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Analytic Model Development for Ceramic Gun Tubes

by Robert Carter

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14. ABSTRACT

The equations for calculating the probability of failure for an internally pressurized ceramic tube are straightforward and well defined in the literature. The most common solution is for a tube subjected only to an internal pressure. This approach neglects any external pressure, over wrap, or sheathing system that may be used to maintain or promote a beneficial compressive pre-stress. The current research has focused on the development of a model, based on elasticity theory, of a sheathed ceramic tube augmented with probability of failure calculations used to calculate stress, strain, and probability of failure of the ceramic tube component. The model calculated the Weibull probability of failure for volumetric- and surface-strength-limiting flaws with the consideration of predicted (isothermal, mechanical, or combined) stress states on the surfaces and throughout the volume.

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ceramic gun tubes, Weibull statistics, failure surface

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1. Introduction

Ceramic materials are being investigated as bore materials for high performance gun barrels. The superior high temperature behavior and excellent erosion resistance make them strong candidates for application in the harsh environment produced during a ballistic event. The application of these materials is not a novel approach. Several previous investigations by the U.S. Army, Navy, and different contract organizations have considered the use of ceramic materials in gun bores. The success of these previous investigations has been limited at best, but advances in ceramic material processing, probabilistic design, and sheathing technologies have prompted the U. S. Army Research Laboratory to renew investigations into ceramic materials.

The primary factor preventing the simple insertion of ceramics into gun bores has been the inability to design around the low tensile strength, large variability in the observed strength, and brittle behavior of the materials. The objective of the present research is to develop analytic models for the design of ceramic-lined gun barrels capable of surviving interior ballistic events. The first section of this report will focus on the derivation of the statistical equations for predicting failure in ceramics, while the second will deal with the development of a model for calculating stress. The results of the completed model will be presented showing the usefulness of the model.

1.1 Statistical Model Development

Statistical methods are necessary to properly design around the variability in observed strength of ceramic components. The most recognized approach incorporates the Weibull distribution equation. The original Weibull equation calculates a probability of failure (P_f) for a brittle material subjected to a uniaxial stress distribution:

$$P_f = 1 - e^{-\int \left(\frac{\sigma}{\sigma_o}\right)^m dV}, \tag{1}$$

with σ being the stress, σ_o is the Weibull strength or scale parameter, and m being the Weibull modulus. This expression considers only one type of flaw population located in the volume of the ceramic body subjected to a uniform stress (*1*). For a pressurized tube, additional conditions need to be evaluated, namely the probability for a nonuniform stress state and multiple flaw populations. This report will derive the equations needed to calculate the probability of failure due to volume and surface flaws for a tube subjected to internal and external pressures only. Failure calculations evaluate the nonuniform hoop tensile stresses only and assume that the probability of failure of a part in compression is zero (as described in ASTM Standard C 1239-00) (*2*). The calculations also assume that the tube is loaded along its entire length, thus eliminating the consideration of any edge effects.

1.2 Volume Flaws

For the condition when the stress distribution is unidirectional, but not uniform,

$$P_{fV} = 1 - e^{-k_v V\left(\frac{\sigma_{\max}}{\sigma_{oV}}\right)^{m_V}} , \tag{2}$$

where

$$k_v V = \int \left(\frac{\sigma(r)}{\sigma_{\max}}\right)^{m_V} dV , \tag{3}$$

σ_{max} is the maximum stress in the material, $\sigma(r)$ is the function describing the stress distribution, m_v is the volumetric Weibull modulus, and $k_v V$ is the effective volume of the sample (*3*). Some distinction needs to be placed on the Weibull material scale parameter (σ_o) since it is not always the same as the Weibull characteristic strength (often listed as σ_θ– but not to be confused with hoop stress in this report). The characteristic strength term, σ_θ, is often reported, but is test and sample geometry dependant. The volumetric material scale parameter, σ_{oV}, is strength per unit volume of uniform, uniaxial tension (hence the unusual units of $\text{MPa}*\text{mm}^{3/m_v}$).

