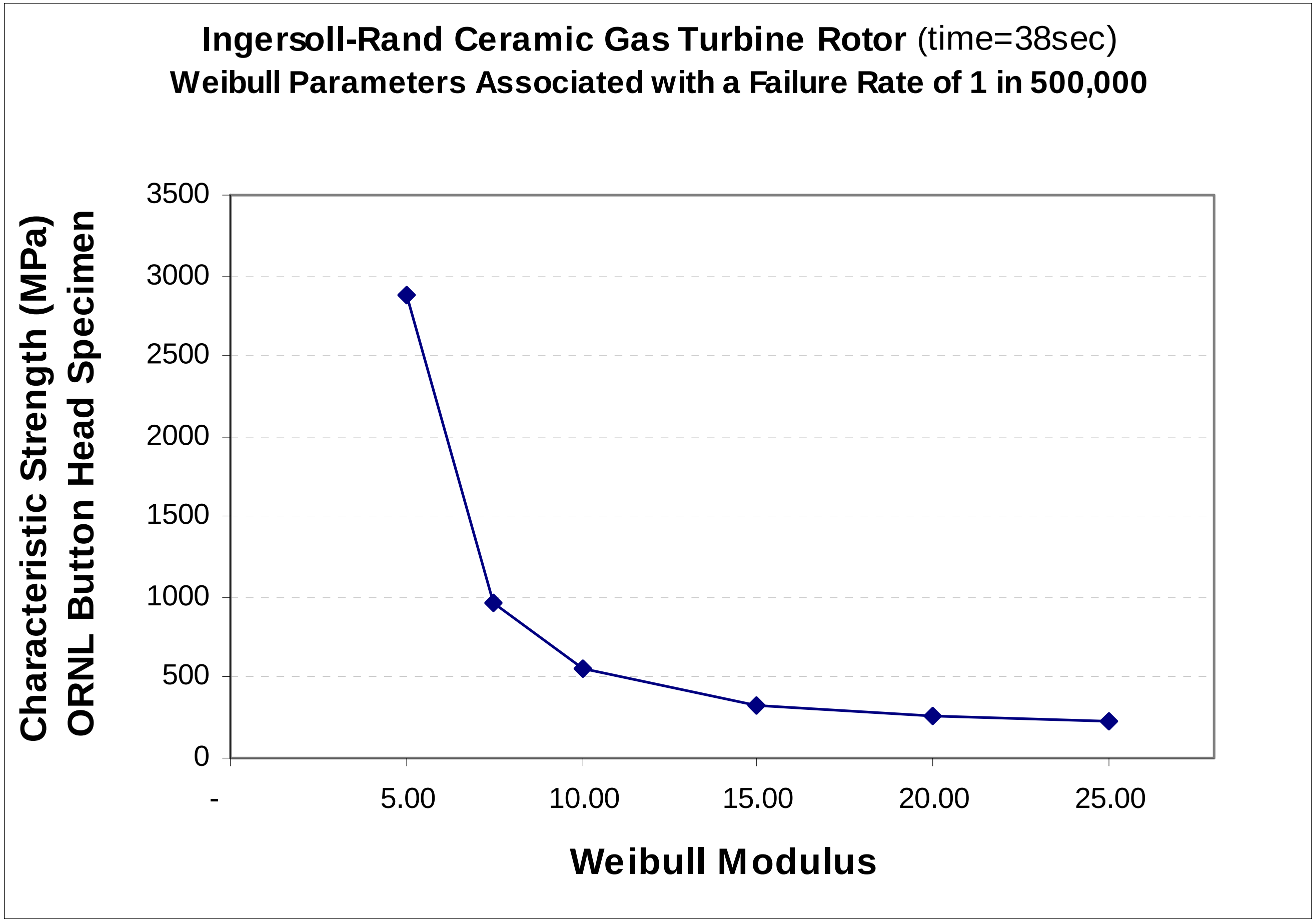
Material Performance Curve - Volume Flaw Analysis

Ingersoll-Rand



Ingersoll-Rand

Material Performance Curve - ORNL Button Head Tensile Specimen



Effective volume (referred to as $k_V \cdot V$ *) relationship is used to transform* σ_0 *from the previous graph into* σ_θ *for a tensile specimen in the presented here.*

This graph can be used as a target performance curve for material vendors using tensile specimens to characterize their material

Material Performance Curves – Surface Flaw Analysis

An attempt was made to conduct a surface flaw analysis using the Ingersoll-Rand rotor. This analysis is particularly relevant since the greatest tensile stresses were located at the rotor surface. The surface flaws would be assumed concurrent with volume flaws. Unfortunately the ANSYS model provided had been optimized in a way as to preclude the execution of a surface flaw analysis with CARES at this point in time.

