LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T1300218-v1 LIGO 3/18/13

Creep of SLC Maraging Steel Suspension Blades

Michael Smith

Distribution of this document:
LIGO Scientific Collaboration

This is an internal working note
of the LIGO Laboratory.

California Institute of Technology
LIGO Project

Massachusetts Institute of Technology
LIGO Project

LIGO Hanford Observatory

LIGO Livingston Observatory

http://www.ligo.caltech.edu/

Table of Contents

1 Introduction *3*
1.1 Summary of Known Creep Characteristics of Maraging Steel Blades 3
1.2 References 3
2 Creep Data *4*
2.1 VIRGO 4
2.2 DeSalvo-SURF 5
2.3 GEO 6
3 Creep Theory *6*
3.1 Dislocation Function 7
3.2 Creep Function 7
4 Analysis of Data *8*
4.1 DeSalvo-SURF Data (Ref: LIGO P070095-02-Z) 8
4.1.1 Creep vs Time, DeSalvo-SURF 8
4.1.2 Creep vs Temperature 10
4.2 VIRGO Data 11
4.2.1 Creep vs Time, VIRGO 11
4.2.2 Creep vs Temperature, VIRGO 14
4.2.3 Initial Creep Rate vs Temperature 14
4.3 Summary of Creep Data 16
5 Creep Ageing *17*
6 Estimated SLC Blade Creep *18*
6.1 OFI 18
6.2 Arm Cavity Baffle, ITM Elliptical Baffle, and the Manifold/Cryo Baffle 19

Table of Figures

Figure 1: Elongation versus Time of Maraging C250 Blade 4
Figure 2: Fit of Theoretical Creep vs Time to DeSalvo-SURF Data 10
Figure 3: Comparison of Measured Creep with Theory versus Temperature, DeSalvo-SURF Data 11
Figure 4: Theoretical Creep vs Time, fit to VIRGO Data 13
Figure 5: Comparison of Measured Creep with Theoretical Values, VIRGO Data 14
Figure 6: Theoretical Initial Creep Rate vs Inverse Temperature, fit to VIRGO Data 16
Figure 7: Theoretical Creep Relaxation Time vs Temperature, DeSalvo-SURF Data 18
Figure 8: OFI Theoretical Creep vs Time, fit to VIRGO Data 19

1 Introduction

The purpose of this technical note is to estimate the vertical height change of the Stray Light Control (SLC) suspended components as a result of vertical creep of the suspension blades used for the Arm Cavity Baffle (ACB), the ITM Elliptical Baffle, the Manifold/Cryopump Baffle, and the output Faraday Isolator (OFI).

Historical creep data are taken from M. Beccaria, et al, Nuclear Instruments and Methods in Physics Research A 404 (1998) 455-469; from N. Virdone, et al, from LIGO-P070095-02--, hereafter referred to as DeSalvo-SURF, and from L1300071 Creep in Blades_GEO Experience.

An empirical formula for creep strain is developed from first principles, which can be matched to the historical creep data reasonably well and which enables a prediction of creep behavior in constant stress Maraging steel blades similar to those used in VIRGO, GEO, and LIGO.

1.1 Summary of Known Creep Characteristics of Maraging Steel Blades

The creep characteristics of constant stress Maraging steel blades, as used in GEO, VIRGO, and LIGO, are summarized in the following.

1. The blade material is Maraging C250. The material was precipitation hardened at 480 deg C for approximately 4 hours.
2. The horizontal blade is tapered from the mounted end to the tip, where the vertical load is applied; the taper produces an approximately constant stress at each cross section, causing the blade to bend into a circular arc (or pre-bent into a circular arc and then flattened by the applied load).
3. The vertical creep strain is independent of the maximum blade stress for temperature < 200 deg C and within the stress range 680 MPa to 1250 MPa, which is the nominal design stress range for the suspension blades. The vertical creep strain is defined as the ratio of the vertical creep sag of the loaded blade after a given time interval to the initial vertical deflection of the loaded blade. The maximum tensile stress occurs at the outside surfaces of the blade.
4. The creep strain increases with time toward an asymptotic maximum value of approximately 0.2 - 0.4%, for temperature < 200 deg C, and/or stress < 1250MPa. The time constant for reaching the maximum creep strain is dependent on temperature and is shortened considerably by increasing the temperature while under load. After the asymptotic value is reached, the creep strain remains constant with time.
5. Run-away creep occurs for temperature > 200 deg C and/or stress > 1250 MPa. This manifests itself as a plastic behavior of the blade in which the vertical creep strain increases indefinitely with time.

1.2 References

1. M. Beccaria, et al., Nuclear Instruments and Methods in Physics Research A 404 (1998) 455-469
2. N. Virdone, et al., LIGO-P070095-02-Z
3. L1300071 Creep in Blades_GEO Experience