For a tube subjected to internal and external pressures, the Lamé cylinder expression for the hoop stress (σ_θ) is

$$\sigma_\theta(r) = \frac{P_i r_i^2 - P_o r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 r_o^2 (P_o - P_i)}{r_o^2 - r_i^2}\frac{1}{r^2} , \tag{4}$$

where r is radius, P is the pressure, and i and o refer to the inner and outer surfaces, respectively (*4*). This distribution exhibits maximum stress at the inner surface when $P_i > P_o$, and is given by

$$\sigma_{\theta\max} = \frac{P_i\left(r_i^2 + r_o^2\right) - 2P_o r_o^2}{r_o^2 - r_i^2} . \tag{5}$$

The effective volume, $k_V V$, for a tube subjected to internal and external pressures is found by substituting equations 4 and 5 into 3:

$$k_v V = 2\pi L \int_{r_i}^{r_o} \left[\frac{P_i r_i^2 - P_o r_o^2}{P_i\left(r_i^2 + r_o^2\right) - 2P_o r_o^2} + \frac{r_i^2 r_o^2 (P_i - P_o)}{P_i\left(r_i^2 + r_o^2\right) - 2P_o r_o^2}\frac{1}{r^2}\right]^{m_v} r dr . \tag{6}$$

It should be noted that including the external pressure condition creates three regimes of behavior: P_i dominant, transition, and P_o dominant. In the P_i dominant condition, where $P_i >> P_o$, the hoop stress is tensile through the thickness, and exhibits a maximum at the inner surface. In the P_o dominant case, where $P_o >> P_i$, it is compressive throughout the thickness. In the transition regime, where $P_i > P_o$, the inner portion of the tube is tension, while the outer is in compression.

The limits for the different dominant behaviors are determined by setting the hoop stress terms to zero at both surfaces and solving for the external pressure:

$$P_{otrans} = \frac{2P_i r_i^2}{r_i^2 + r_o^2} \quad , \qquad P_{ocompression} = \frac{P_i\left(r_i^2 + r_o^2\right)}{2r_o^2} \quad . \tag{7}$$

P_{otrans} is the solution for when the outer surface of the tube goes into compression, while $P_{ocompression}$ is when the entire tube is in compression. In the transition region, the radial position where the hoop stress is zero is necessary for evaluating $k_V V$. This location, termed r_{neu}, is given by

$$r_{neu} = \frac{-r_i^2 r_o^2}{(P_i r_i^2 - P_o r_o^2)} \sqrt{\left(P_i r_i^2 - P_o r_o^2\right)\left(P_o - P_i\right)} \quad . \tag{8}$$

When $P_{otrans} < P_o < P_{ocompression}$, a portion of the tube is in compression (r_i to r_{neu}), so $k_V V$ changes to

$$k_v V = 2\pi L \int_{r_i}^{r_{neu}} \left[\frac{P_i r_i^2 - P_o r_o^2}{P_i\left(r_i^2 + r_o^2\right) - 2P_o r_o^2} + \frac{r_i^2 r_o^2 \left(P_i - P_o\right)}{P_i\left(r_i^2 + r_o^2\right) - 2P_o r_o^2} \frac{1}{r^2} \right]^{m_v} r dr \ . \tag{9}$$

As stated earlier, if $P_o > P_{ocompression}$, then $k_V V = 0$.

With the $k_V V$ term, the expression in equation 2 can be solved for the P_f value for volume flaws.