Alternatively, a simple generic component was used to illustrate a surface flaw analysis, i.e., a thin walled pressure vessel. Model geometry is as follows:

Inner Radius = 100 mm

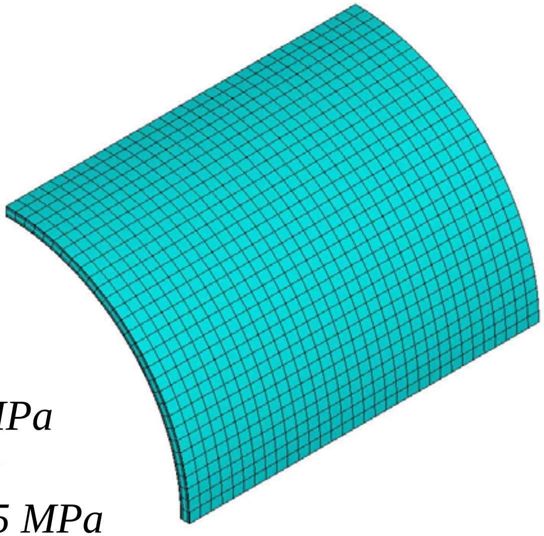
Thickness = 5 mm

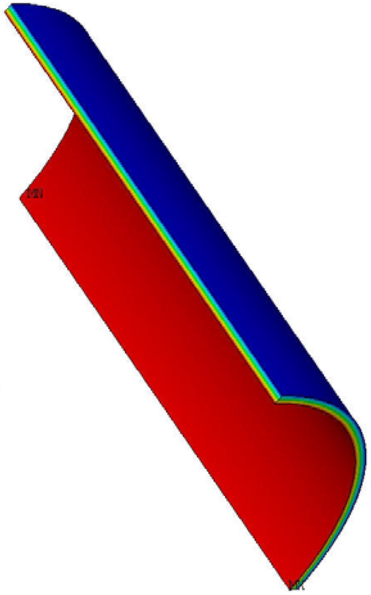
Length = 400 mm