2 Creep Data

2.1 VIRGO

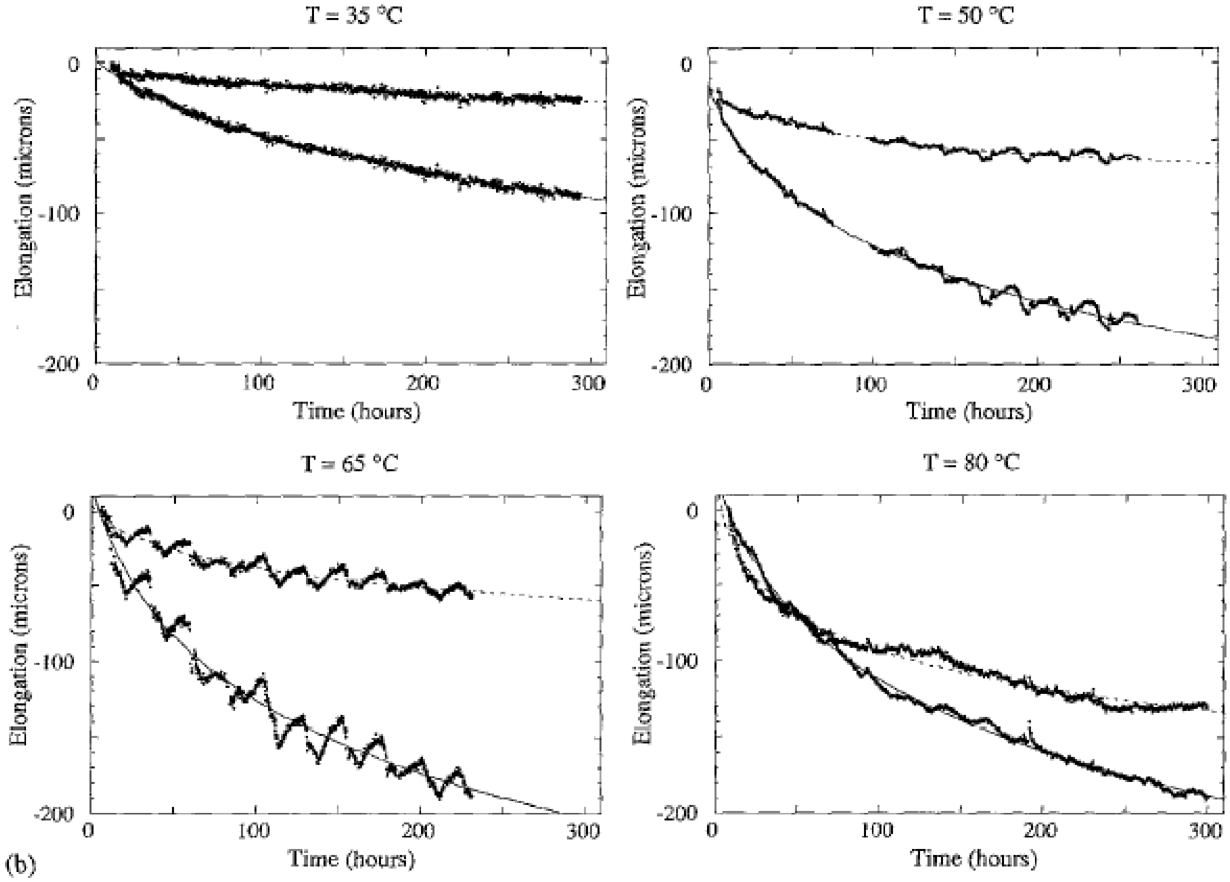

Figure 1: Elongation versus Time of Maraging C250 Blade

The blades were pre-bent, and then resolubilized at 850 deg C for 1 hour to release the internal stresses left by the bending process, cooled to room temperature, and then precipitation hardened at 480 deg C for 4 hrs.

The upper curves of each graph are for blades that had undergone various amounts of age-hardening, after the precipitation hardening, by being held under load at the shown temperature, which apparently locked some of the dislocations into the grain boundaries and reduced the subsequent creep rate; that data will be ignored in this technical note.

The lower curves are data taken directly after precipitation hardening at 480 deg C for 4 hrs, without any prior aging under load.

The creep rate was independent of the applied load within the surface stress range of 680 MPa to 1250 MPa.

The creep deflection in m was taken from the figures above at each temperature and at the time t = 200hrs = 12.5 days, and is presented below. Time is in units of days, deflection is in units of meter, and temperature is in units of deg C.

initial blade deflection under load, m $L_w := 0.1$

Creep data

$T := 35 \quad t := 12.5 \quad y(12.5, 35) = 90 \cdot 10^{-6}$

$T := 50 \quad t := 12.5 \quad y(12.5, 50) = 180 \cdot 10^{-6}$

$T := 65 \quad t := 12.5 \quad y(12.5, 65) = 210 \cdot 10^{-6}$

$T := 80 \quad t := 12.5 \quad y(12.5, 80) = 190 \cdot 10^{-6}$

2.2 DeSalvo-SURF

A similar experiment was conducted by DeSalvo-SURF, using the same material and heat treatment used by VIRGO. Their data, taken from Table 1, is presented below; time is in units of days, deflection is in units of meter, and temperature is in units of deg C.

initial blade deflection under load, m $L_w := 0.336$

Creep data

$T := 60 \quad t := 41 \quad y(41, 60) = 0.26 \cdot 10^{-3}$

$T := 90 \quad t := 20 \quad y(20, 90) = 0.56 \cdot 10^{-3}$

$T := 150 \quad t := 19 \quad y(19, 150) = 1.17 \cdot 10^{-3}$

$T := 170 \quad t := 27 \quad y(27, 170) = 1.33 \cdot 10^{-3}$

$T := 190 \quad t := 14 \quad y(14, 190) = 1.51 \cdot 10^{-3}$

2.3 GEO

Anecdotal data from GEO states that they have observed < 1mm creep of their blades during 12 years of operation. This is further evidence that Maraging steel blades exhibit asymptotic creep strain under load.

3 Creep Theory

Dislocations within each grain of the Maraging steel blade material have activation energies that can be activated by thermal fluctuations and cause grain slippage, which results in integrated creep strain over time. The initial number of available dislocations becomes depleted as time progresses, and the number of dislocations available to be activated at any subsequent time is reduced. The creep strain rate is assumed proportional to the Boltzmann probability function and to the number of dislocations available at any given time to participate.

