Order of Meeting Handouts

A. Intro Kevlar Moot
B. SPIRE Kevlar Moot
C. Cooler Kevlar Moot
D. JPL over Kevlar Moot
E. JPL Tech Kevlar Moot
G. CEA Kevlar Moot
   Kevlar Cords Characteristics

SPIRE Cooler/Kevlar Meeting

- Objectives
  - Assess all the testing on Kevlar and Kevlar suspended units in SPIRE and PACS
  - Come to a common understanding about the mechanisms leading to the changes found in the performance of Kevlar from warm to cold
  - Assess the qualification status of the SPIRE and PACS coolers
  - Agree on 0.29/0.5 mm Kevlar for evaporator or a process to decide
  - Assess the qualification status of the SPIRE (and PACS?) detector suspension
  - Assess the qualification status of the SPIRE (and PACS?) 300 mK strap support units

Agenda

- 09:30 - Introduction selection board members
- 09:45 - SPIRE thermal model results
- 10:00 - SPIRE/PACS cooler programme
- 10:45 - Q+A with Lionel
- 11:00 - SPIRE BDA programme.
- 11:45 - Q+A with Gary
- 12:30 – Lunch
- 13:30 – SPIRE 300 mK bar support
- 14:15 - Q+A with Pete
- 14:30 - PACS detector support programme
- 15:00 - Q+A with Louis/Jerome
- 15:30 - Summary
- 16:30 - Board meets
- 17:30(ish) - Report from board and identification of immediate actions

SPIRE 300-mK
System Considerations

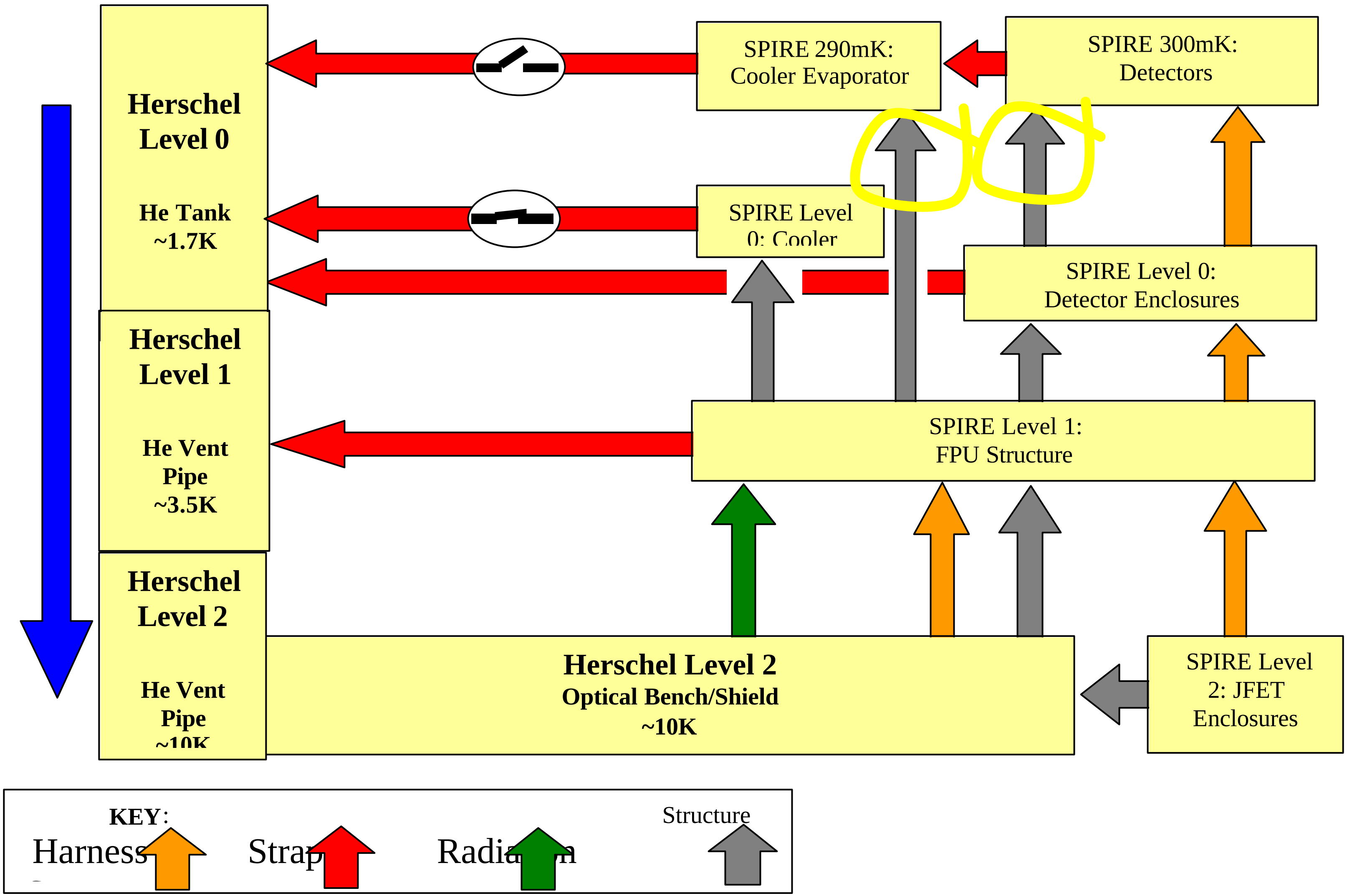
Douglas Griffin

RAL
Space Science and Technology Department

Ø0.29 vs. Ø0.5 Cooler Evaporator Kevlar Trade-off

- Thermal
  - Watershed => 48 hour Cooler hold time
  - Hold time proportional to total cooler load (Parasitics + Cooling power)
  - Analysis indicates negative margin on Cooler hold time
  - Big science impact of not meeting 46hour requirement
- Structural / Reliability
  - Single point failure mode
- Other things being equal – there should be a parity of risk across different S/Ss

Thermal Heat flow ladder



300-mK Heat loads

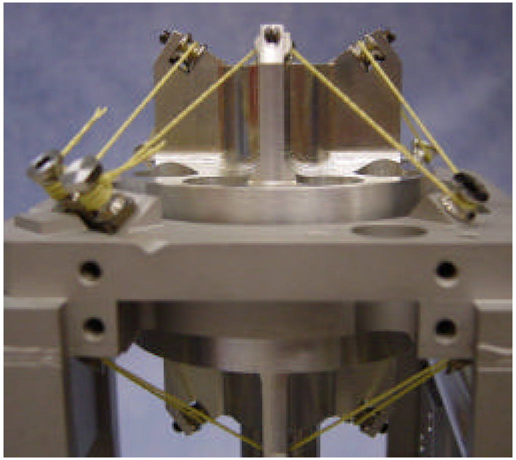
Cooler Load (mW)		Comments
photo detectors	16.47	
spectro detectors	5.76	
Level1 Parasitic	7.21	Kevlar support ? =0.5mm
Shunt	7.24	
Evap HS	2.98	Heat Leak through Heat switch via radiation and Conduction
total	**39.66**	
hold	**32.7**	**Hrs** *(assuming Tevap = 2.4K at end of condensation phase)*

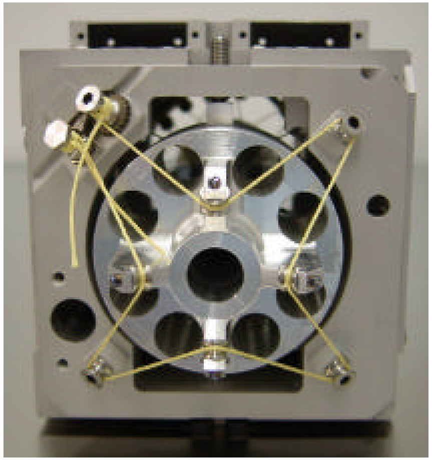
Structural considerations

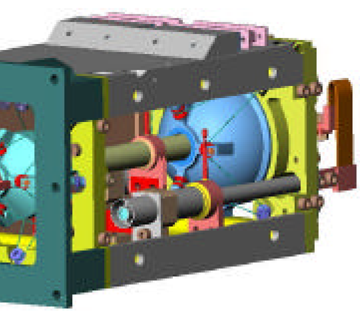
- Cooler has survived cryogenic qualification vibration loads
- The qualification vibration load levels have been set by applying margin (≈50%) to the levels predicted by Instrument FEA
- These levels will be verified in the next several weeks by test.

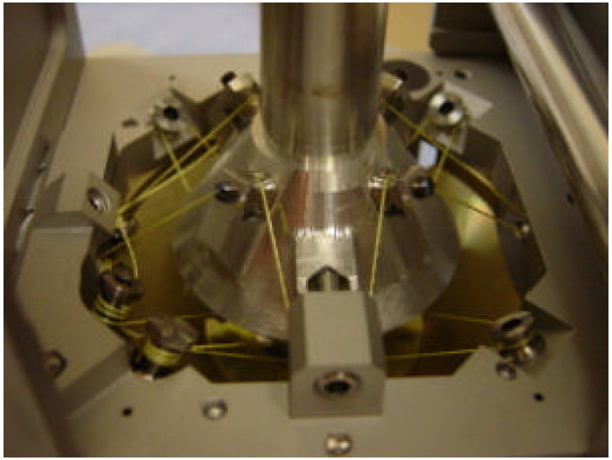
BDA details

KEVLAR SUSPENSION SYSTEM









L. Duband, L. Clerc, L. Guillemet, R. Vallco
N. Luchier, E. Ercolani
SERVICE DES BASSES TEMPERATURE
DRFMC / DSM - CEA GRENOBLE

WHY DO WE USE KEVLAR ?

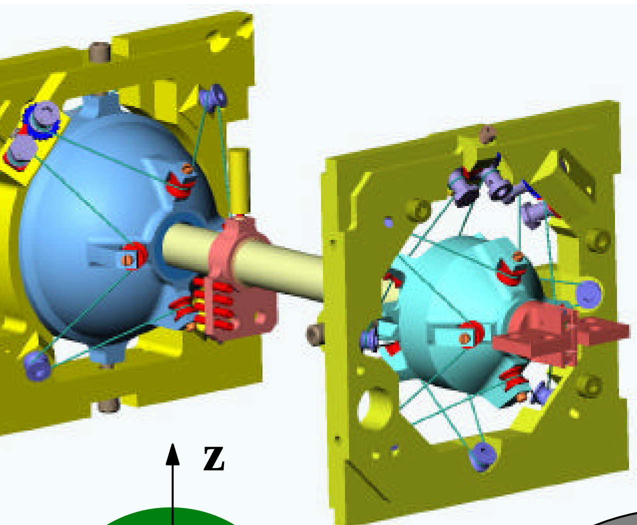
	Nylon	S. Steel	Ta6V	Kevlar 29
σ (MPa)	100	550	875	**1600**
Y (MPa)	3000	200 000	110 000	65 000
$I = \int_{0.3}^{2} k\,dT$				
$\sigma Y^{0.5} / I$	$0.9\ 10^{8}$	$1.2\ 10^{8}$	$2.9\ 10^{8}$	**$58\ 10^{8}$**

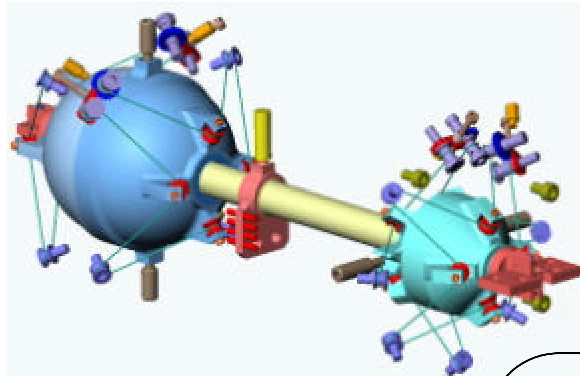
Keeping resonant frequencies the same

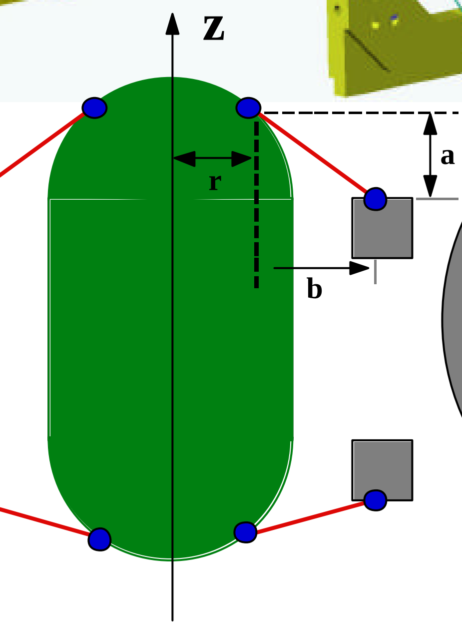
Titanium → load X 8.6 !