Applied Pressure = 10 MPa

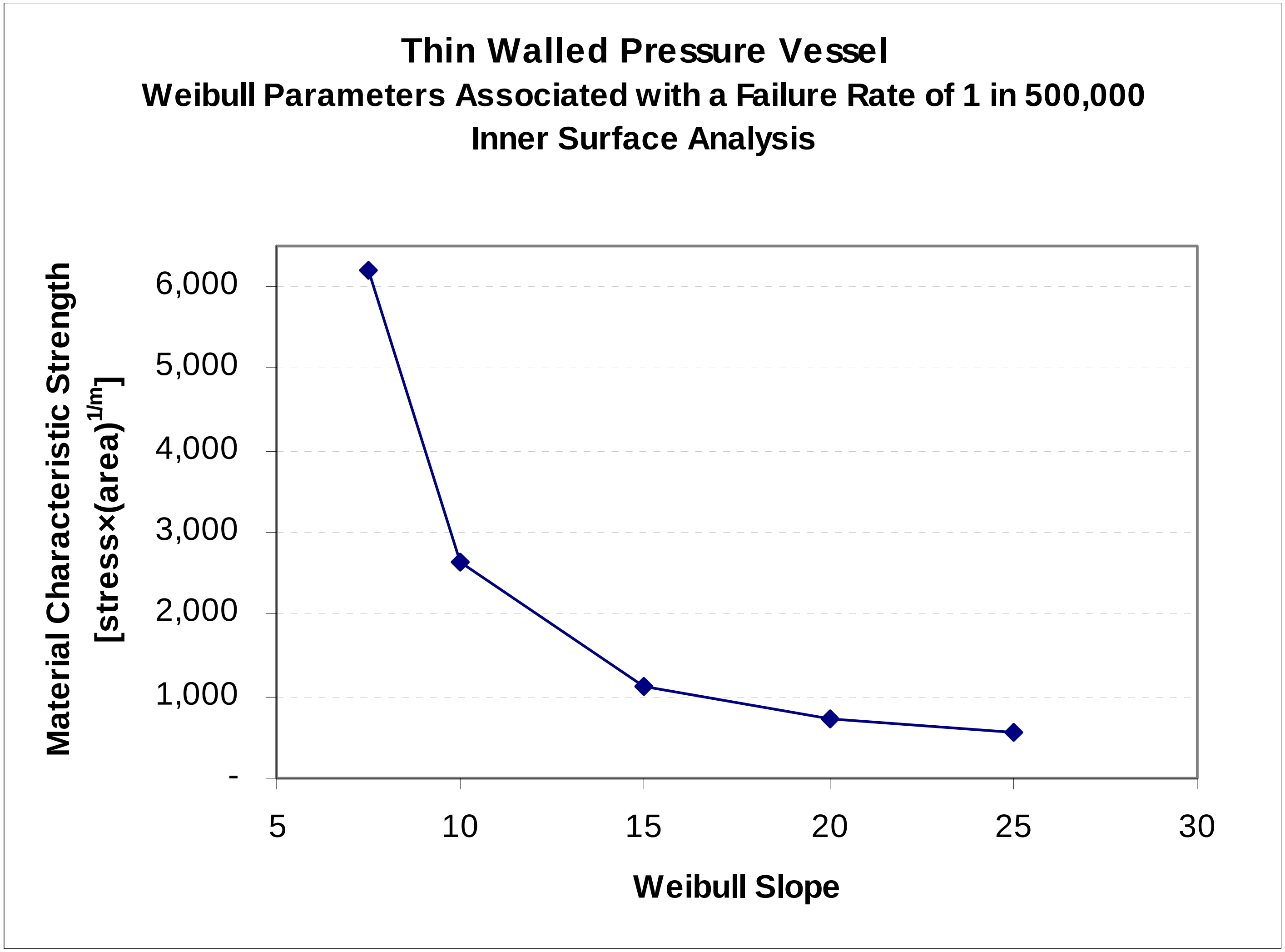
Estimated Stress (pr/t) = 200 MPa

Inner Surface FEA Stress = 205 MPa

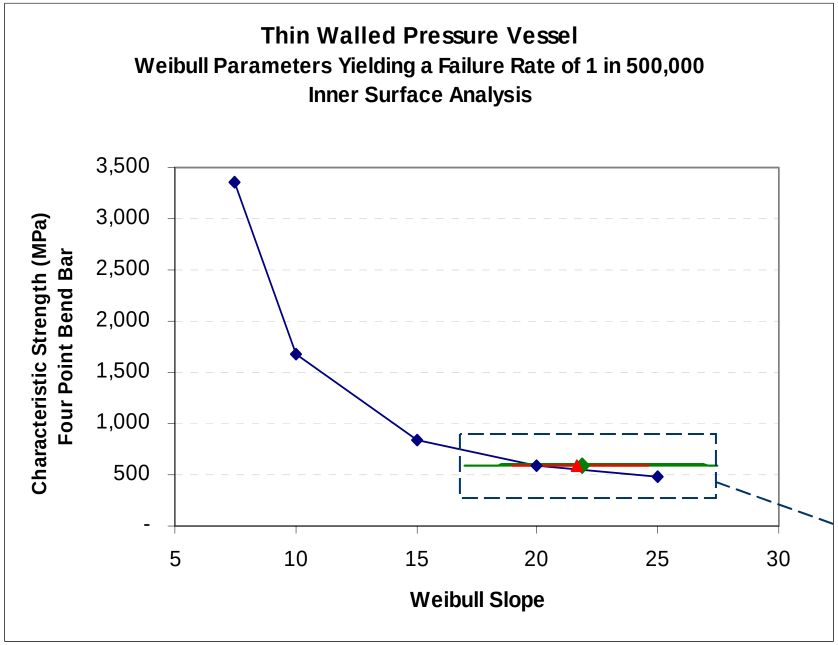




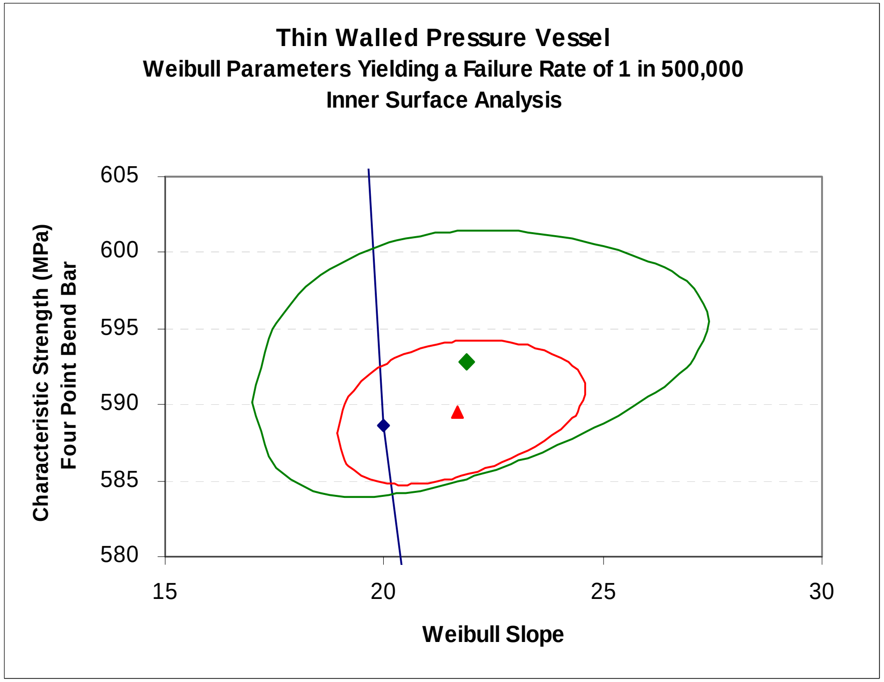
Material Performance Curve – Surface Flaw Analysis



Material Performance Curve - Four Point Bend Specimen