1.3 Surface Flaws

The expression for the probability of failure is similar to that of the volume flaws:

$$P_{fA} = 1 - e^{-k_A A \left(\frac{\sigma_{\theta \max}}{\sigma_{oA}} \right)^{m_A}} \ , \tag{10}$$

however, due to the population of flaws located at surface the integral for the effective area, $k_A A$ operates over the surface area, not the volume. The effective area is evaluated over the inner surface, the two ends, and the outer surface as shown in equation 11:

$$k_A A = 2\pi L r_i + 4\pi \int_{r_i}^{r_o} \left[\frac{P_i r_i^2 - P_o r_o^2}{P_i\left(r_i^2 + r_o^2\right) - 2P_o r_o^2} + \frac{r_i^2 r_o^2 \left(P_i - P_o\right)}{P_i\left(r_i^2 + r_o^2\right) - 2P_o r_o^2} \frac{1}{r^2} \right]^{m_A} r dr$$
$$+ 2\pi L r_o \left[\frac{2P_i r_i^2 - P_o\left(r_i^2 + r_o^2\right)}{\left(r_i^2 + r_o^2\right)P_i - 2P_o r_o^2} \right]^{m_A}. \quad (11)$$

In the case when $P_{otrans}<P_o<P_{ocompression}$, the $k_A A$ expression changes to

$$k_A A = 2\pi L r_i + 4\pi \int_{r_i}^{r_{neu}} \left[\frac{P_i r_i^2 - P_o r_o^2}{P_i\left(r_i^2 + r_o^2\right) - 2P_o r_o^2} + \frac{r_i^2 r_o^2 \left(P_i - P_o\right)}{P_i\left(r_i^2 + r_o^2\right) - 2P_o r_o^2} \frac{1}{r^2} \right]^{m_A} r dr \quad . \quad (12)$$

Since the outer surface is in compression the outer surface term is dropped and the integral is evaluated on the tensile region. If $P_o > P_{ocompression}$, then $k_A A = 0$.

1.4 Total Probability of Failure

The two expressions for probability of failure, one for volume flaws and one for surface flaws, are combined to calculate the probability of failure for the tube (*5*):

$$P_f = 1 - \prod_{i=1}^{N} \left(1 - P_{fi}\right) , \quad (13)$$

where P_f is the total probability of failure for the component and P_{fi} is the probability of failure for the i^{th} flaw population or location. Given the two Weibull parameters (for each flaw population), the new P_f value can be calculated for a combination of internal and external pressure. Also, more terms can be added to equation 13 to address multiple flaw populations or to address each flaw type encountered.

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2. Sheathed Tubes

In order to develop a gun system capable of withstanding the pressure loads induced by the ballistic firing, sheathing material needs to be applied in a way to generate beneficial compressive pre-stress. The level of the pre-stress is highly dependant upon the elastic properties of the sheath and ceramic, the strengths of both materials, and the thermal expansion coefficients. Analytic models are available to describe the response of tubes to the loading conditions that can be expected from a gun system.

2.1 Sheathed Tube Mechanics

The simplest model for sheathed tubes is that of two isotropic materials, which is adequate for a metal-sheathed ceramic tube. The equations located in the text by Herakovich and the works by Rousseau and Hyer provide good guidance to calculating the stress, strain, and displacement relations for a system of axisymmetric, nested tubes subjected to uniform internal and external pressure, axial tension and compression, axial torsion, and uniform temperature changes (*6–8*). They are sufficient to model interference stresses from shrink-fit and press-fit operations which are needed for imparting a beneficial pre-stress into the ceramic.

The most well known and simplest expression for stress in an isotropic tube due to internal and external pressure is the Lamé cylinder expression:

$$\sigma_\theta(r) = -\frac{a^2b^2(p_o - p_i)}{(b^2 - a^2)}\frac{1}{r^2} + \frac{p_i a^2 - p_o b^2}{(b^2 - a^2)}$$

$$\sigma_r(r) = \frac{a^2b^2(p_o - p_i)}{(b^2 - a^2)}\frac{1}{r^2} + \frac{p_i a^2 - p_o b^2}{(b^2 - a^2)} \quad , \tag{14}$$

where

σ_θ = hoop stress
a = inner radius
b = outer radius
p_o = external pressure
p_i = internal pressure
r = radial location.