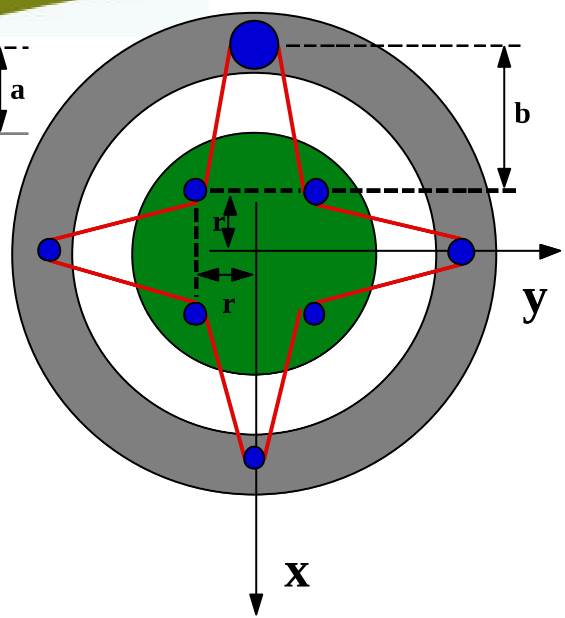
Nylon → load X 25.7

KEVLAR SUSPENSION SYSTEM









$$f_{x,y} = \frac{1}{2p}\sqrt{\frac{8AY(b^2+r^2)}{ml^3}}$$

$$f_z = \frac{1}{2p}\sqrt{\frac{16AYa^2}{ml^3}}$$

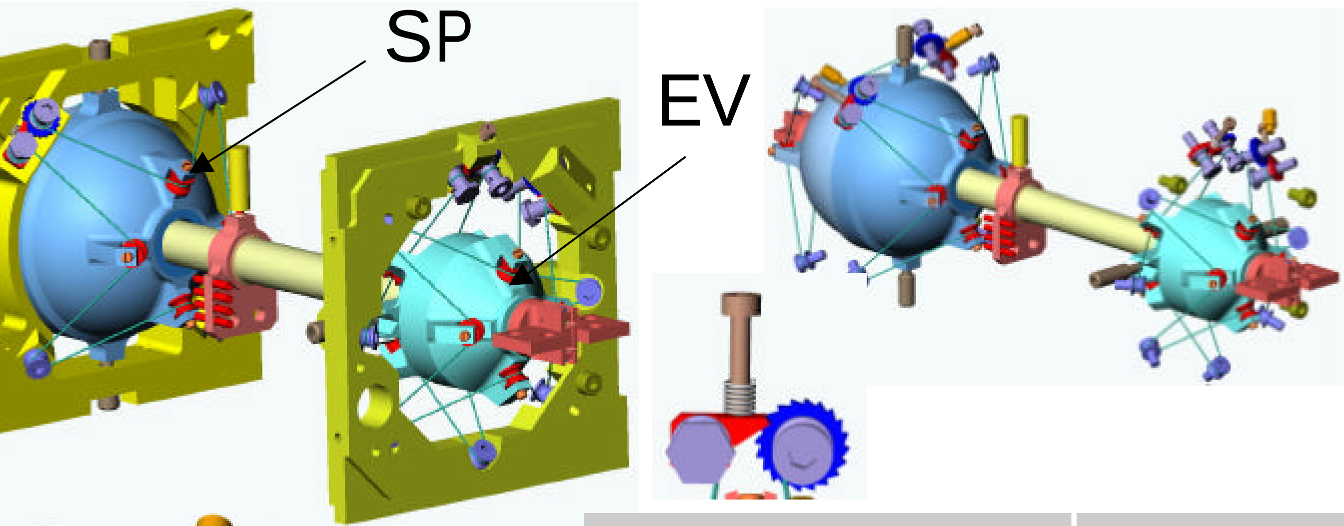
A : string cross section

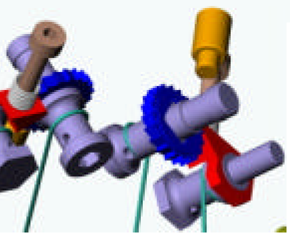
Y : Young 's modulus

M : suspended object mass

$l = (a^2+b^2+r^2)^{0.5}$

KEVLAR SUSPENSION SYSTEM





Nominal loading constraint:
EV & SP :
15 DaN / 760 MPa

(breaking strength 1600

Failure	Lowest frequency (Hz)	RMS constrai (MPa)
No defect	482	16.8
Broken cord on EV side	295.5	41
Broken cord on SP side	310.8	104
All cords on EV broken	119	198

(calculations performed at roo

alculations performed ing specification as of nid 2001 ~ 21 G rms ew spec. down to 14 G rms max.

Test report : HSO-SBT-TN 055
"SPIRE & PACS Sorption cooler Comportement dynamique"

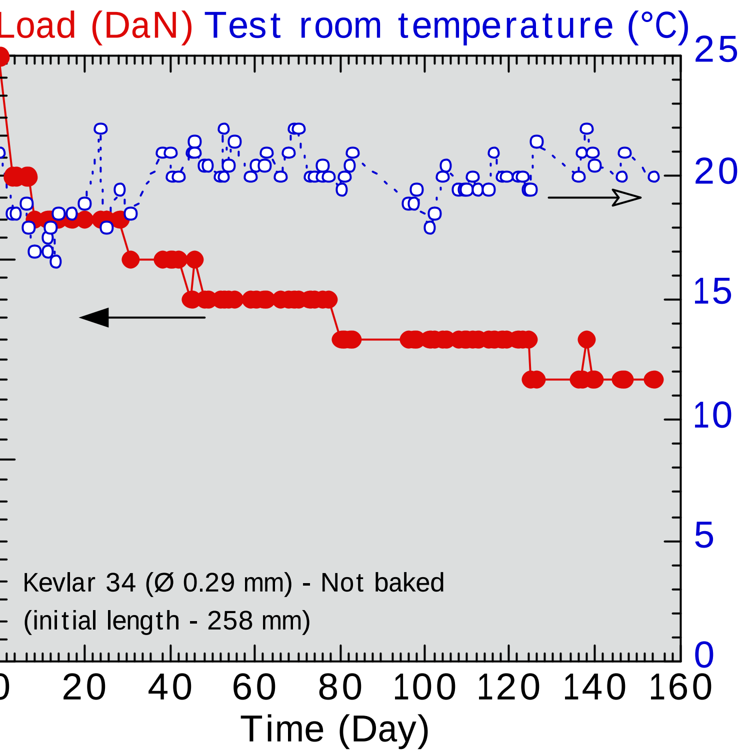
KEVLAR CHARACTERIZATION

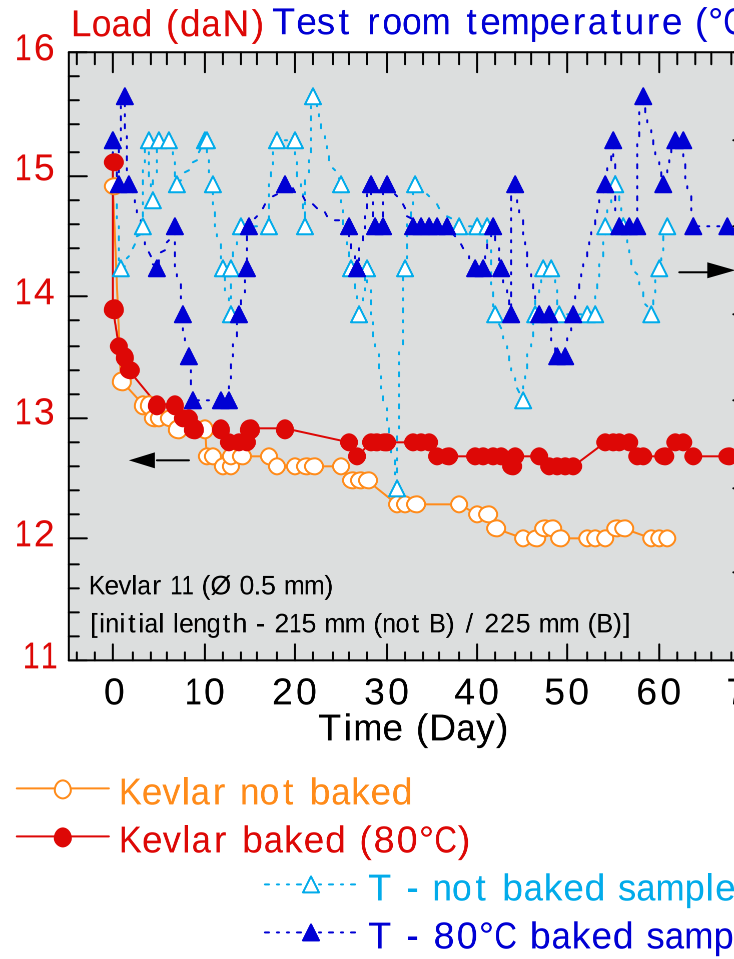
Tests performed	Status	Comments
Ultimate strength	Checked	Consistent with available data
Young's modulus – room T	Checked	Idem
Young's modulus – LN2	Checked	Idem
Influence of Ø pulley	Checked	Integrated in design
Influence of turns around pulley	Checked	Idem
Tensioning and locking technique	Available	Procedure established
Creep at room T	Checked	No problem foreseen
Influence of baking	Checked	No problem spotted so far
Fatigue behaviour – room T	Checked	On K34 – expected to be similar for K11
Low T cycling under tension	On going	Peculiar behaviour
Thermal conductivity	- checked	-
Moisture	On going	Definitely has an influence

Test report available : HSO-SBT-TN 046 Issue 1.2

"EXPERIMENTAL CHARACTERISATION OF KEVLAR 29 CO

KEVLAR - CREEP

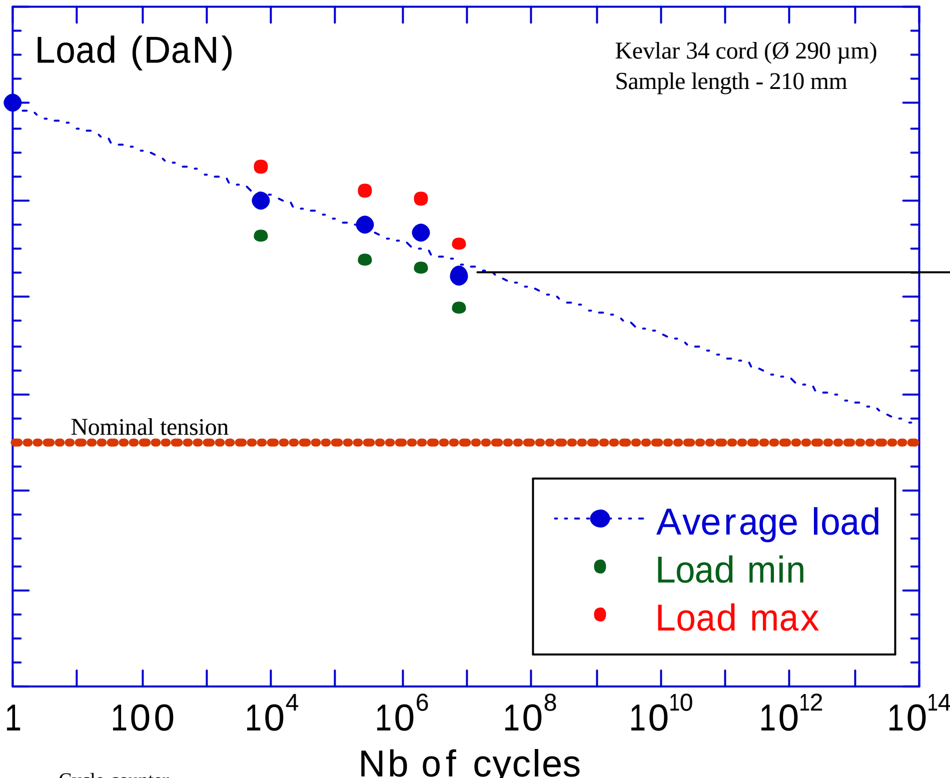




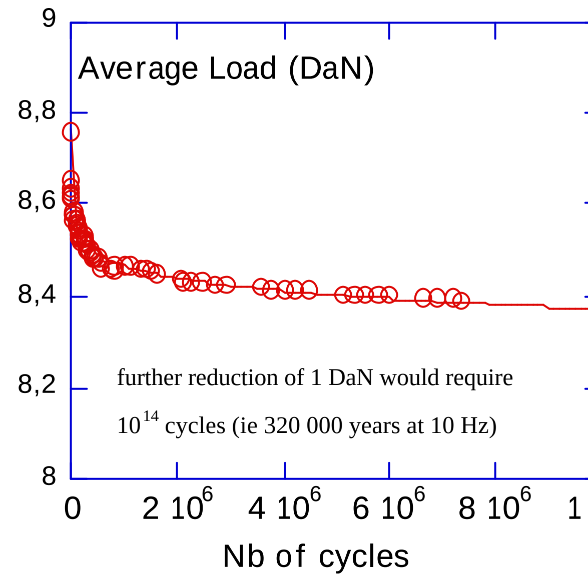
tension 10%

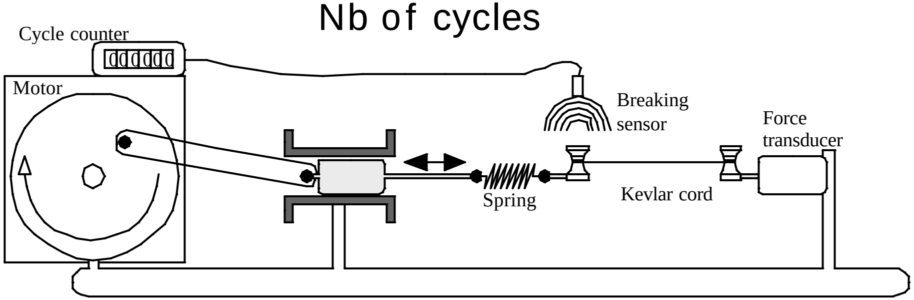
- ***4 years for Kev. 34***
- ***40 years for Kev. 11***

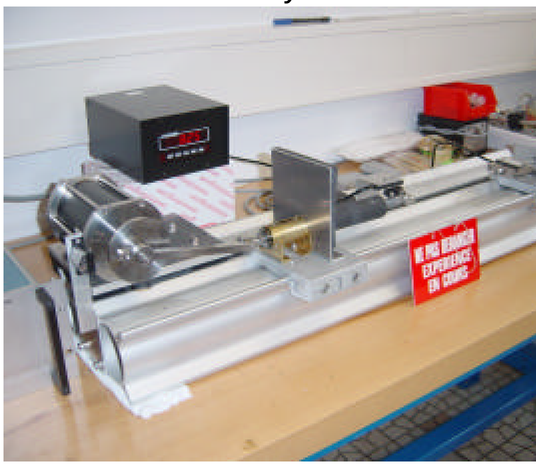
KEVLAR - FATIGUE (+ CREEP)