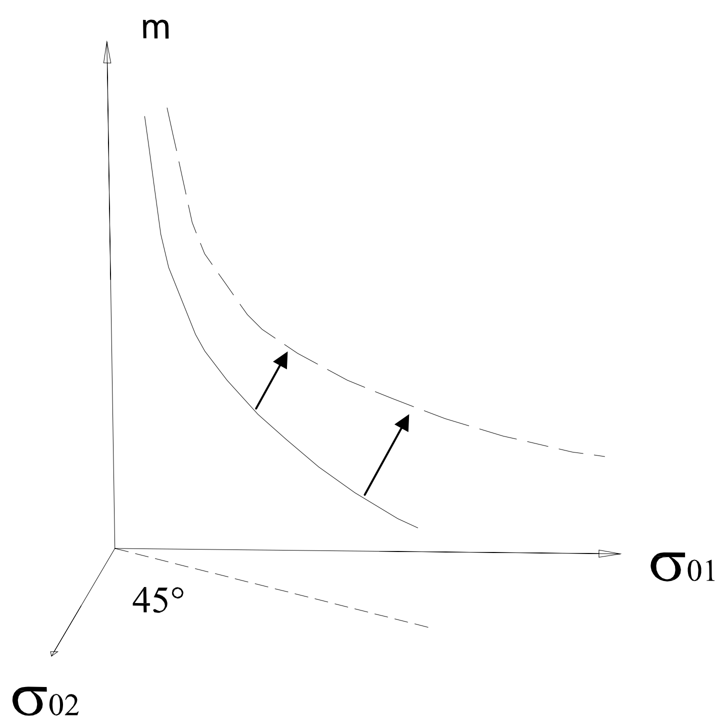


Generic data sets were generated via Monte Carlo simulation. The green curve corresponds to a data set with 30 test specimens. The red curve corresponds to a data set with 100 test specimens.



Both curves represent the 90th percentile confidence interval.