Boltzmann's constant1.38*10^-23, J/K	$k_B := 1.38\cdot 10^{-23}$
Dislocation activation energy, J	E_a
Temperature of blade, deg C	T
vertical deflection of blade under load, m	L_v
maximum vertical creep, m	y_m
maximum vertical creep strain, m/m	$\varepsilon_m := \frac{y_m}{L_v}$
based on the DeSalvo-SURF data	$\varepsilon_m = 0.004$
probability of dislocation activation	$f_{Boltz}(T) := \exp\left[\frac{-E_a}{k_B\cdot(T+273)}\right]$
time interval of applied load, day	t
activation rate constant, day^-1	a
initial number of available dislocations per unit vertical deflection of blade	n_0

3.1 Dislocation Function

activation rate of dislocations

$$\frac{dn}{dt} = -a \cdot n \cdot f_{Boltz}(T)$$

$$\int \frac{1}{n}\, dn = \int -a \cdot f_{Boltz}(T)\, dt$$

$$\ln\left(\frac{n(t)}{n_0}\right) = -a \cdot f_{Boltz}(T) \cdot t$$

number of available dislocations per unit vertical deflection of blade after interval t

$$n(t, T) = n_0 \cdot \exp\left(-a \cdot f_{Boltz}(T) \cdot t\right)$$

3.2 Creep Function

vertical deflection of blade per dislocation event, m δ_y

integrated vertical creep of blade after time t, m

$$y(t, T) = L_v \cdot \left(n_0 - n(t)\right) \cdot \delta_y$$

maximum vertical creep, m $y_m := L_v \cdot n_0 \cdot \delta_y$

Then, integrated vertical creep of blade after time t, m

$$y\left(t, T, E_a, a, y_m\right) := y_m \cdot \left[1 - \exp\left[-a \cdot \exp\left[\frac{-E_a}{k_B} \cdot \left[\frac{1}{(T + 273)}\right]\right] \cdot t\right]\right]$$

initial creep rate, m/day

$$\sigma_0\left(T, E_a, a, y_m\right) := y_m \cdot a \cdot \exp\left[\frac{-E_a}{k_B} \cdot \left[\frac{1}{(T + 273)}\right]\right]$$

4 Analysis of Data

The theoretical formula for creep will be fit to the experimental data by choosing the best values of the parameters E_a, a, and y_m, using a least sum of squares regression method, to match the theoretical formula with the experimental data.

4.1 DeSalvo-SURF Data (Ref: LIGO P070095-02-Z)

initial blade deflection under load, m $L_{vsurf} := 0.33($

maximum stress, Pa $S_{wms} := 680 \cdot 10^6$

SURF Creep data

$T := 6($ $t := 41$ $y(41, 60) = 0.26 \cdot 10^{-3}$

$T := 9($ $t := 2($ $y(20, 90) = 0.56 \cdot 10^{-3}$

$T := 15($ $t := 1($ $y(19, 150) = 1.17 \cdot 10^{-3}$

$T := 17($ $t := 27$ $y(27, 170) = 1.33 \cdot 10^{-3}$

$T := 19($ $t := 14$ $y(14, 190) = 1.51 \cdot 10^{-3}$

4.1.1 Creep vs Time, DeSalvo-SURF

A least squares fit of activation energy, activation rate, and maximum creep to the SURF creep data was performed by minimizing the difference between the experimental data and the theoretical expression for creep at each data point.

Creep theory, m

$$y(t, T, E_a, a, y_m) := y_m \cdot \left[1 - \exp\left[-a \cdot \exp\left[\frac{-E_a}{k_B} \cdot \left[\frac{1}{(T + 273)} \right] \right] \cdot t \right] \right]$$

difference between data and theory at each data point

$$\Delta_0(E_a, a, y_m) := y_{data_0} - y(41, 60, E_a, a, y_m)$$

$$\Delta_1(E_a, a, y_m) := y_{data_1} - y(20, 90, E_a, a, y_m)$$

$$\Delta_2(E_a, a, y_m) := y_{data_2} - y(19, 150, E_a, a, y_m)$$

$$\Delta_3(E_a, a, y_m) := y_{data_3} - y(27, 170, E_a, a, y_m)$$

$$\Delta_4(E_a, a, y_m) := y_{data_4} - y(14, 190, E_a, a, y_m)$$

Least sum of squares optimization:

$$\left[\left(\Delta_0(E_a, a, y_m)\right)^2 + \left(\Delta_1(E_a, a, y_m)\right)^2 + \left(\Delta_2(E_a, a, y_m)\right)^2 + \left(\Delta_3(E_a, a, y_m)\right)^2 + \left(\Delta_4(E_a, a, y_m)\right)^2\right]^{0.5} = 2.04298 \times 10^{-4}$$

The optimized parameter values are shown below.

activation energy, J	$E_{asurfy} = 6.20628 \times 10^{-20}$
activation energy, eV	$E_{asurfy\_ev} = 0.38789$
activation rate constant, day^-1	$a_{surfy} = 4.73629 \times 10^{3}$
maximum creep, m	$y_{msurfy} = 1.41003 \times 10^{-3}$
maximum vertical creep strain, m/m	$\varepsilon_{msurfy} = 4.19651 \times 10^{-3}$

The activation energy of 6.2E-20 J = 0.39 eV is in reasonable agreement with the value of 2.0 +/- 1.0 EV determined by DeSalvo-SURF, and by the statement in M. Beccaria *et al* that the activation energy is of the order of eV. The asymptotic creep value y_m = 1.4 mm, which is a creep strain of

4.2E-3 m/m. The daily activation rate, a = 4736, is a new parameter that is not mentioned in either of the two reference papers.