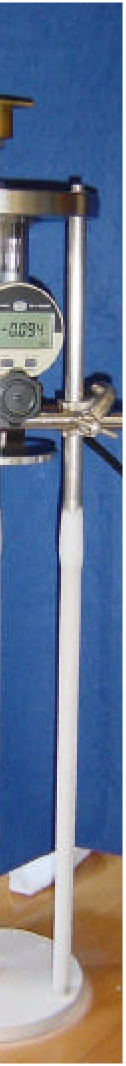
Broke after ˜ 3 months







YOUNG'S MODULUS



Already measured many times

...but experiment repeated with set-up made of Invar

Previous measurements

Sogan 1999

K34/RT : 68 to 85 GPa

K11/RT : 68 Gpa

Chenévier 2001

K34/RT : 66 GPa tensioning

K34/RT : 91 GPa detensionin

K34/LN2 : 110 GPa tensionin

K34/LN2 : 118 GPa detensioni

Neri 2002

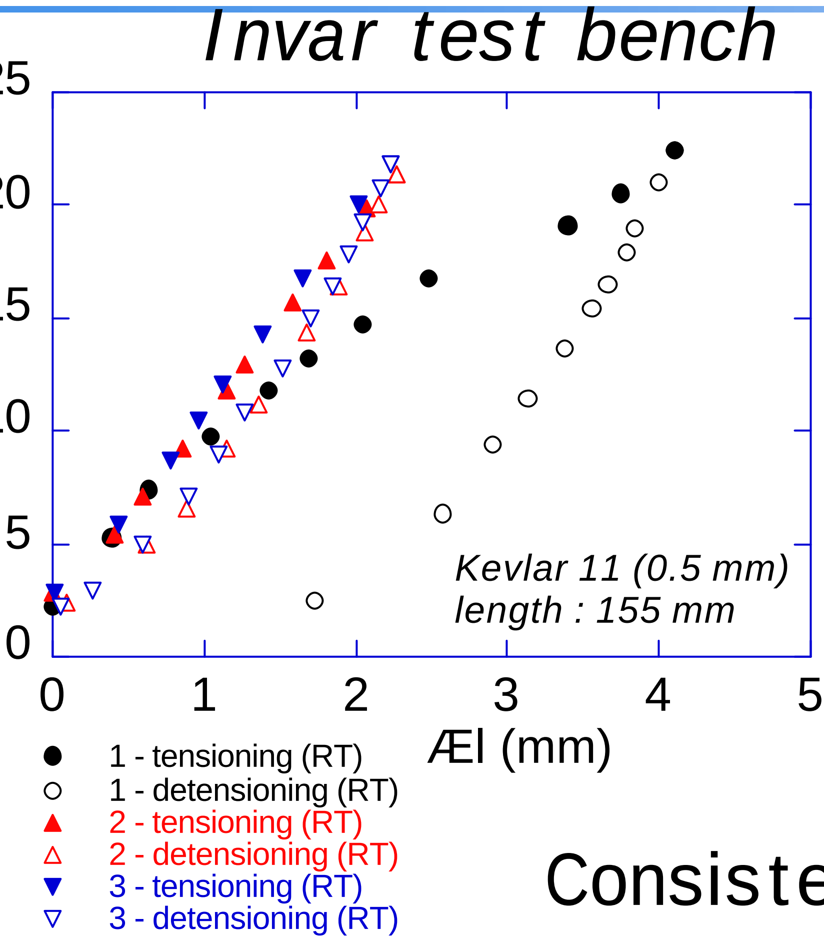
K11/RT : 82 GPa tensioning

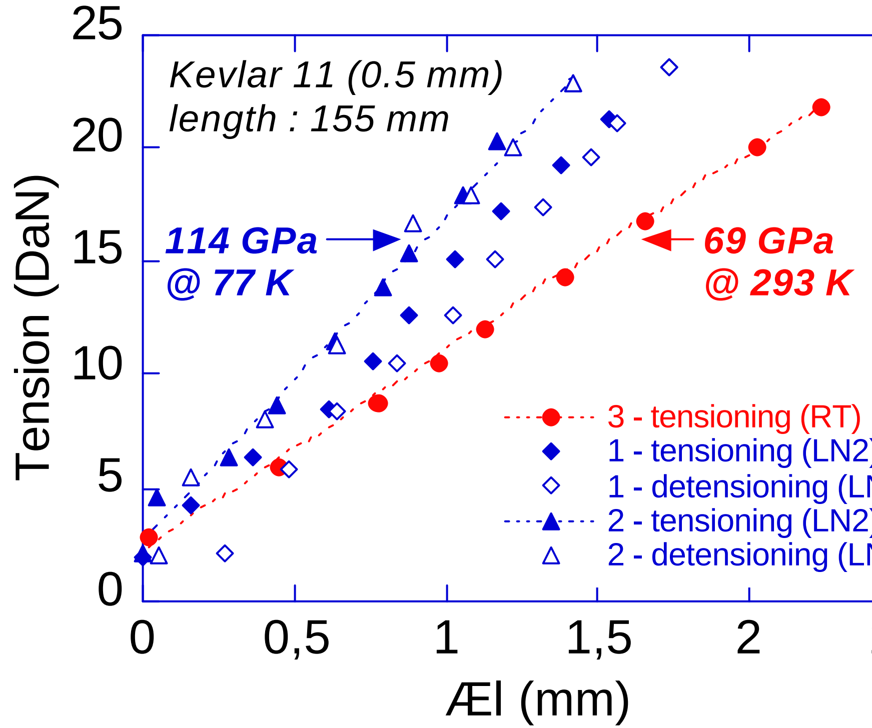
K11/LN2 : 122 GPa tensionin

K11/RT : 82 GPa after T cycli

K11/LN2 : 120 GPa after T cycl

YOUNG'S MODULUS - 300 K / 77 K





Consistent with previous measuremen

In static : this is the Young's modulu

300 K - 77 K CYCLING UNDER TENSION

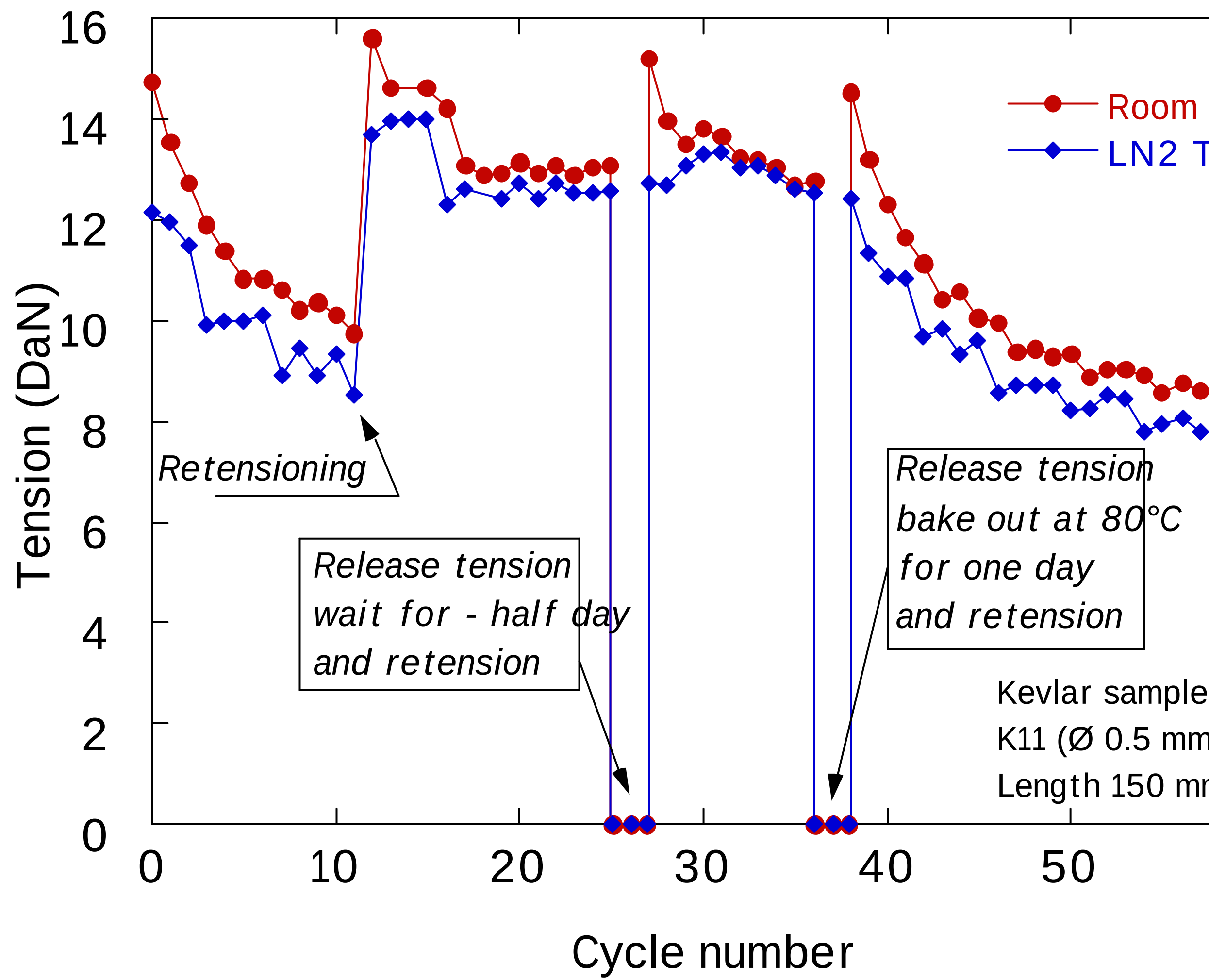
Reminder

culiar behaviour

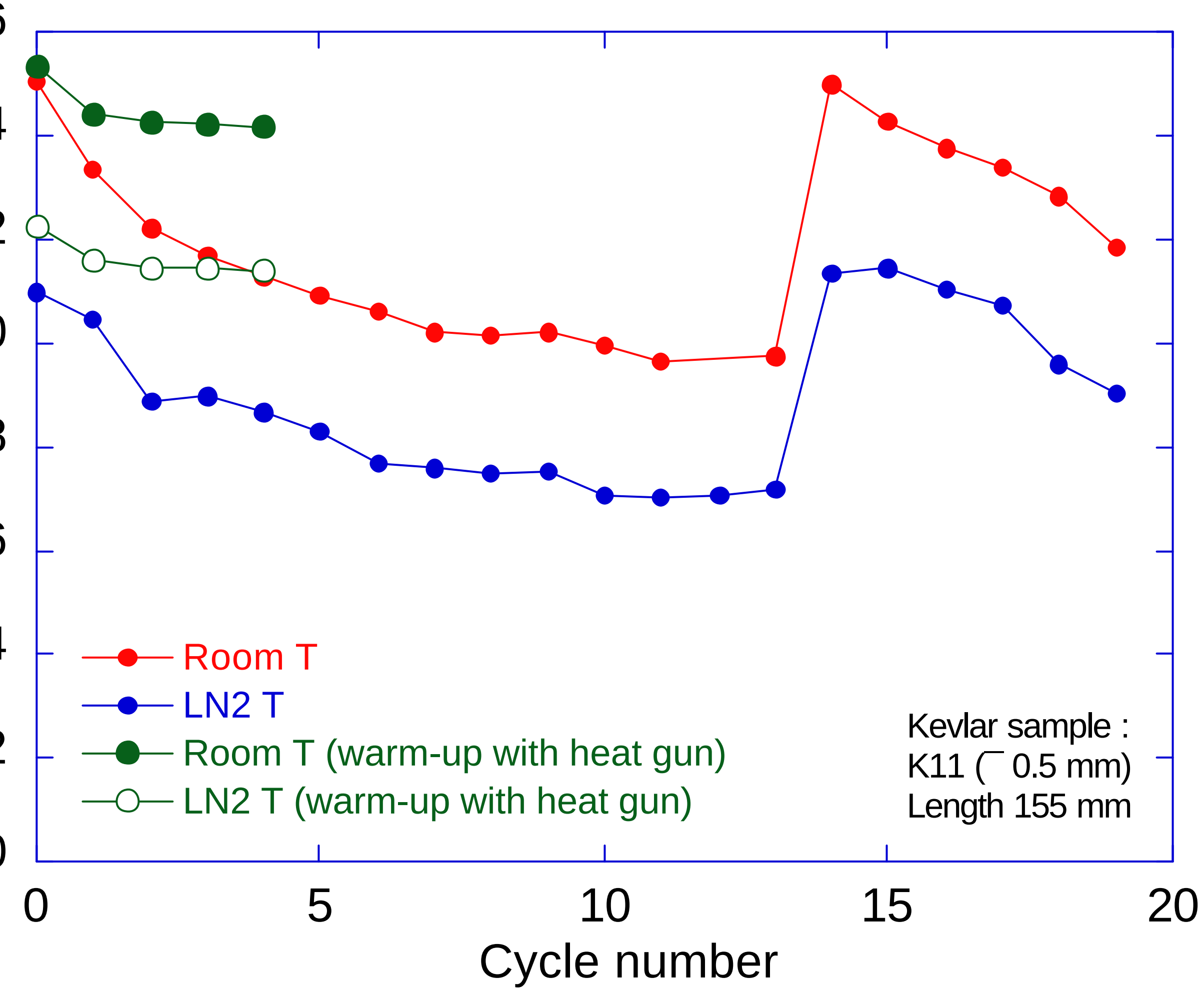
Experiment

epeated with

var test bench



300 K - 77 K CYCLING UNDER TENSION



Pretty much same
behaviour as befo

BUT

Moisture effect

var test bench

MOISTURE : EXAMPLE FOR NYLON (~ SAME FAMILY)

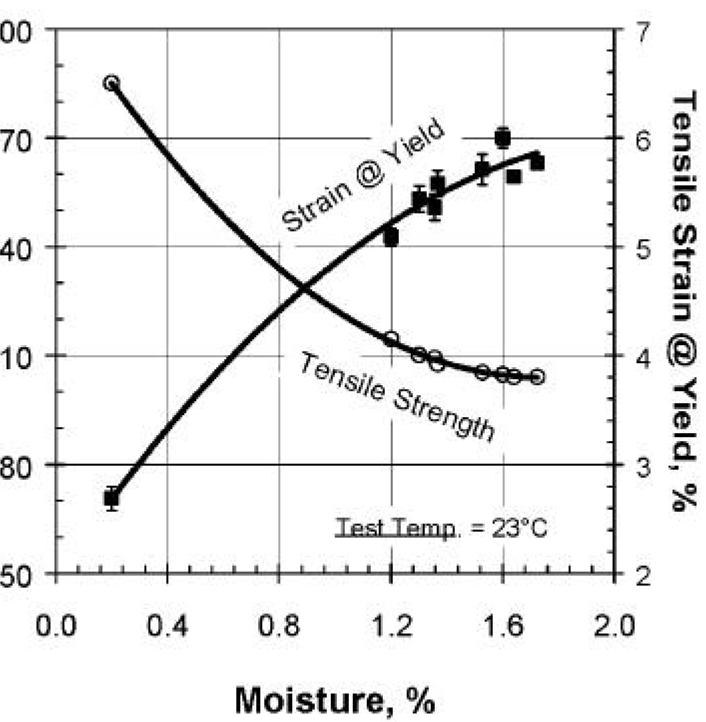


Figure 3. Effect of moisture on tensile properties of reinforced nylon 6 (33% glass fiber): tensile strength and strain at yield vs. moisture at room temperature.