This expression is useful for calculating the stresses in a monolithic ring with an external pressure representing the effects of the sheath. Simulations using this approach are useful for determining the effects of varying the material properties, but it is not effective for simulating a sheathed system since the external pressure on the ceramic is constant.

In order to accurately model a sheathed system, a more comprehensive model is necessary. In the chapter on laminated tubes in the text by Herakovich, expressions for a layered tube are developed. The following expressions use the cylindrical coordinate system labeled x (axial), θ (circumferential), and r (radial) directions.

For an isotropic material, the axial, tangential, and radial displacements, $u(x)$, $v(x, r)$, and $w(r)$ respectively, are defined as

$$u(x) = \varepsilon_x^o x$$

$$v(x,r) = \gamma^o xr$$

$$w(r) = A_1 r + A_2 r^{-1} \quad , \tag{15}$$

where A_1, A_2, ε_x^o, and γ^o are unknown constants. Similarly, the expressions for anisotropic materials are identical for $u(x)$ and $v(x,r)$, but $w(r)$ becomes

$$w(r) = A_1 r^{\lambda} + A_2 r^{-\lambda} + \Gamma \varepsilon_x^0 r + \Omega \gamma^0 r^2 + \Psi r \Delta T$$

$$\Gamma = \left(\frac{\overline{C}_{12} - \overline{C}_{13}}{\overline{C}_{33} - \overline{C}_{22}} \right)$$

$$\Omega = \left(\frac{\overline{C}_{26} - 2\overline{C}_{36}}{4\overline{C}_{33} - \overline{C}_{22}} \right)$$

$$\Psi = \left(\frac{\widetilde{\Sigma}}{\overline{C}_{33} - \overline{C}_{22}} \right)$$

$$\widetilde{\Sigma} = \sum_i \left(\overline{C}_{i3} - \overline{C}_{i2} \right) \alpha_i \quad , \tag{16}$$

where $\overline{C}_{ij}$ is a transformed stiffness matrix value.

For a single ply, there are the four unknowns for which to solve, but the number of unknown scales for laminates of more than one ply. There are single values for ε_x^o and γ^o, but there are values for A_1 and A_2 for every layer. For a structure with N layers, this translates to a total number of unknowns of $2N + 2$.

The first step to solve for the unknown values is to transform the equations for displacement to the strain and stress relations. This allows for the use of the stress and strain boundary conditions to help define the unknown values. First consider the strain-displacement relations for cylindrical coordinates:

$$\varepsilon_x = \frac{\partial u}{\partial x} \quad \gamma_{r\theta} = \frac{\partial v}{\partial r} - \frac{v}{r}$$
$$\varepsilon_\theta = \frac{w}{r} \quad \gamma_{xr} = \frac{\partial u}{\partial r}$$
$$\varepsilon_r = \frac{\partial w}{\partial r} \quad \gamma_{x\theta} = \frac{\partial v}{\partial x} \quad . \tag{17}$$

Substituting equations 15–17, the strains can be written in terms of the unknown values. Using the three-dimensional constitutive equations in cylindrical coordinates, the stress expression can be derived from the strain equations:

$$\begin{bmatrix} \sigma_x \\ \sigma_\theta \\ \sigma_r \\ \tau_{\theta r} \\ \tau_{xr} \\ \tau_{x\theta} \end{bmatrix} = \begin{bmatrix} \overline{C}_{11} & \overline{C}_{12} & \overline{C}_{13} & 0 & 0 & \overline{C}_{16} \\ \overline{C}_{12} & \overline{C}_{22} & \overline{C}_{23} & 0 & 0 & \overline{C}_{26} \\ \overline{C}_{13} & \overline{C}_{23} & \overline{C}_{33} & 0 & 0 & \overline{C}_{36} \\ 0 & 0 & 0 & \overline{C}_{44} & \overline{C}_{45} & 0 \\ 0 & 0 & 0 & \overline{C}_{45} & \overline{C}_{55} & 0 \\ \overline{C}_{16} & \overline{C}_{26} & \overline{C}_{36} & 0 & 0 & \overline{C}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_\theta \\ \varepsilon_r \\ \gamma_{\theta r} \\ \gamma_{xr} \\ \gamma_{x\theta} \end{bmatrix} \quad , \tag{18}$$