A time evolution plot of the theoretical creep values for various temperatures, using the optimized parameters, is shown in Figure 2.

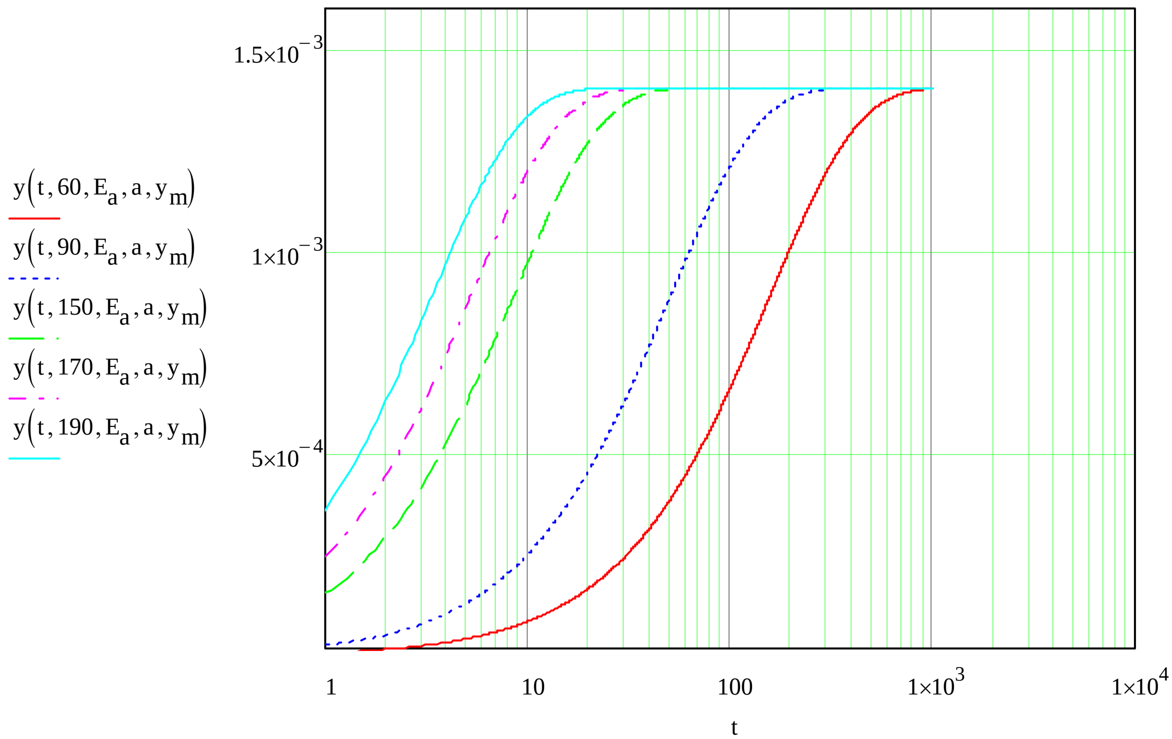

Figure 2: Fit of Theoretical Creep vs Time to DeSalvo-SURF Data

4.1.2 Creep vs Temperature, DeSalvo-SURF

The measured creep data is compared with the theoretically calculated values over the temperature range in Figure 3.

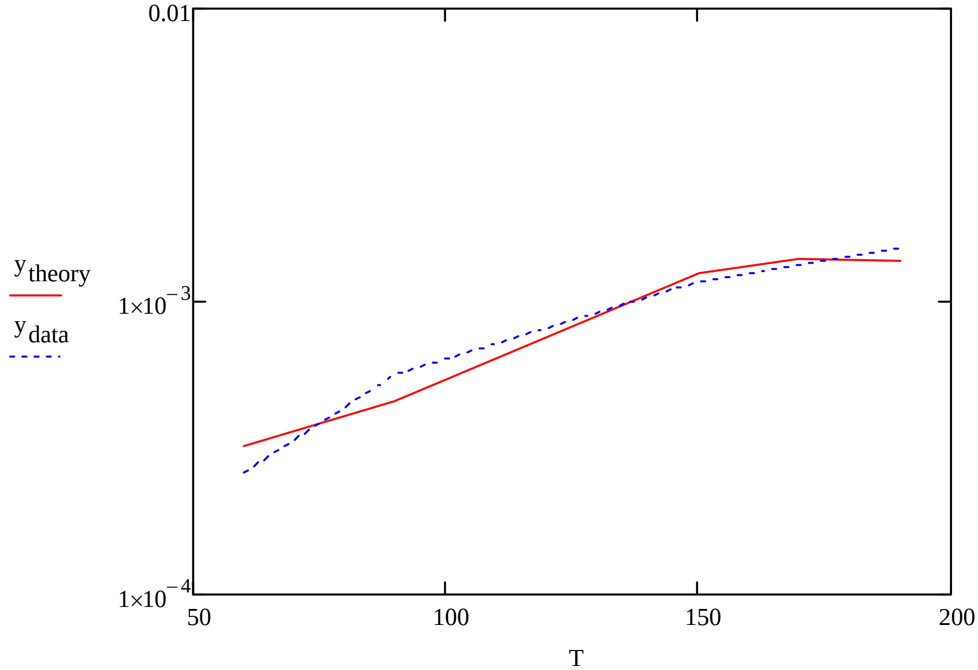

Figure 3: Comparison of Measured Creep with Theory versus Temperature, DeSalvo-SURF Data

4.2 VIRGO Data

initial deflection of blade under load, m $L_{vvirgo} := 0.1$

maximum stress, N/mm^2 $S_{Nmm2} := 125($

maximum stress, Pa $S_{wms} := S_{Nmm2} 10^6$

$S_{wms} = 1.25\times 10^9$

4.2.1 Creep vs Time, VIRGO

A least squares fit of activation energy, activation rate, and maximum creep to the VIRGO creep data was performed by minimizing the difference between the experimental data and the theoretical expression for creep at each data point.