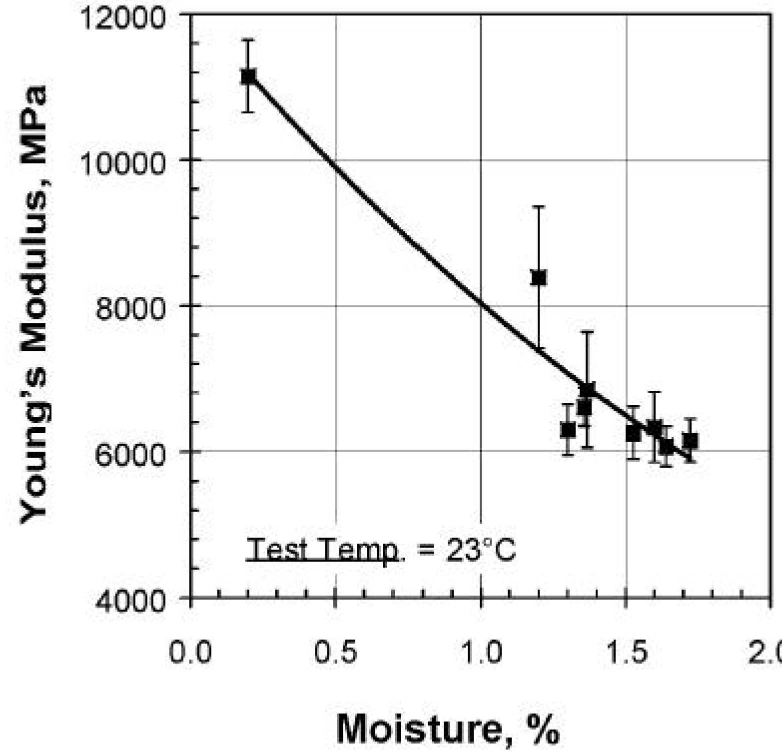
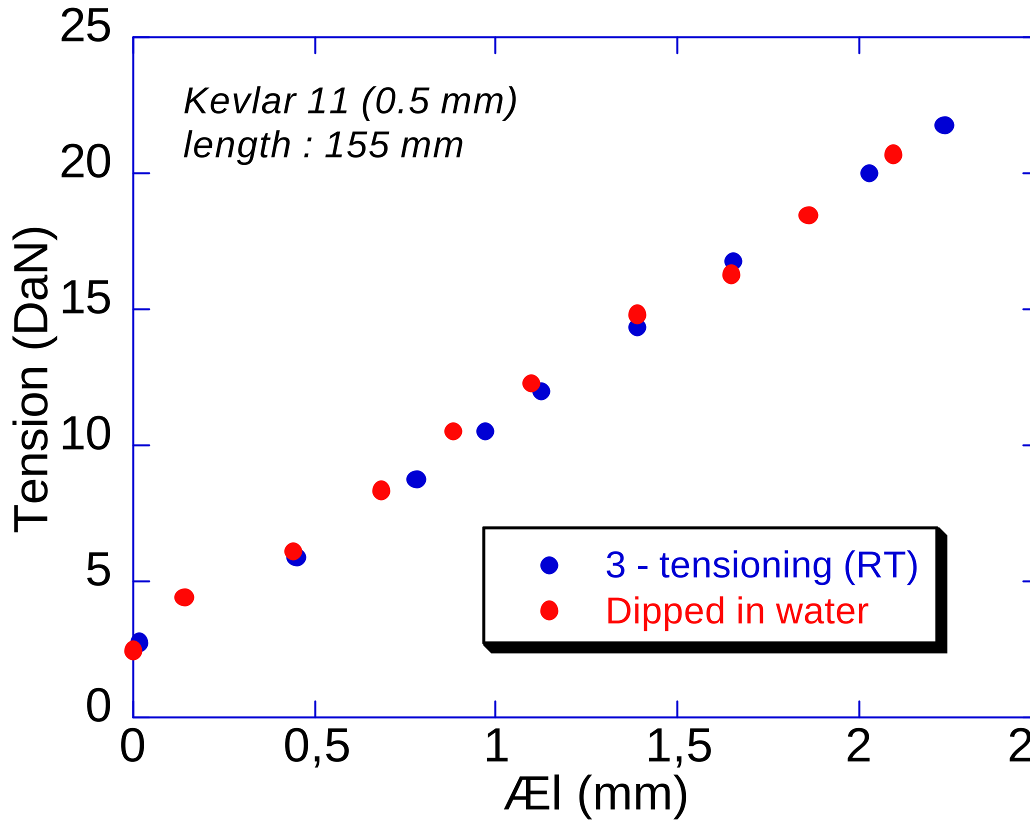


Figure 4. Effect of moisture on Young's modulus: 33% glass fiber reinforced nylon 6.

Could it be the same for Kevlar ??

YOUNG'S MODULUS AND H_2O

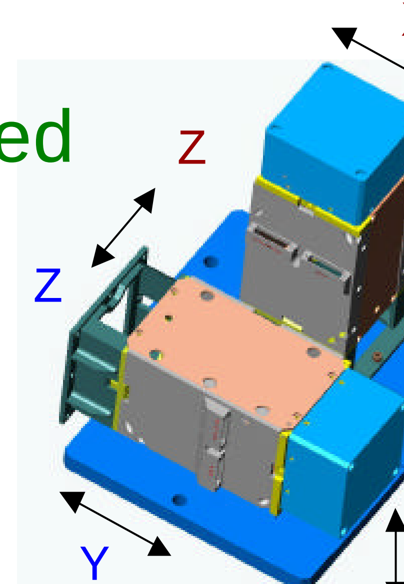


Liquid H_2O : no apparent impact on Young's modulus

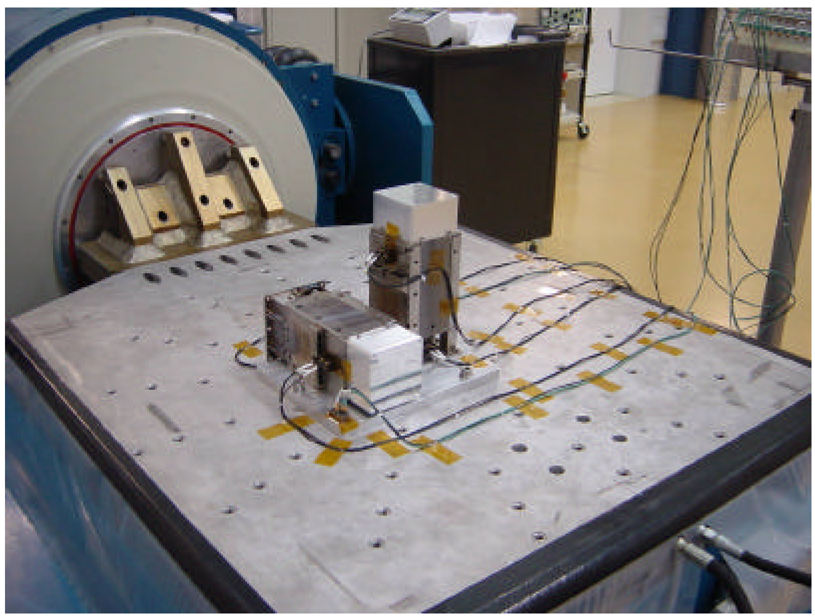
?

oth STMs vibration tested at CSL (BE)

sted simultaneously : highest level selected



Input spec.



Sinus [0 - 100 Hz]

X : **40 G**

Y, Z : 25 G

Random [0 - 2000

X : **14** G rms

Y : 11.3 G rms

Z : 9.9 G rms

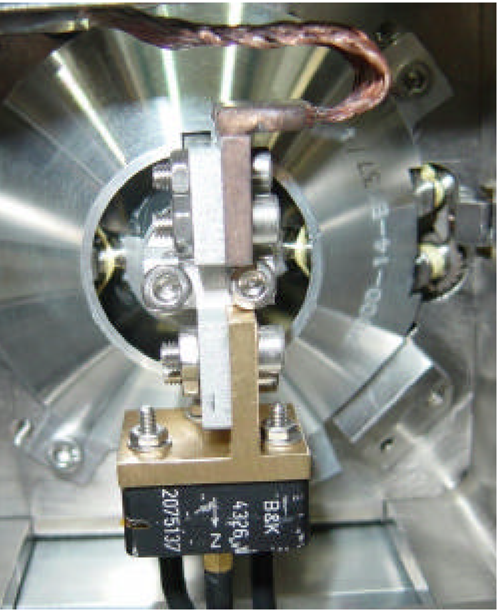
STM : ROOM T V TEST (CSL) - 2

To gain additional margin on the parasitics (therm

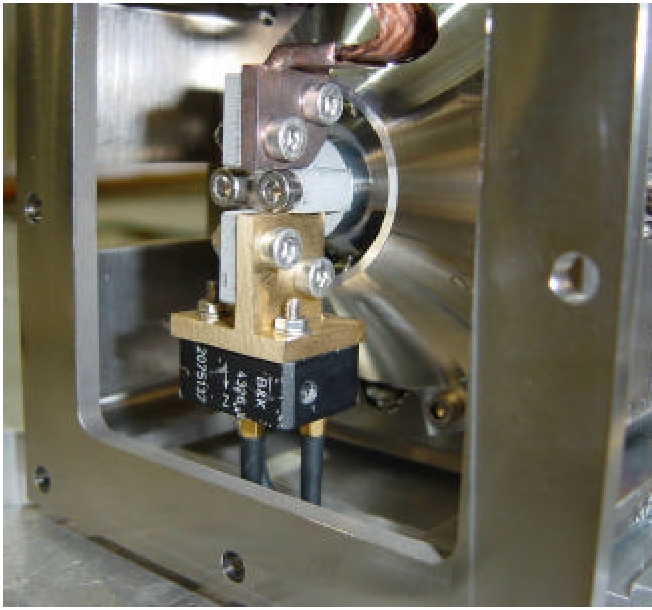
Use of Kevlar 34 : Ø 0.29 mm (instead of K11 Ø 0.5 mm)

Fully supported by mechanical analysis

Additional mass (30 grams), off centered



Supposedly representative of thermal bus



STM : ROOM T V TEST (CSL) RESULTS - 2

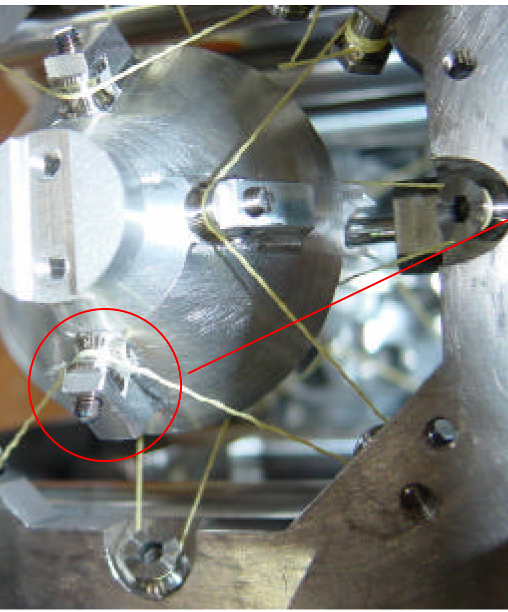
40 G sinus, X_{SPIRE}/Y_{PACS} : OK

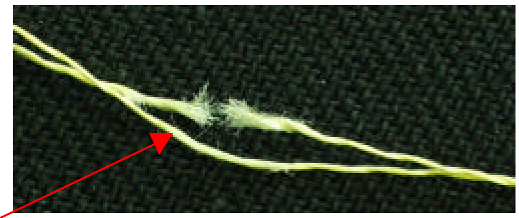
Sinus 0.5 G : frequency response slightly modified

14 G rms, X_{SPIRE}/Y_{PACS} : ~ OK but lateral motion of evaporator visible

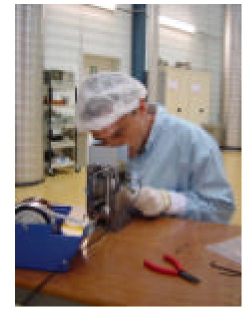
Note : lowest reso
frequency > 450 H

sual inspection : rupture of one "stitch"





Cord replaced :
same result again !