where σ and τ are normal and shear stresses, $\overline{C}ij$ is the transformed stiffness matrix, and ε and γ are the normal and shear strains. Thermal and filament winding stresses can be included with a modification to the constitutive equations. If the strain values are modified to include thermal and winding strain values, as in

$$\varepsilon = \varepsilon^{E} - \varepsilon^{Th} + \varepsilon^{w} \quad , \tag{19}$$

where ε is the total strain, ε^{E} is the elastic strain, ε^{Th} is the thermal strain ($\alpha \Delta T$), and ε^{w} is the elastic strain in the tow due to winding tension. Winding strain is the elastic strain imparted due to tow tension in winding, or

$$\varepsilon^{w} = \frac{F}{AE} \quad , \tag{20}$$

where *F* is the force on the tow, *A* is the area of the tow, and *E* is the elastic modulus of the fibers (*9*).

With the equations for stress, strain, and displacement, the unknowns can be found by applying different boundary conditions. There are force and torque conditions that must be met:

$$\begin{aligned} F_x &= 2\pi \sum_{k=1}^{N} \int_{r_{k-1}}^{r_k} \sigma_x^{(k)} r dr \\ T_x &= 2\pi \sum_{k=1}^{N} \int_{r_{k-1}}^{r_k} \tau_{x\theta}^{(k)} r^2 dr \quad . \end{aligned} \tag{21}$$

The applied axial force (F_x) and axial torque (T_x) are equal to the sum of the axial and shear stresses integrated over the area of each layer. This provides two equations for the $2N + 2$ unknowns.

Two more equations come from the balance of stresses at the inner and outer surfaces of the tube. The radial stress at each surface must balance the applied pressure, or

$$\begin{aligned} -p_i &= \sigma_r^1(R_i) \\ -p_o &= \sigma_r^N(R_o) \quad . \end{aligned} \tag{22}$$

The final $2N - 2$ equations come from continuity of traction and displacement at each internal interface. The radial stresses and displacements must be continuous across each interface, so

$$\begin{aligned} w^{(k)}(r_k) &= w^{(k+1)}(r_k) \\ \sigma_r^{(k)}(r_k) &= \sigma_r^{(k+1)}(r_k) \quad . \end{aligned} \tag{23}$$

There are now $2N + 2$ equations and $2N + 2$ unknowns, so the system can be solved for a given loading conditions.

2.2 Failure Surfaces for Pressurized Sheathed Tubes

The stress relations are used to calculate the stress profile through the wall of the ceramic tube. The values are the input into the probability of failure expressions derived in the previous sections, and the probability of failure for a pressurized tube is calculated. Mathcad* software was used to solve for variations in the material properties of the sheath and ceramic, geometry of the tubes, and operating conditions. With the implementation of a failure criterion for the sheath, the model can be used for designing optimal pre-stress generation with failure of the different materials.

A good example of this problem is the effect of the change in temperature has on the volumetric P_f of a steel-sheathed silicon nitride tube with an internal pressure of 500 MPa. The material properties are listed in table 1, and the failure curves in figure 1 are for a tube with an inner diameter (ID) of 10 cm, and outer diameter (OD) of 20 cm, length of 1 m. The thickness of the ceramic was varied from 2.5, 5, and 7.5 cm with the remaining portion of the 10-cm thickness being steel. Due to the thermal expansion mismatch between steel (α = 12.8 ppm/°C) and silicon nitride (α = 3 ppm/°C), cooling the tube assembly will generate compressive stresses in the ceramic. The probability of failure decreases as the ΔT value becomes more negative.