VIRGO Creep data

$T := 35$ $t := 12.5$ $y(12.5, 35) = 90 \cdot 10^{-6}$

$T := 50$ $t := 12.5$ $y(12.5, 50) = 180 \cdot 10^{-6}$

$T := 65$ $t := 12.5$ $y(12.5, 65) = 210 \cdot 10^{-6}$

$T := 80$ $t := 12.5$ $y(12.5, 80) = 190 \cdot 10^{-6}$

Creep theory, m

$$y(t, T, E_a, a, y_m) := y_m \cdot \left[1 - \exp\left[-a \cdot \exp\left[\frac{-E_a}{k_B} \cdot \left[\frac{1}{(T + 273)}\right]\right] \cdot t\right]\right]$$

difference between data and theory at each data point

$$\Delta_0(E_a, a, y_m) := 90 \cdot 10^{-6} - y(12.5, 35, E_a, a, y_m)$$

$$\Delta_1(E_a, a, y_m) := 180 \cdot 10^{-6} - y(12.5, 50, E_a, a, y_m)$$

$$\Delta_2(E_a, a, y_m) := 210 \cdot 10^{-6} - y(12.5, 65, E_a, a, y_m)$$

$$\Delta_3(E_a, a, y_m) := 190 \cdot 10^{-6} - y(12.5, 80, E_a, a, y_m)$$

Least sum of squares optimization:

$$\left[\left(\Delta_0(E_a, a, y_m)\right)^2 + \left(\Delta_1(E_a, a, y_m)\right)^2 + \left(\Delta_2(E_a, a, y_m)\right)^2 + \left(\Delta_3(E_a, a, y_m)\right)^2\right]^{0.5} = 3.2955 \times 10^{-5}$$

The fit to the data is accurate to approximately +/-16E-6 m.

The optimized parameter values are shown below.

activation energy, J	$E_{avirgoy} = 6.78326\times 10^{-20}$
activation energy, eV	$E_{avirgoy\_ev} = 0.42395$
activation rate constant, day^-1	$a_{virgoy} = 5.09497\times 10^{5}$
maximum creep, m	$y_{mvirgoy} = 2.06456\times 10^{-4}$
maximum vertical creep strain, m/m	$\varepsilon_{mvirgoy} = 2.06456\times 10^{-3}$

The activation energy of 6.8E-20 J = 0.42 eV is in reasonable agreement with the statement in M. Beccaria *et al* that the activation energy is of the order of eV. The asymptotic creep value y_m = 0.2 mm, which is a creep strain of 2.1E-3 m/m.

theoretical creep vs time, m/day

$$y(t,T,E_a,a) := y_m\cdot\left[1-\exp\left[-a\cdot\exp\left[\frac{-E_a}{k_B}\cdot\left[\frac{1}{(T+273)}\right]\right]\cdot t\right]\right]$$

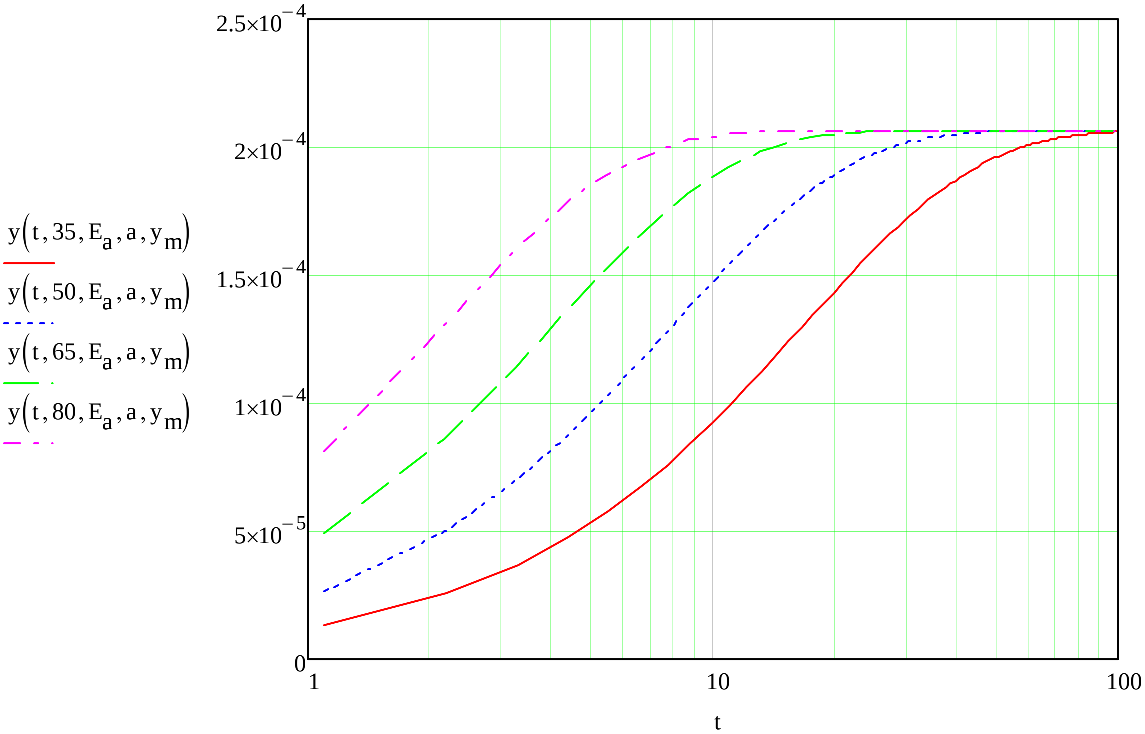

Figure 4: Theoretical Creep vs Time, fit to VIRGO Data

4.2.2 Creep vs Temperature, VIRGO

The measured creep data is compared with the theoretically calculated values over the temperature range in Figure 5.