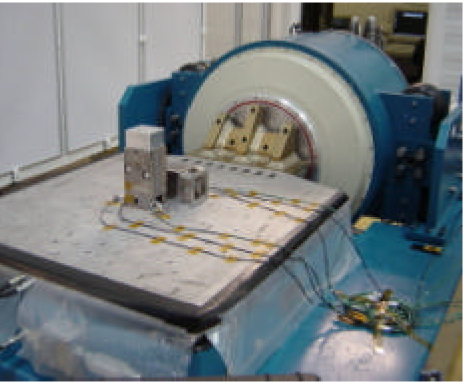
Analysis : high G level ⇒ Lateral motion ⇒ Rubbing & ruptur

Solution : ➡ Kevlar 34 Replaced by Kevlar 11 (Ø 0.29 mm to 0.5 mm)

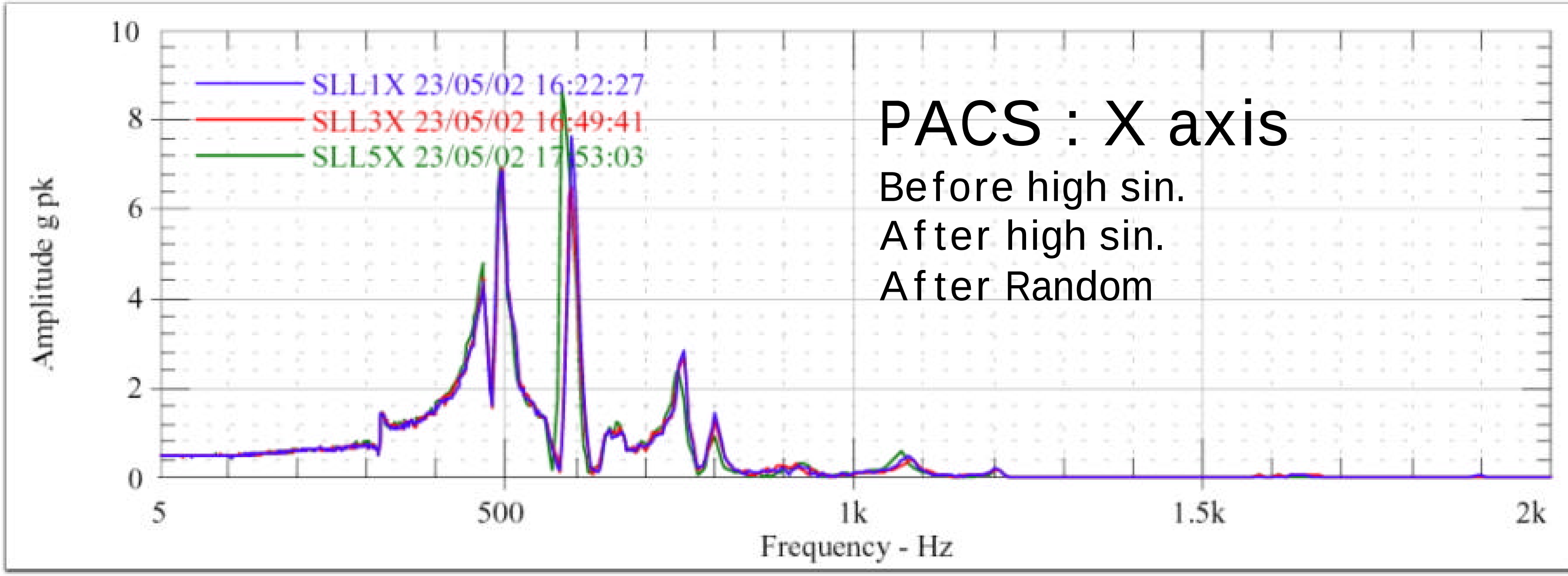
- Stronger
- easier to manipula
- Nominal tension x

Impact on cooler thermal performance : Yes but remain within spe

STM : ROOM T V TEST (CSL) RESULTS - 3



All susbsequent tests successfully passed with larger Kevlar cords



STM : COLD V TEST (RAL) - 1

Input spectrum

Random [0 - 2000 Hz]

20 - 200 Hz : + 3 dB

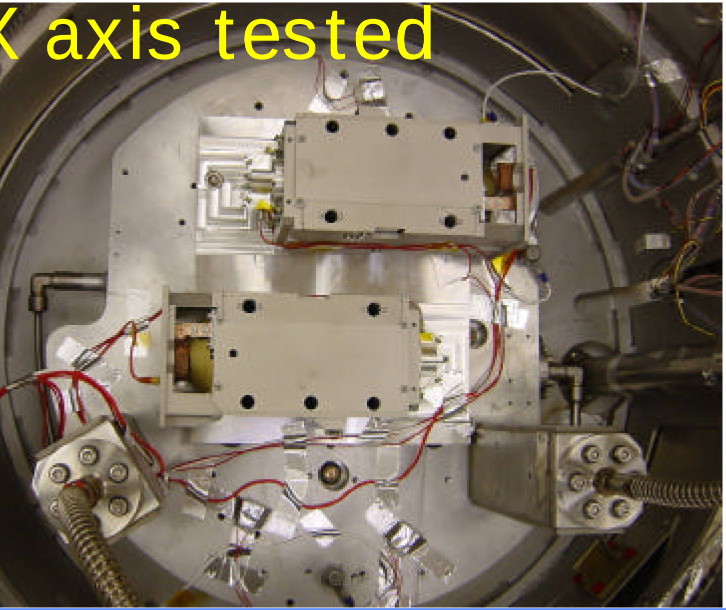
200 - 250 Hz : 0.28 g2/H

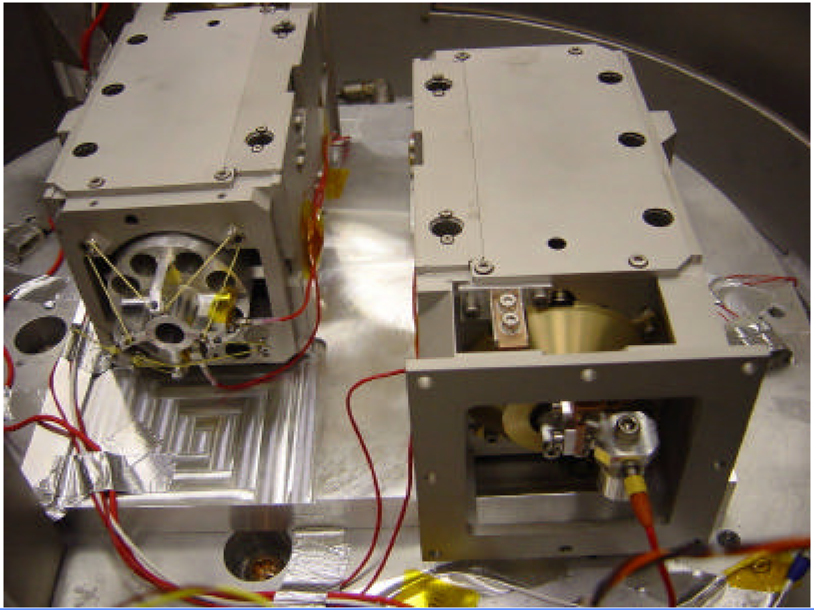
250 - 2000 Hz : - 12 dB

~ **8.06** G rms

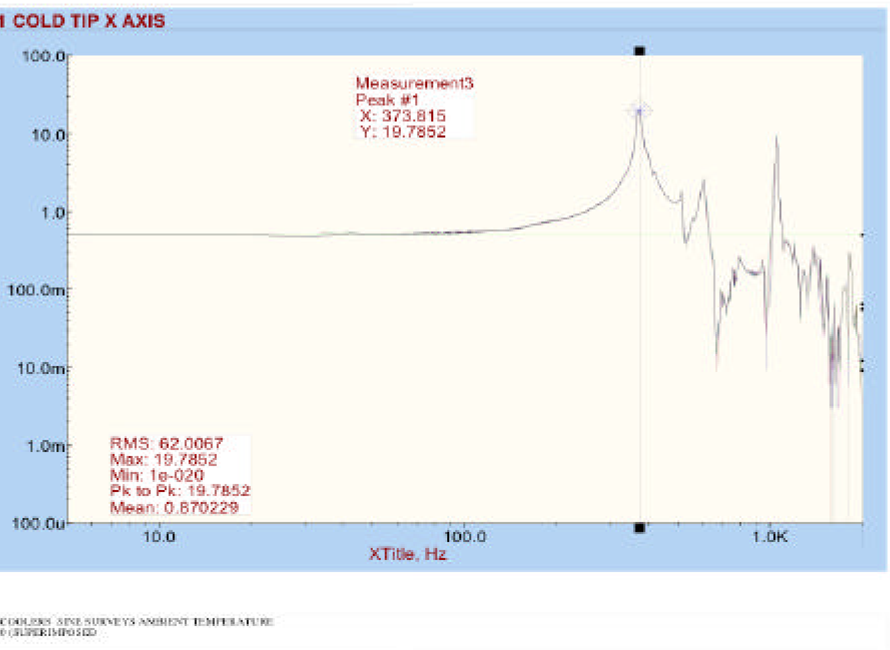
Sinus [0 - 100 Hz] : **30 G**

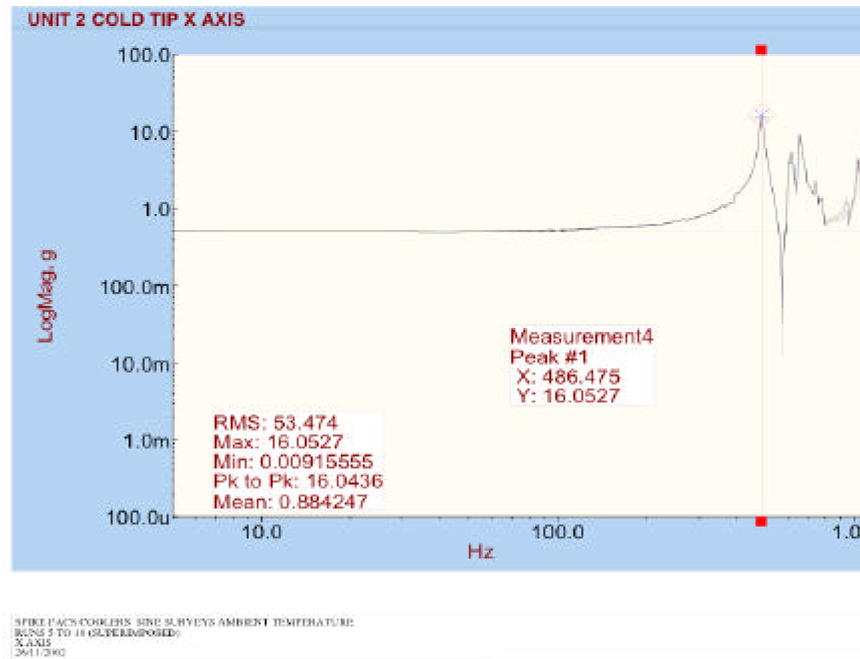
Both units mounted PACS like.





STM : COLD V TEST (RAL) - Room T results





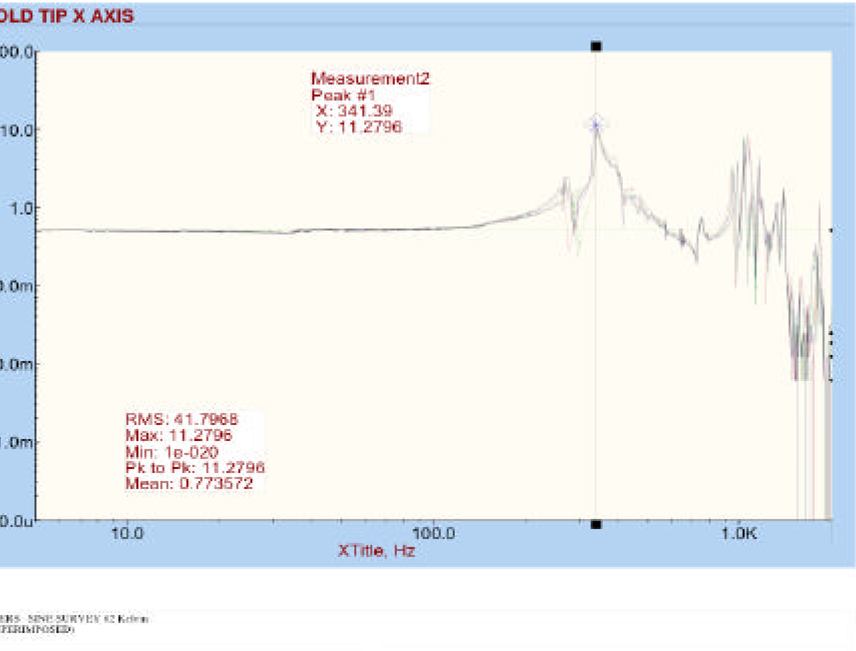
SPIRE STM (0.3/0.5)

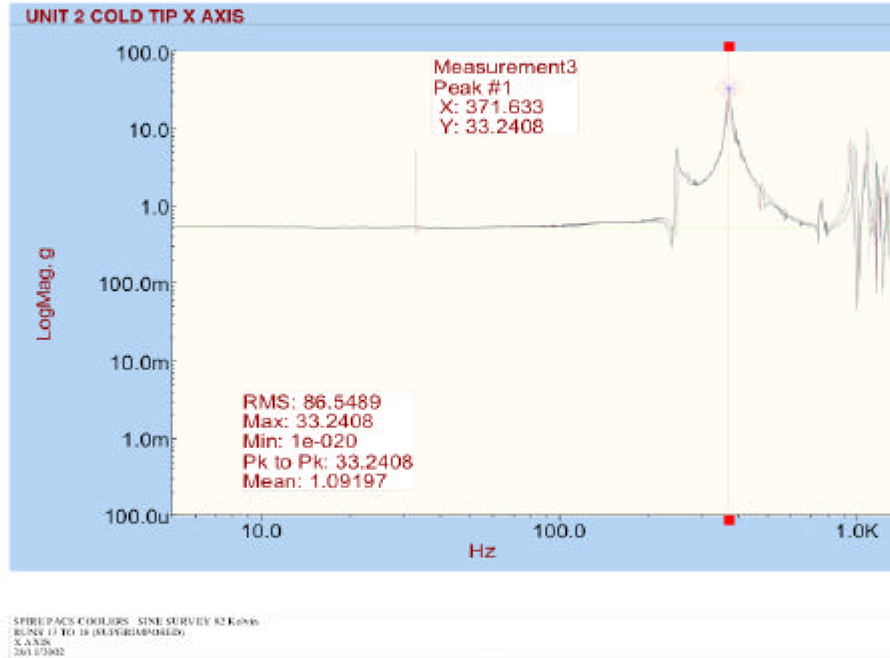
Room temperature

PACS STM (0.5/0.5)

Tests successfully passed

STM : COLD V TEST (RAL) - Low T results





SPIRE STM
(0.3/0.5)