Table 1. Material properties for steel and silicon nitride.

Property	Steel	Si_3N_4
Modulus (GPa)	200	310
Poisson's ratio	0.32	0.24
CTE (ppm/°C)	12.8	3
σ_{oV} (MPa*mm$^{3/m}$)	—	1190
m_v	—	25

The probability of failure is plotted on a logarithmic scale to illustrate the behavior when the values become increasingly small. The thinner ceramic wall has a larger probability of failure at a small ΔT, but surpasses the thicker ceramic assemblies between –100 and –200 °C.

A more informative method of displaying the effects of varying ceramic wall thickness and pre-stress levels is to create failure surfaces for the sheath and ceramic materials (*10*). This is accomplished by fixing the total wall thickness and varying the ceramic-to-sheath ratio. Also, the pre-stress level can be varied from an unstressed condition to a large magnitude stress. Failure will be calculated by the probability of failure of the ceramic and by a yield failure criterion for the sheath. The resulting plot is illustrated in figure 2. The *x*-axis is the change in temperature from when the sheath makes initial contact with the ceramic for a shrink-fit operation. The *y*-axis is the ratio of the ceramic wall thickness to total wall thickness (0% is a steel tube with no ceramic and 100% is all ceramic with no sheath). The color codes are for the log of the probability of failure—zero is a P_f of 100% or zero chance of success, negative six is a

*Mathcad is a registered trademark of Mathsoft.

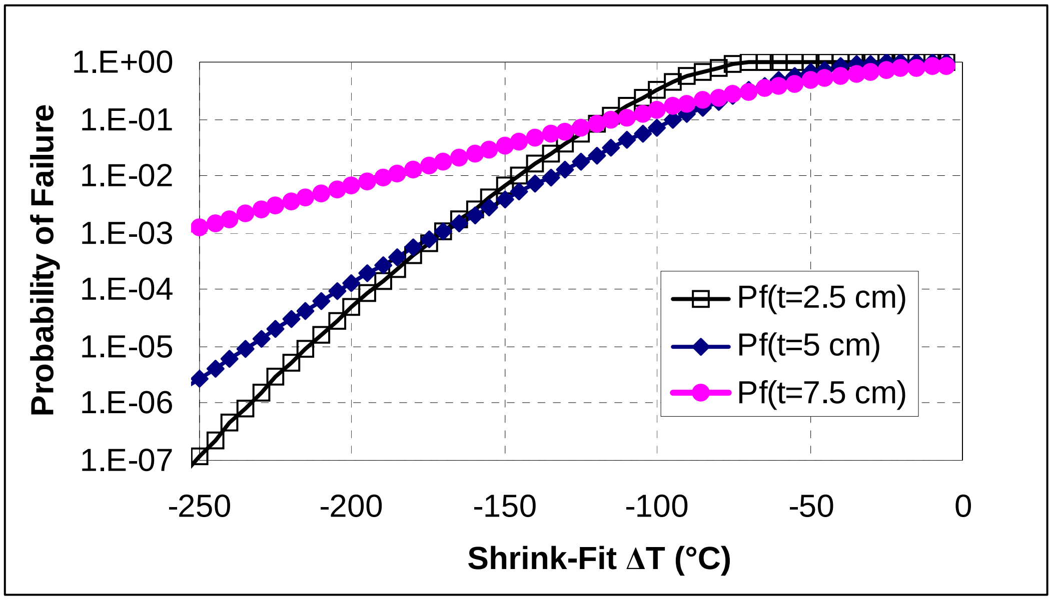

Figure 1. Probability of failure for a steel-sheathed silicon nitride tube with an internal pressure of 500 MPa. The three curves are for different ceramic wall thickness for a tube with an ID of 10 cm, an OD of 20 cm, and a length of 1 m.