.

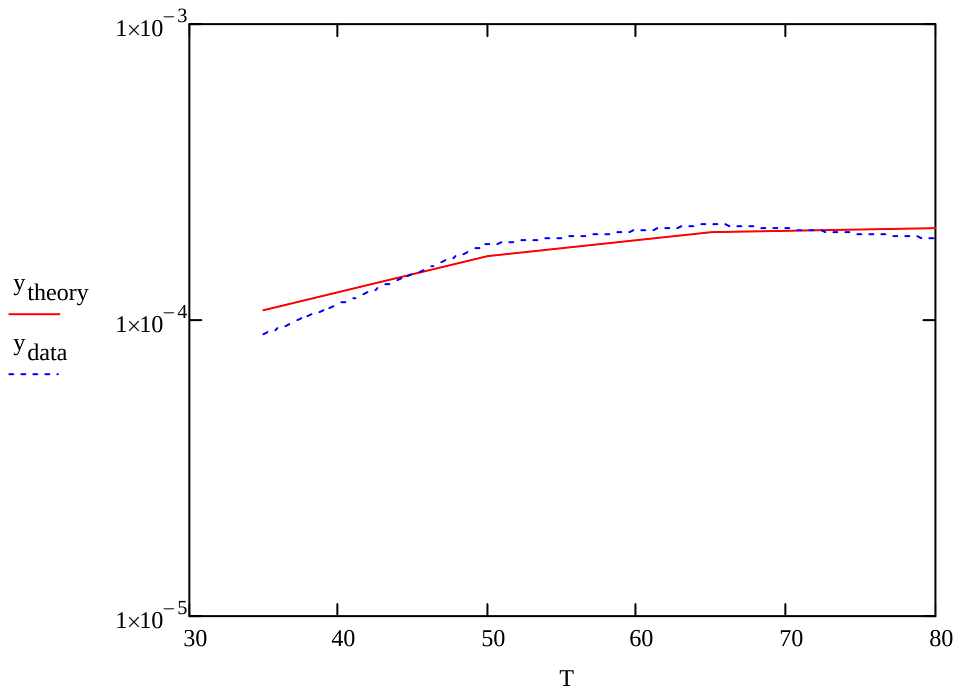

Figure 5: Comparison of Measured Creep with Theoretical Values, VIRGO Data

4.2.3 Initial Creep Rate vs Temperature

The initial creep rate for each temperature was determined from the initial slopes of the VIRGO graphs of creep vs time. A least squares fit to this data was used to determine the optimum values for the activation energy and the activation rate constant; the maximum creep parameter, $y_{m,}$ was previously determined in sec 4.2.1.

VIRGO Initial Creep Rate data

$T := 35$ $\sigma_{0.35} := \frac{200 \cdot 24 \cdot 10^{-6}}{255}$ $\sigma_{0.35} = 1.88235 \times 10^{-5}$

$T := 50$ $\sigma_{0.50} := \frac{200 \cdot 24 \cdot 10^{-6}}{70}$ $\sigma_{0.50} = 6.85714 \times 10^{-5}$

$T := 65$ $\sigma_{0.65} := \frac{200 \cdot 24 \cdot 10^{-6}}{60}$ $\sigma_{0.65} = 8 \times 10^{-5}$

$T := 80$ $\sigma_{0.80} := \frac{200 \cdot 24 \cdot 10^{-6}}{40}$ $\sigma_{0.80} = 1.2 \times 10^{-4}$

maximum creep, m

$y_m := y_{mvirgoy}$

$y_m = 2.06456 \times 10^{-4}$

theoretical initial creep rate, m/day

$$\sigma_0(T, E_a, a, y_m) := y_m \cdot a \cdot \exp\left[\frac{-E_a}{k_B} \cdot \left[\frac{1}{(T + 273)}\right]\right]$$

difference between data and theory at each data point

$$\Delta_0(E_a, a, y_m) := \sigma_{0.data_0} - \sigma_0(35, E_a, a, y_m)$$

$$\Delta_1(E_a, a, y_m) := \sigma_{0.data_1} - \sigma_0(50, E_a, a, y_m)$$

$$\Delta_2(E_a, a, y_m) := \sigma_{0.data_2} - \sigma_0(65, E_a, a, y_m)$$

Least sum of squares optimization:

$$\left[\left(\Delta_0(E_a, a, y_m)\right)^2 + \left(\Delta_1(E_a, a, y_m)\right)^2 + \left(\Delta_2(E_a, a, y_m)\right)^2 + \left(\Delta_3(E_a, a, y_m)\right)^2\right]^{0.5} = 2.6421 \times 10^{-5}$$

The fit to the data is accurate to approximately +/-13E-6 m.