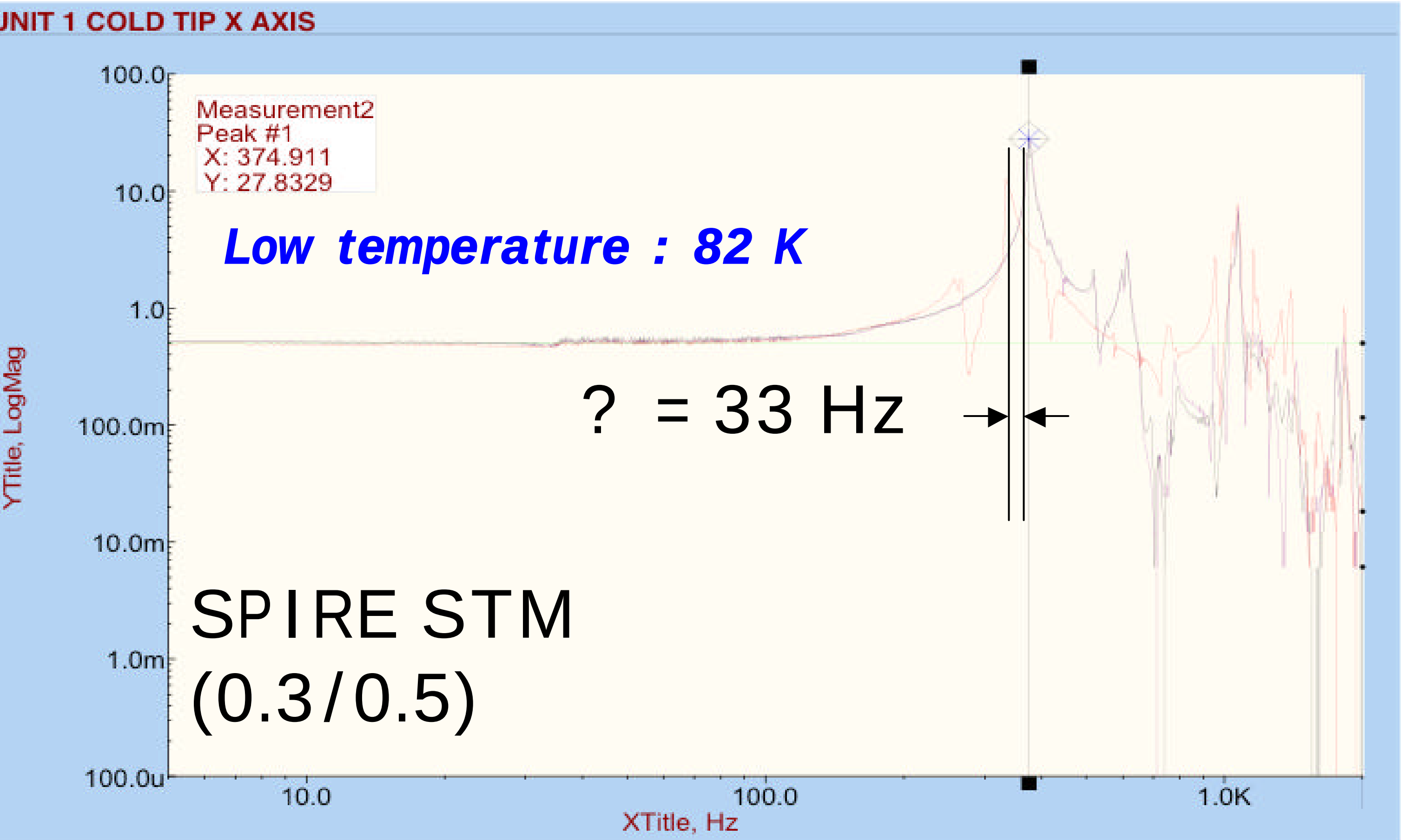
Low temperature : 82 K

PACS STM
(0.5/0.5)

Tests successfully passed

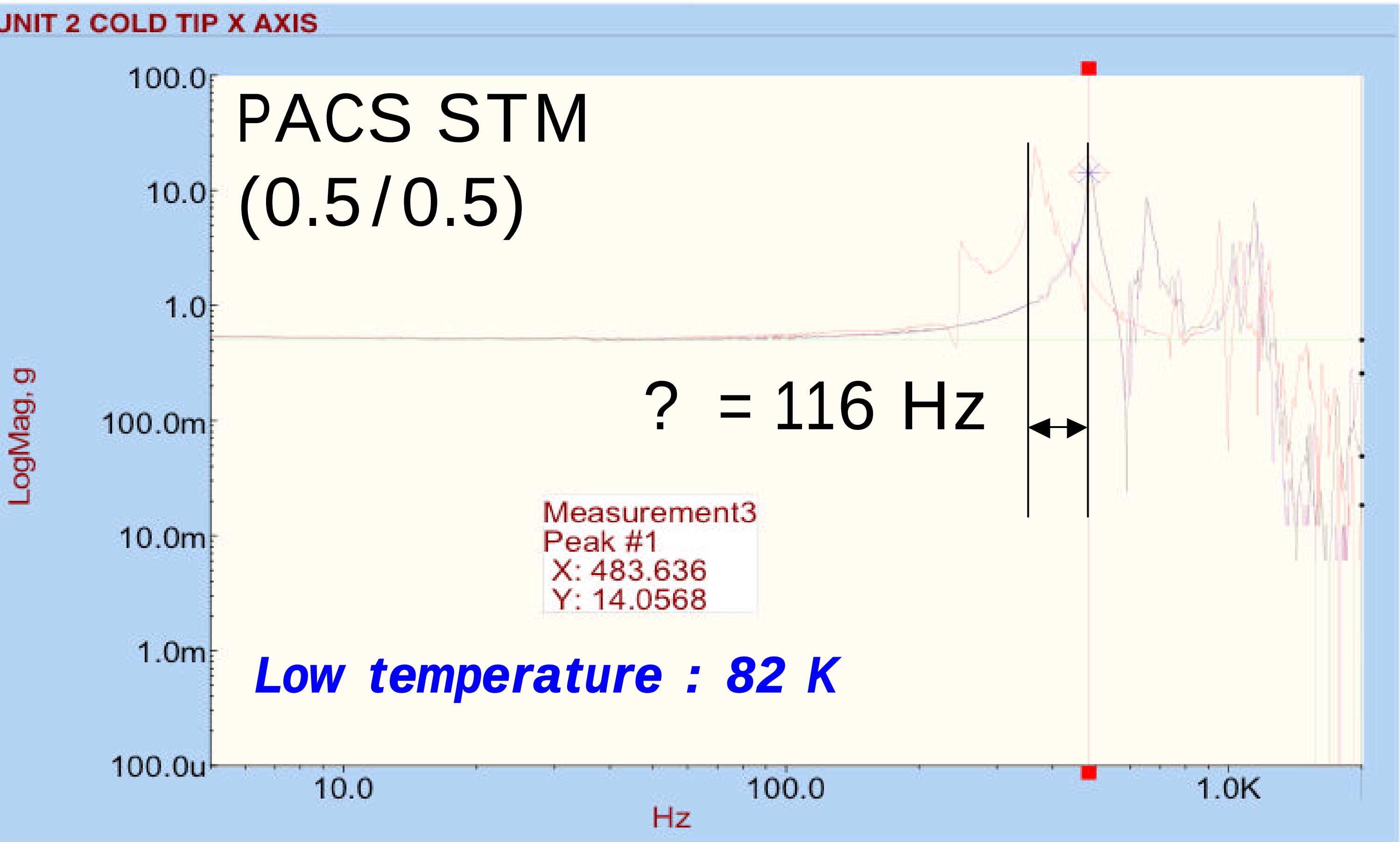
But...

STM : COLD V TEST (RAL) - Decrease of resonant freq. ?



NOTE : same signature after warm up at room

STM : COLD V TEST (RAL) - Decrease of resonant freq. ?

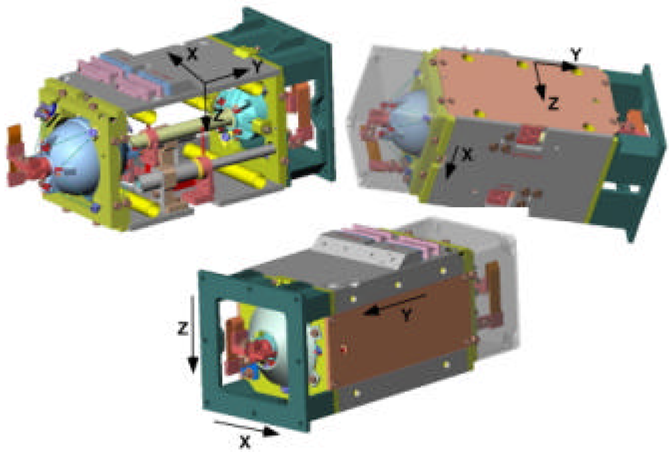


RE PACS COOLERS SINE SURVEY
N 000021
XIS
15:27 26/11/2002

NOTE : same signature after warm up at room

STM V TEST -SUMMARY

Test	SPIRE			PACS			Remark
	X	Y	Z	X	Y	Z	
CSL - Room Temperature .5 mm cords everywhere unless otherwise noted	**490** **(*407)**	**677**	**502**	**471**	**673** **(*571)**	**493**	*with 0.29 mm cords on evap. Before rupture Accelero + plateÊ 30
RAL - Room Temperature REÊ 0.29 mm/evap. 0.5 mm/pump ACSÊ 0.5 mm cords everywhere	**373**			**486**			Accel.+plateÊ 35-40
AL - Low Temperature: 85 K REÊ 0.29 mm/evap. 0.5 mm/pump ACSÊ 0.5 mm cords everywhere	**340**			**370**			Accel.+plateÊ 35-40



VARIATION OF FREQUENCIES WITH TEMPERATURE ?

$$f_{x,y} = \frac{1}{2p}\sqrt{\frac{8AY(b^2+r^2)}{ml^3}} \qquad f_z = \frac{1}{2p}\sqrt{\frac{16AYa^2}{ml^3}}$$

oung's modulus :
5 to 105 GPa

- static versus dynamic ?
- Tensioning versus detensionin
- Tension dependent ?

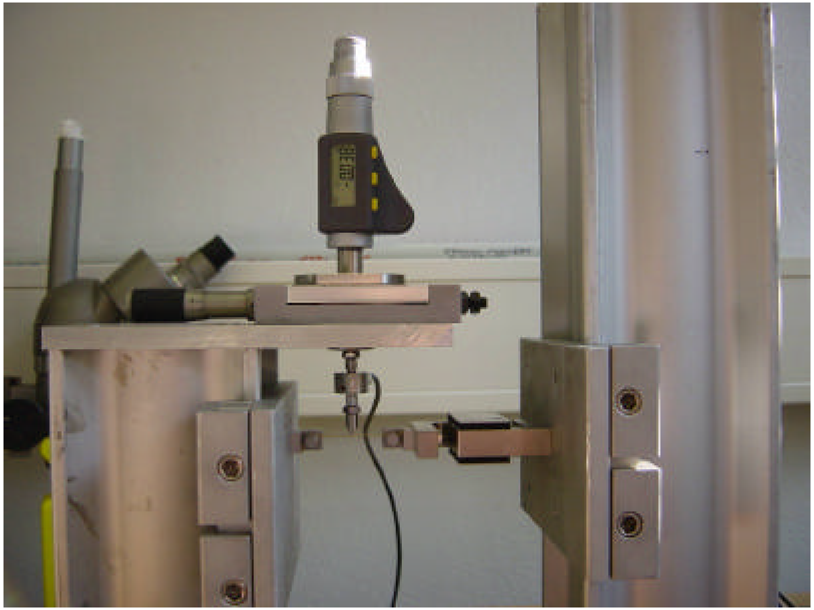
ension dependant
 and/or Y)

Kevlar Thermal expansion
Published : - 9 10^{-4}
JPL : - 3 10^{-3} ! *(SBT : -3.3 10*

(*: extracted from

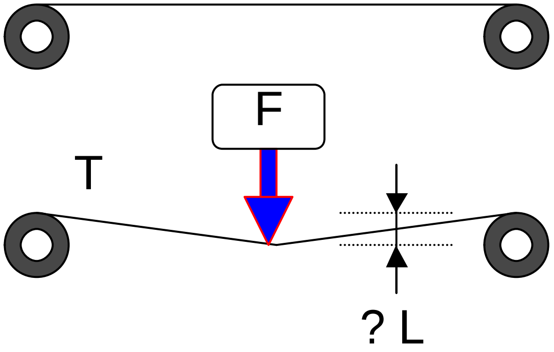
Is it tension dependent ?

NEW TOY : TENSIOMETER

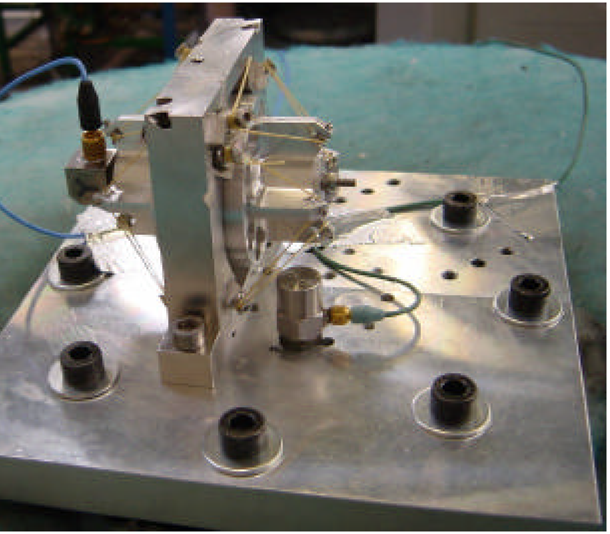


any ideas evaluated
implest" one finally selected

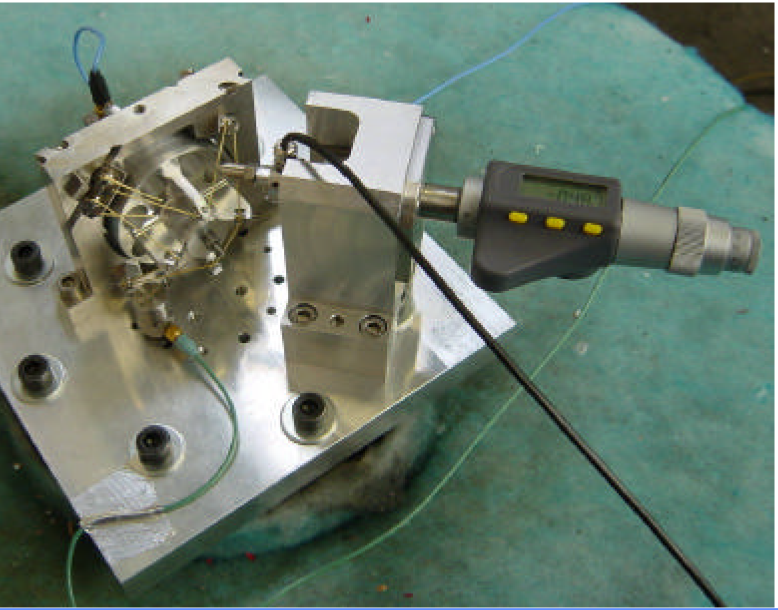
rinciple : Tension versus contact
orce for a deflection of 500 µm