Material Performance Curves – Multiple Temperature Regime



Previous analyses assumed that $\sigma_{01} = \sigma_{02}$

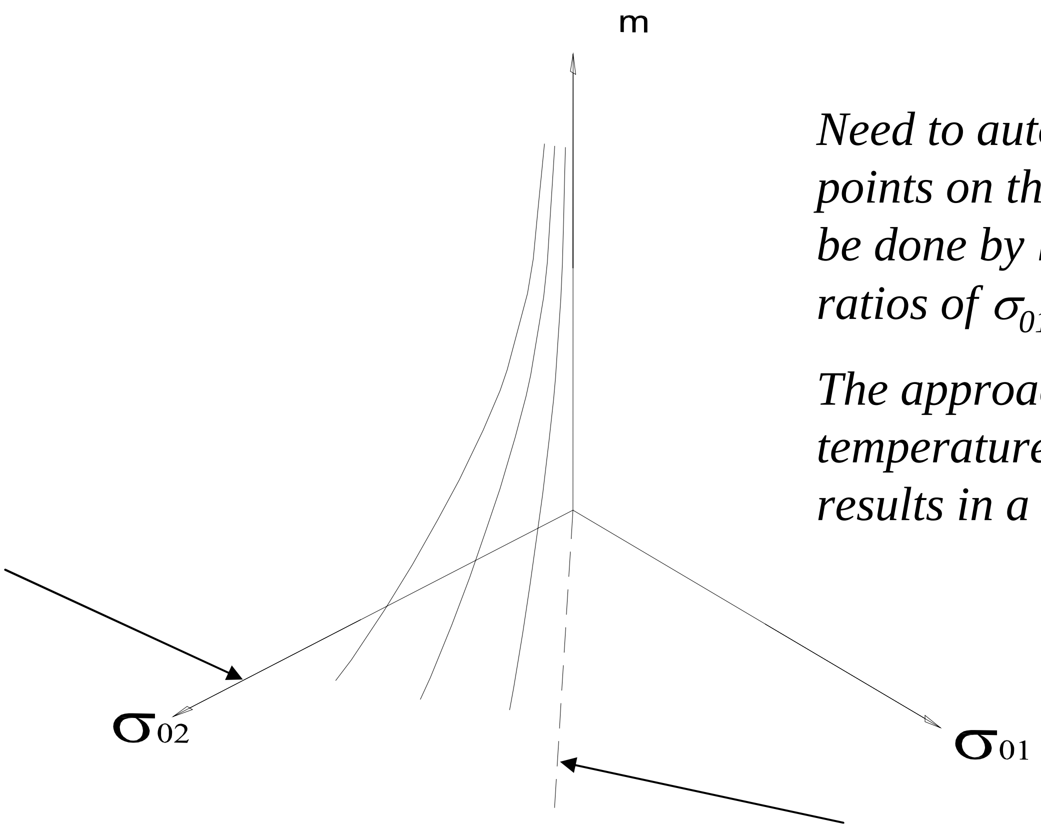
Previously a temperature independent regime was assumed.

Now assume that test data is available at two temperatures - ambient temperature and maximum component operating temperature (or higher).

Further take the Weibull modulus as being independent of temperature.

Now there are two material characteristic strength parameters in need of being characterized, i.e., σ_{02} (ambient) and σ_{01} (high temperature)

Material Performance Response Surface – Multiple Temperature Regime



Need to automate CARES to generate points on the response surface. This can be done by looking at curves with fixed ratios of σ_{01} to σ_{02}.

The approach can be extended to multiple temperatures, but the ability to present results in a graphic fashion is soon lost.

Response surface will be constrained to map within this region

Summary

A methodology is established for generating material performance curves/surfaces for any given component geometry - stress state combination. Curves were determined for standard test specimen geometries.

The effect that the number of test specimens per failure data set has on the size of the likelihood ratio confidence rings was demonstrated.

The approach for volume-flaw or surface-flaw strength limiting populations was demonstrated using a DER component and a generic component, respectively.

Further programming required to automate CARES to generate performance curves/surfaces.

Once response surface generation is automated look to develop optimization routines to establish the best set of Weibull parameters for a given component.