activation energy, J $E_{avirgo\sigma} = 4.75926\times 10^{-20}$

activation energy, eV $E_{avirgo\sigma\_ev} = 0.29745$

activation rate constant, day^-1 $a_{virgo\sigma} = 1.11096\times 10^{4}$

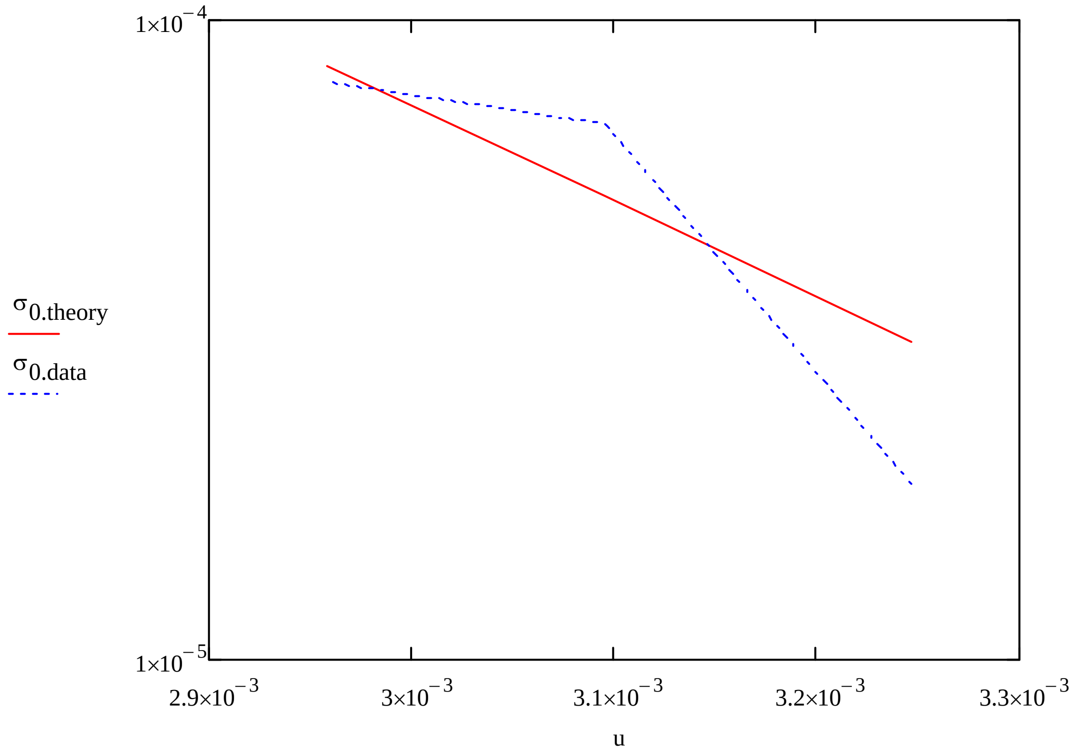

Figure 6: Theoretical Initial Creep Rate vs Inverse Temperature, fit to VIRGO Data

4.3 Summary of Creep Data

Table 1: Summary of Theoretical Creep Parameters

Parameter Name	DeSalvo-SURF	VIRGO, creep	VIRGO, creep rate
activation energy, J	6.2E-20	6.7E-20	4.8E-20
activation energy, eV	0.39	0.42	0.30
activation rate constant, day^-1	4.7E3	5.1E5	1.1E4
maximum vertical creep strain, m/m	4.2E-3	2.1E-3	2.1E-3

5 Creep Ageing

It is known that future blade creep can be reduced significantly by baking the blade under load at an elevated temperature for duration on the order of the creep relaxation time, which is the time in units of days for the creep value to achieve 1/e of its final asymptotic value.

Creep relaxation time, days

$$\tau_{creep}(T) := \frac{1}{\left[a \cdot \exp\left[\frac{-E_a}{k_B} \cdot \left[\frac{1}{(T + 273)}\right]\right]\right]}$$

E.g., with a creep aging temperature of 120 deg C, the blade should be baked under load for approximately 20 days, as shown in Figure 7.