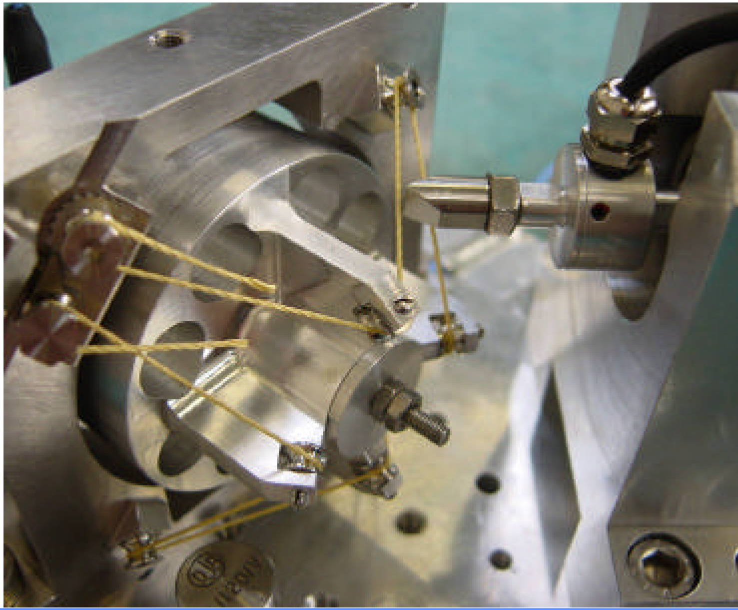


RESONANT FREQUENCIES VERSUS TENSION - SET UP

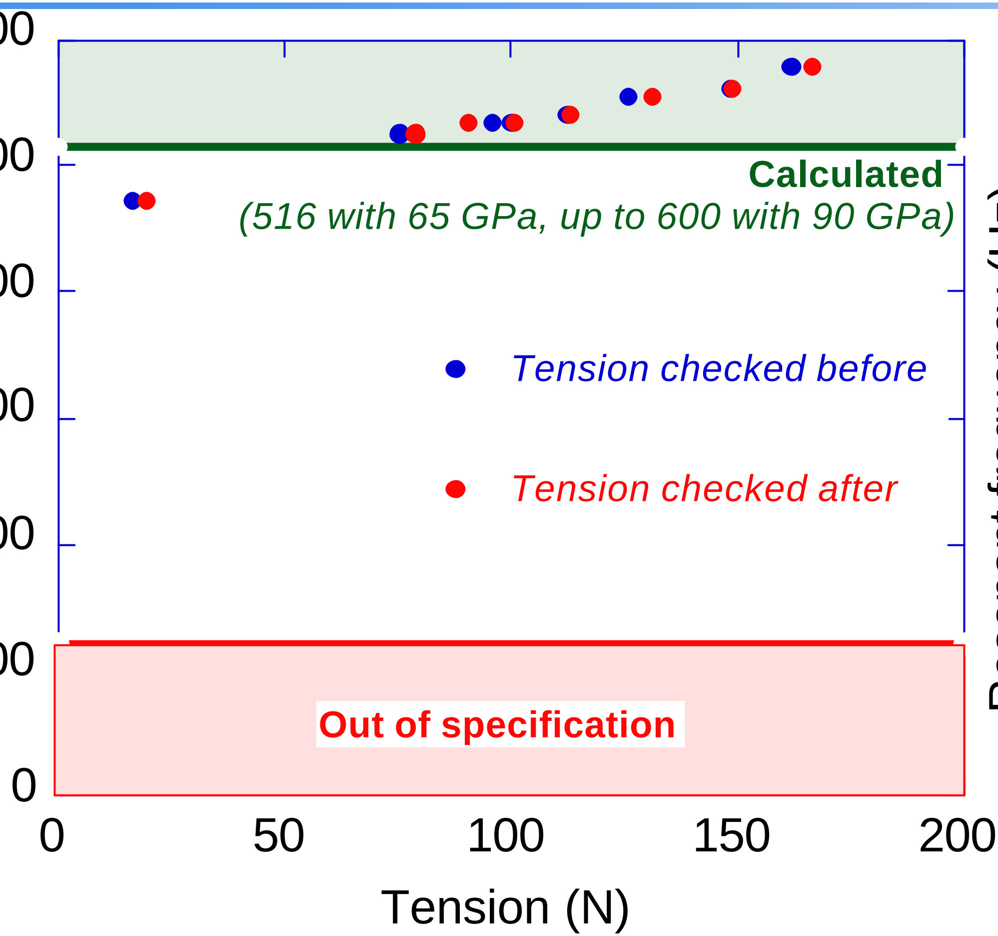


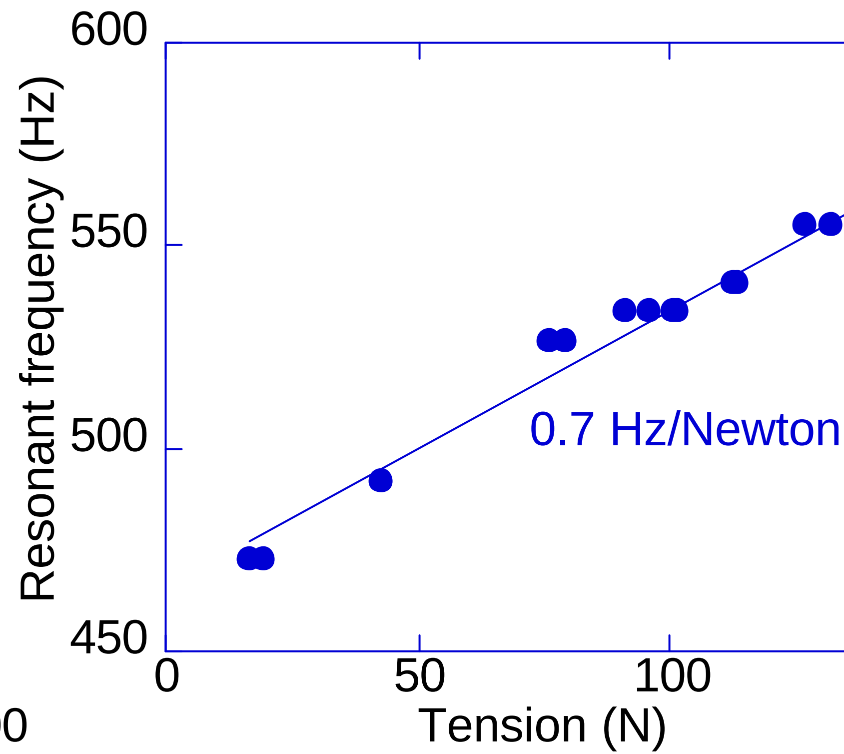
Manufacturing of mock-up of pum
support system





RESONANT FREQUENCIES VERSUS TENSION - RESULTS





SLIGHT EFFECT INDEED

Kevlar Summit

Overview of Lessons Learned

Gary S. Parks

19 March 2003

First Signs of a Problem

- Last Fall our ambient temperature vibration testing was successful
- But, some of our cryogenic vibration testing had anomalies
  - Mode frequencies were not as sharp and reduced in amplitude
  - In one case, a mode frequency disappeared
  - In most cases the mode frequencies appeared to shift down to a lower frequency
  - Metrology results indicated that the array position had shifted more than 100 microns, outside of our specification for that shift
  - In all cases the array survived the testing, without damage
- Our BDA was intended to be an "athermalized" design, and the modeling indicated that it should be working, and that no significant change in mode frequencies, or change in detector position, should occur

---

- We decided to conduct a basic materials characterization test/study

Basic Materials Characteristics

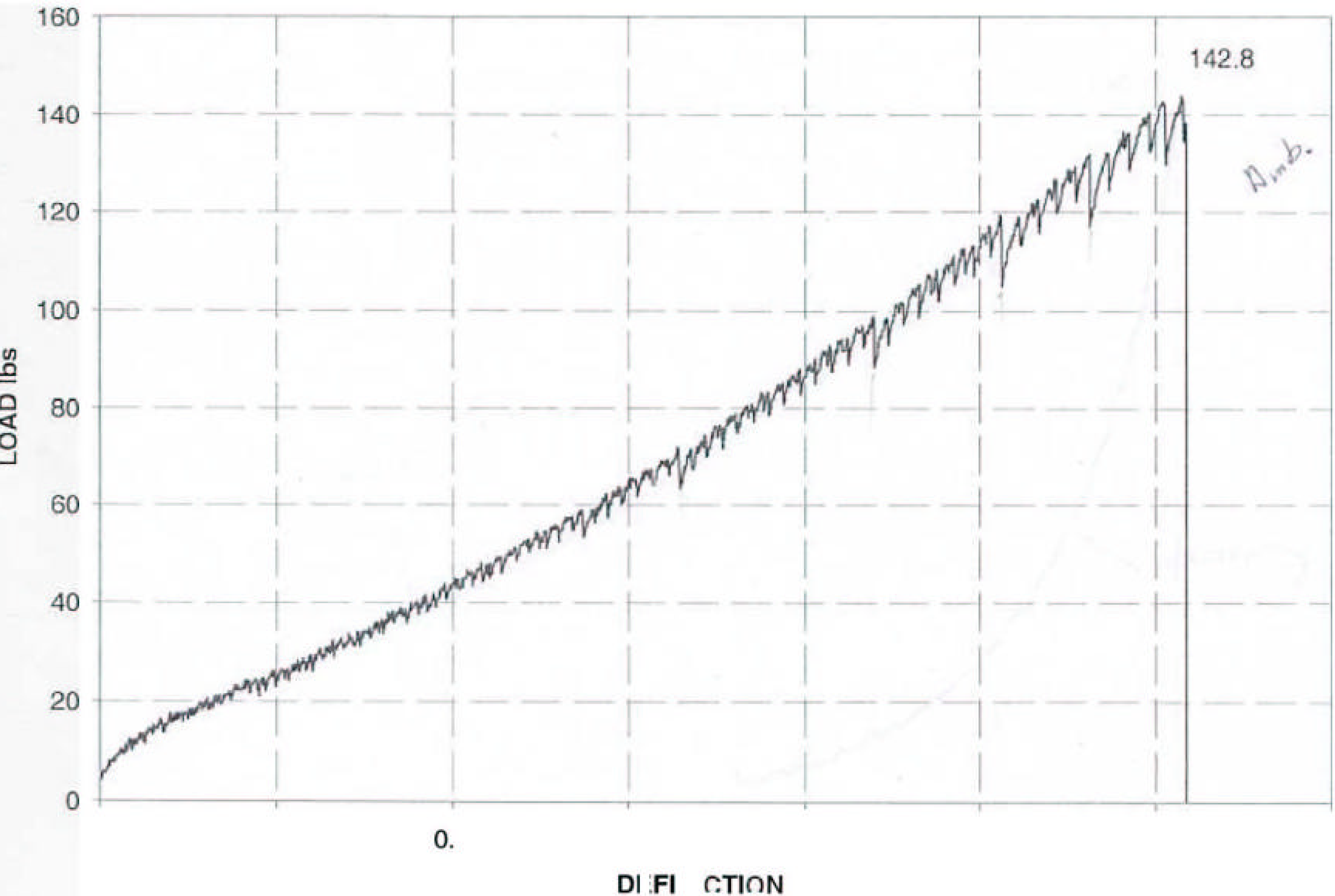
- **The first surprise we encountered was that the CTE was about three times higher than our predictions**
  - implies that we did not have an athermalized design
  - Suggests that we are losing some tension when cooled
  - As a parallel activity, to mitigate schedule problems, we initiated the stringing and testing of a BDA with higher Kevlar tension (50 lbs instead of 33)
- **Initial stiffness tests seemed ok, with a linear behavior with displacement**
  - So how could we explain the shift to lower mode frequencies?
  - At this time there was not a viable explanation for this result

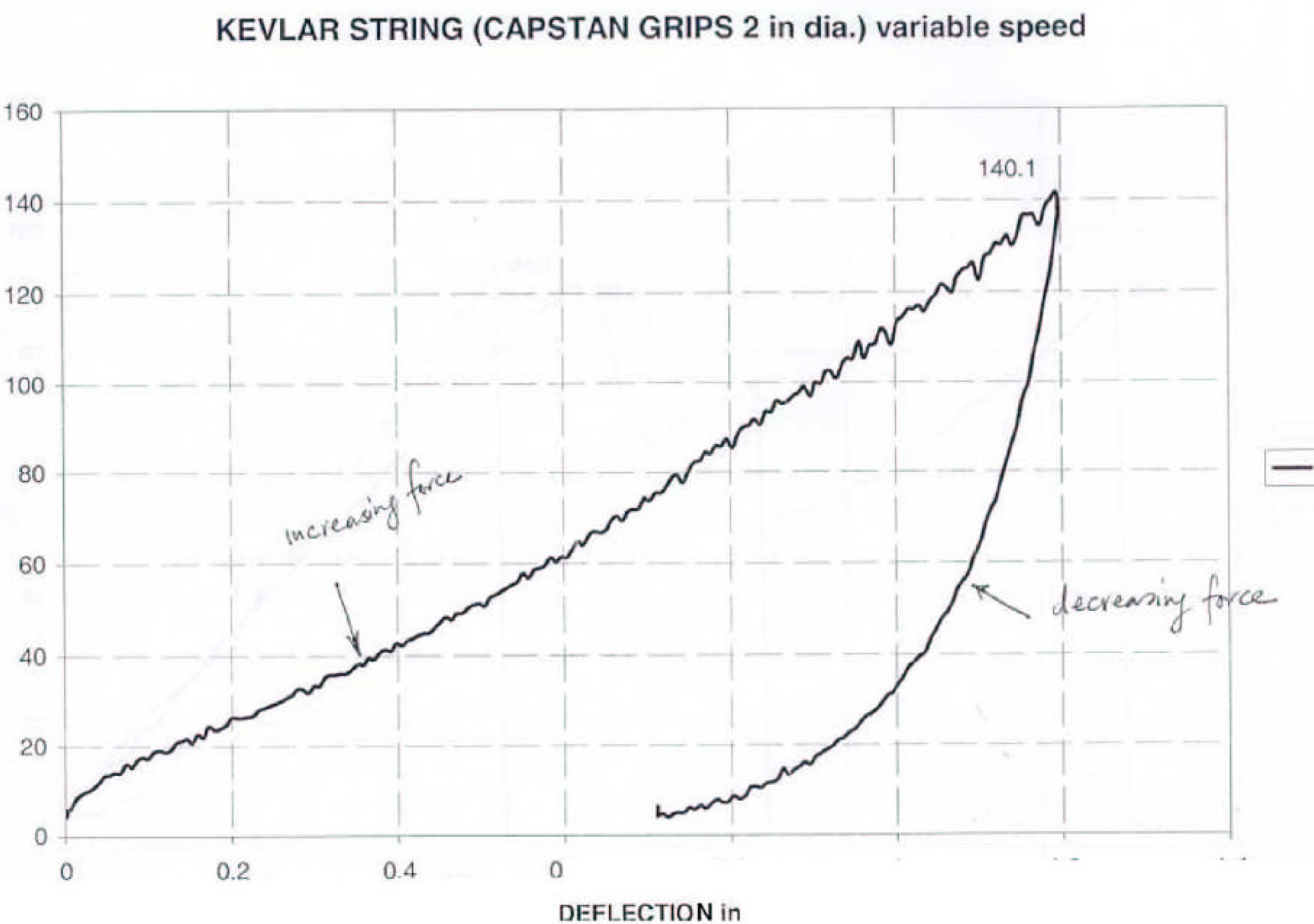
Nuances of Measuring Kevlar Stiffness

- **When we examined the stiffness results carefully, Henry noticed an anomaly within the results.**
  - **Small fluctuations with displacement suggested that the data might not accurately represent pure stiffness**
  - **It was realized that we should test the reversibility of the process to see if there is some kind of non-linear or hysteresis effect**
- **After investigation, it was clear that our previous stiffness tests were invalid**
  - **Stiffness is clearly higher than previously understood**
  - **And, stiffness is <u>non-linear with displacement!</u>**