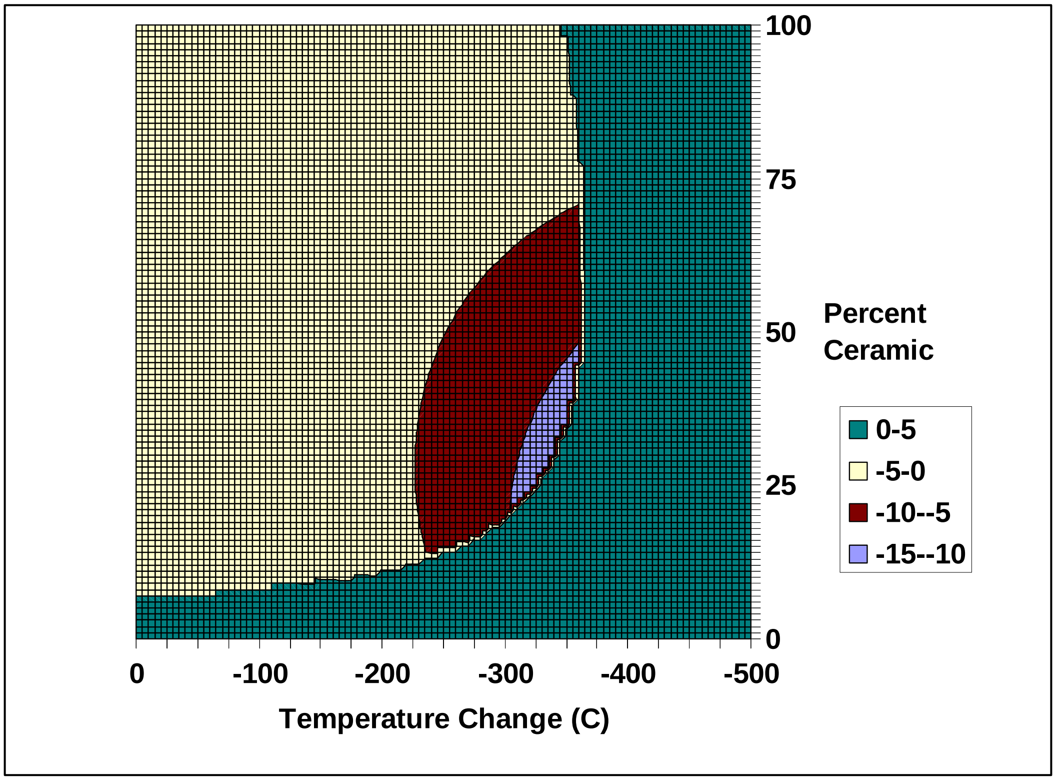

Figure 2. Failure surface for a pressurized tube. The yellow is ceramic failure, green is the sheathing failure, and red and purple are the optimal designs.

one in 1 million chance of failure. Also, the sheathing material can be evaluated for failure as well, allowing for the determination of an optimal design space for the system. For the materials selected here, a Von Mises yield criterion was used to calculate failure in the sheathing layer. When the sheathing failure criterion is met, the value is boosted to a value of one to separate it from the ceramic failures ($log(P_f)$ is always less than or equal to zero).

For this example, the design space with the optimal chance of success would be to have the wall thickness between 20%–40% ceramic and a ΔT of –300 to –375 °C.

3. Summary

This work derived equations for calculating the effective area and volume and the probability of failure for a ceramic tube subjected to internal and external pressure. The equations have been connected to an elasticity model to calculate the probability of failure for a sheathed ceramic tube. By combining the probability of failure for the ceramic and a failure criterion for the sheath, maps of the optimal design spaces can be generated. A sample calculation demonstrated the ability to model a pressurized, sheathed tube with varying amounts of thermal expansion mismatch.

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