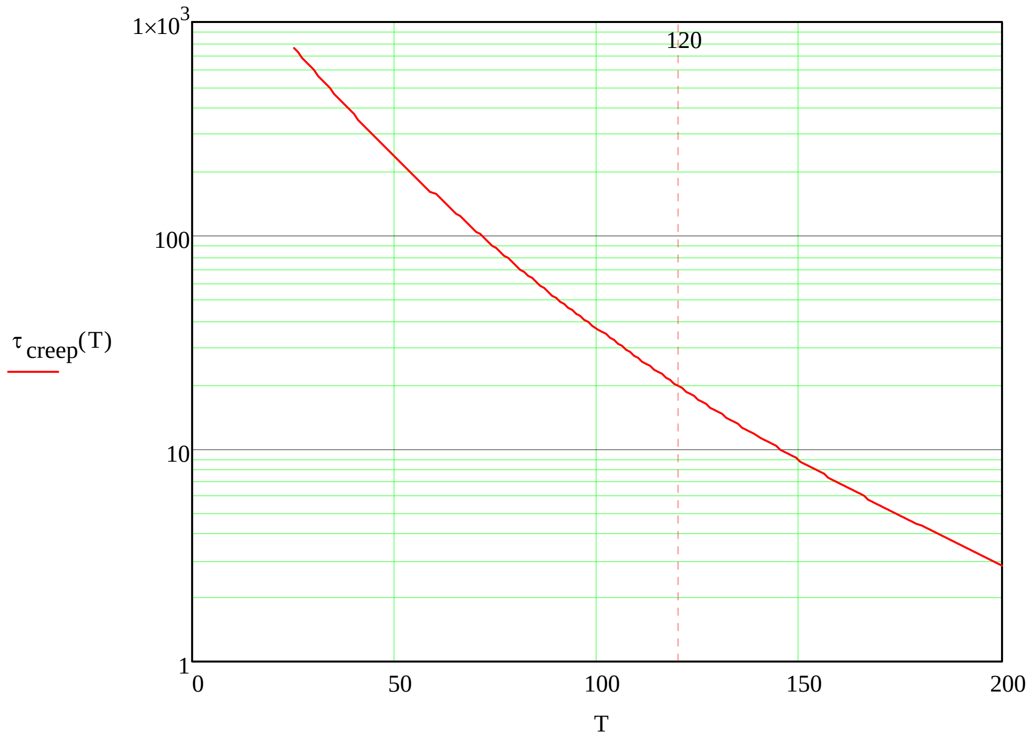

Figure 7: Theoretical Creep Relaxation Time vs Temperature, DeSalvo-SURF Data

6 Estimated SLC Blade Creep

6.1 OFI

The creep of the SLC OFI during a period of 10 yrs (3.65E3 days) will be estimated using the creep theory.

creep parameters based on VIRGO Data

maximum strain, m/m $\varepsilon_{mofi} := \varepsilon_{mvirgoy}$ $\varepsilon_{mofi} = 2.06456\times 10^{-3}$

maximum creep, m $y_m := Lvofi \cdot \varepsilon_{mofi}$ $y_m = 1.93057\times 10^{-4}$

activation energy, J $E_a := E_{avirgoy}$ $E_a = 6.78326\times 10^{-20}$

activation rate constant, day^-1 $a := a_{virgoy}$ $a = 5.09497\times 10^{5}$

theoretical creep vs time, m/day

use the VIRGO parameters

$$y(t,T,E_a,a,y_m) := y_m \cdot \left[1 - \exp\left[-a \cdot \exp\left[\frac{-E_a}{k_B} \cdot \left[\frac{1}{(T+273)}\right]\right] \cdot t\right]\right]$$

10 year time period, days $t := 10 \cdot 365$ $t = 3.65 \times 10^3$

maximum creep @ 27 deg C for 10 years, m $y(3.65 \times 10^3, 27, E_a, a, y_m) = 1.93057 \times 10^{-4}$

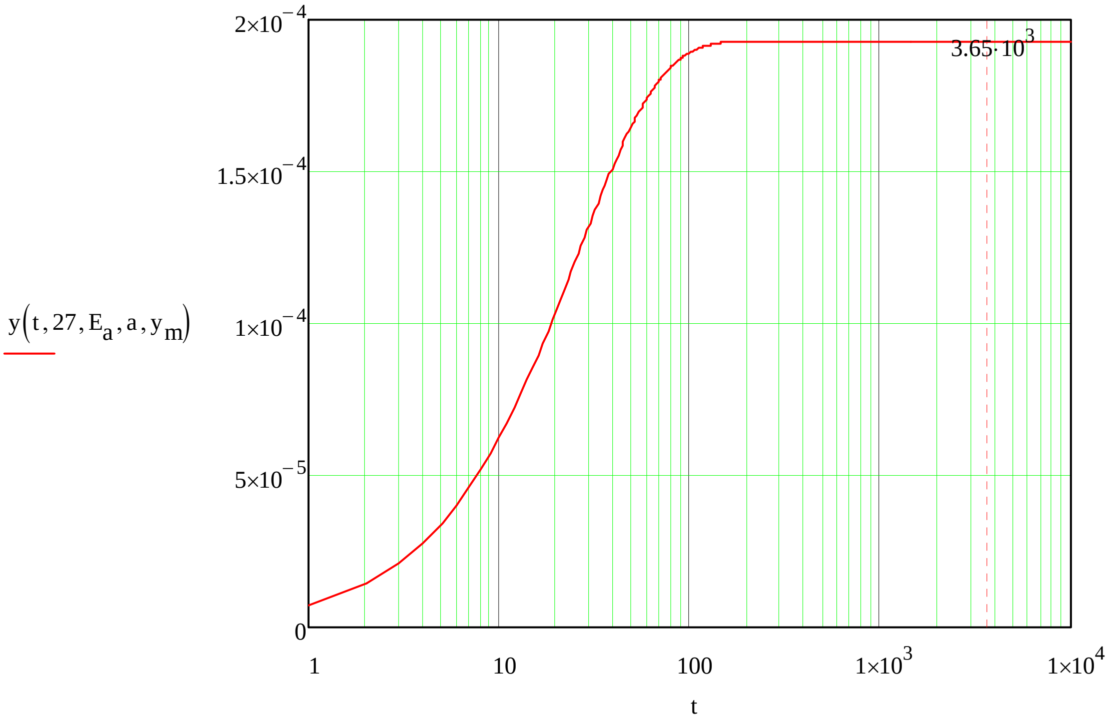

Figure 8: OFI Theoretical Creep vs Time, fit to VIRGO Data

With an assumed temperature of 27 deg C, the OFI blade will creep approximately the maximum amount, 0.2 mm. This will not cause a problem with the functioning of the OFI.

6.2 Arm Cavity Baffle, ITM Elliptical Baffle, and the Manifold/Cryo Baffle

The Arm Cavity Baffle, the ITM Elliptical Baffle, and the Manifold/Cryo Baffle all have initial blade deflections of approximately 0.1 m, and therefore will have approximately the same long-term creep shown above, 0.2 mm, which is acceptable.