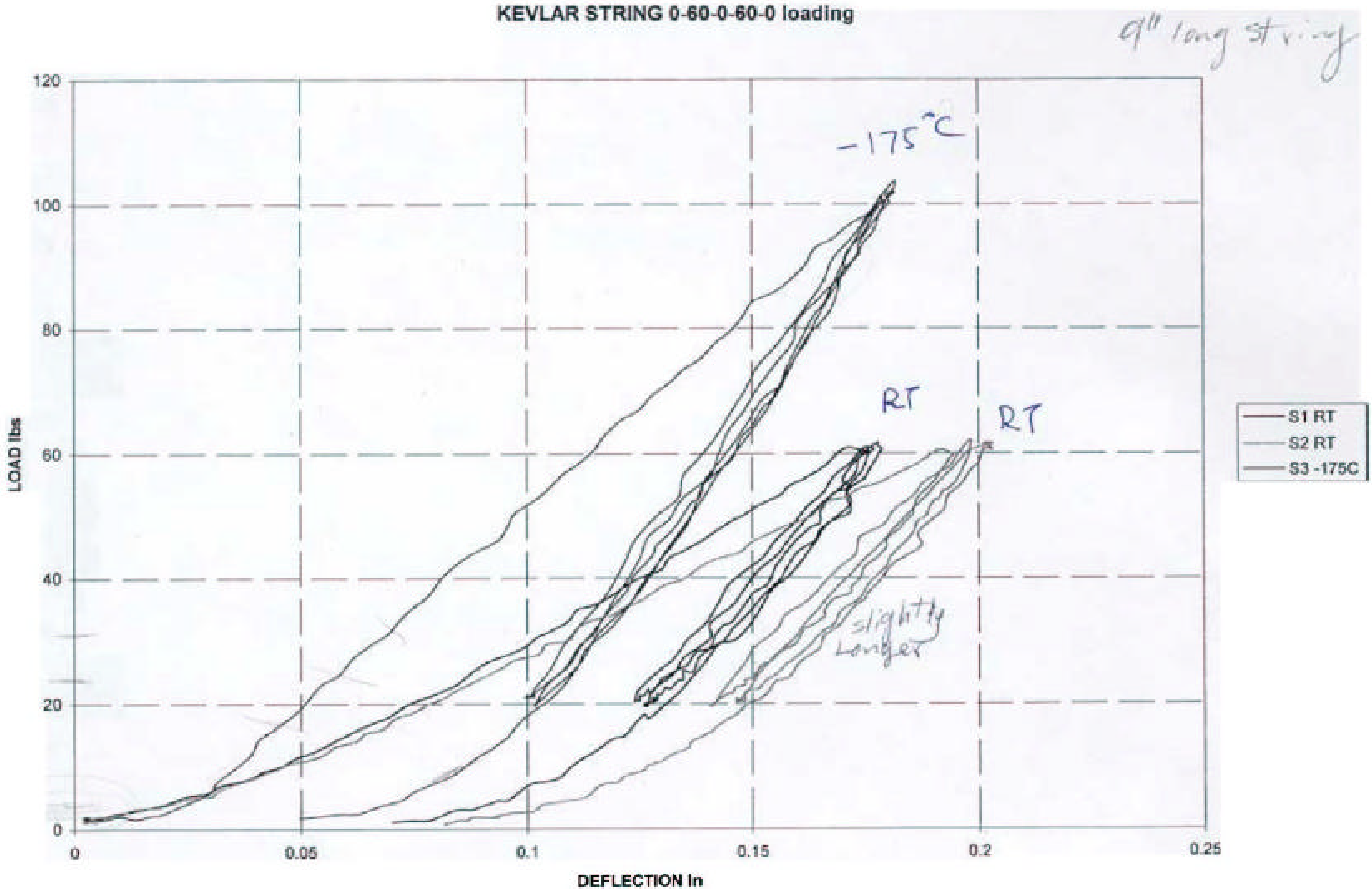
- **For the first time we had a viable explanation for the downward shift in mode frequencies**

K VLAR TRIN CAP TAN GR P n dia val ab e peed





KEVLAR STRING (CAPSTAN GRIPS 2 in dia.) variable speed
160
140
120
100
80
60
40
20
0
0
0.2
0.4
0
DEFLECTION in
140.1
increasing force
decreasing force


KEVLAR STRING 0-60-0-60-0 loading
9" long string
-175°C
RT
RT
slightly Longer
LOAD lbs
DEFLECTION In
0
20
40
60
80
100
120
0
0.05
0.1
0.15
0.2
0.25
S1 RT
S2 RT
S3 -175C

Simulation of Kevlar Environmental Exposure Up To Cryogenic Testing

- **We decided to simulate, in a laboratory, all of the steps the Kevlar goes through up until cryogenic vibration testing**
  - **Tension, including removing the effect of near-term creep**
  - **Bake-out**
  - **Cool-down**
- **Initial tests suggested**
  - **Bake out process <u>reduced the tension by almost half</u>!**
  - **As previously identified, CTE effect reduced the tension even further**

- **The surprising conclusion is that we were losing about 90% of our design tension when previously conducting cryo-vibration tests**

Objective: To investigate the hypothesis that the disappearance of resonance peaks during full-level, cold random vibration tests and the changes in the BDA alignment measured before and after the vibration test are due to a decrease in the nominal Kevlar tension (33 lbs), which resulted in reduced friction and slippage of the Kevlar over the pulleys.

Test Results:

1. 11/22 -- A 12 inch length of Kevlar loaded to 33 lbs, with extension of 0.290 in.

2. 11/23 --Readjusted tension from 27.3 lbs to 33 lbs.

3. 11/23 -- After five hours at 75 C, tension dropped to 18 bs.

4. 11/25 -- After ~40 hours at ambient, tension rose to 22.7 lbs.

5. 11/25 -- After reducing temperature to -175 C , tension increased to 30.5 lbs.

6. 11/24 -- At -175 C, gradual unloading indicated: 500 lbs/in. < K = AE/L < 600 lbs/in.

Analysis:

1. K ambient = 33/.29 = 114 lbs/in.

2. Increase in tension from 27.3 lbs to 33 lbs in 16 hours of creep

3. Tension drop from 33 to 18 lbs in 5 hours at 75 C is big humidity effect.

4. Increase in tension from 18 to 22.7 lbs in 40 hrs is humity diffusing back in.

5. Rise in tension from 22.7 to 30.5 lbs due to competing effect of 12 inch of steel shrinking, and 12 in. of Kevlar stretching.

   a. Steel: 20*10^-6 * 200 * 12in * 600lbs/in. = + 29 lbs

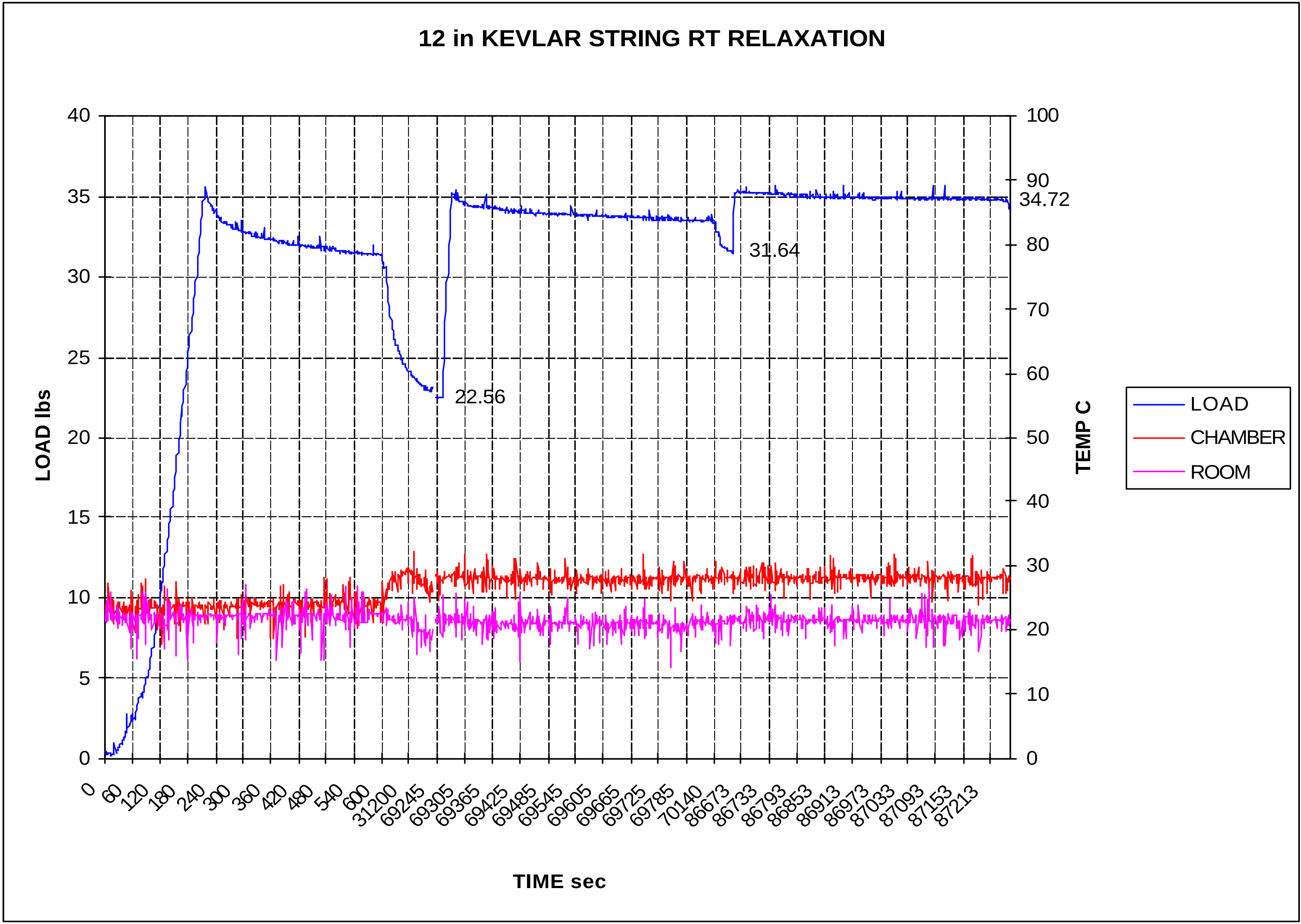
   b. Kevlar: 13*10^-6 * 200 * 12in * 600lbs/in. = -19 lbs

   c. Predicted net increase from 23 lbs to 33 lbs. (actual 30.1 lbs)

NOTE; IF EFFECT OF STEEL IS SUBTRACTED OUT, KEVLAR TENSION WOULD GO FROM 22.7LBS DOWN TO 22.7 -19 = 3.7 LBS!!!!!!!!!!!!

The Need For Conditioning Kevlar

- **Henry conducted numerous additional tests, to provide a detailed understanding how the Kevlar material characteristics change with various conditioning steps**
  - Humidity changes and possible annealing effect
  - Creep versus stress relaxation – an important distinction
  - The need for conducting the conditioning while under tension
  - Environment for adequate conditioning
  - Number of cycles to be sure that the Kevlar is fully conditioned
  - Effect of change in humidity after conditioning
- **We now have a fully tested conditioning process that meets the needs of the SPIRE BDA design**



12 in KEVLAR STRING RT RELAXATION
LOAD lbs
TEMP C
TIME sec
40
35
30
25
20
15
10
5
0
100
90
80
70
60
50
40
30
20
10
0
34.72
31.64
22.56
0
60
120
180
240
300
360
420
480
540
600
31200
69245
69305
69365
69425
69485
69545
69605
69665
69725
69785
70140
86673
86733
86793
86853
86913
86973
87033
87093
87153
87213
LOAD
CHAMBER
ROOM

The Worry About Long-term Stress Relaxation

- Given the fact that the Kevlar stiffness is several times higher than previously understood, our immediate concern was long-term stress relaxation
  - Note: many people think about this as creep, but in the BDA, the displacement is constant, and the tension is the variable
- We immediately conducted longer-term testing to determine to bound the magnitude of this problem after appropriate conditioning
- This testing fortunately confirmed that this effect is small if, and only if, the Kevlar is conditioned properly

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- When the Kevlar is conditioned properly, the remaining stress relaxation is a small percentage of the tension

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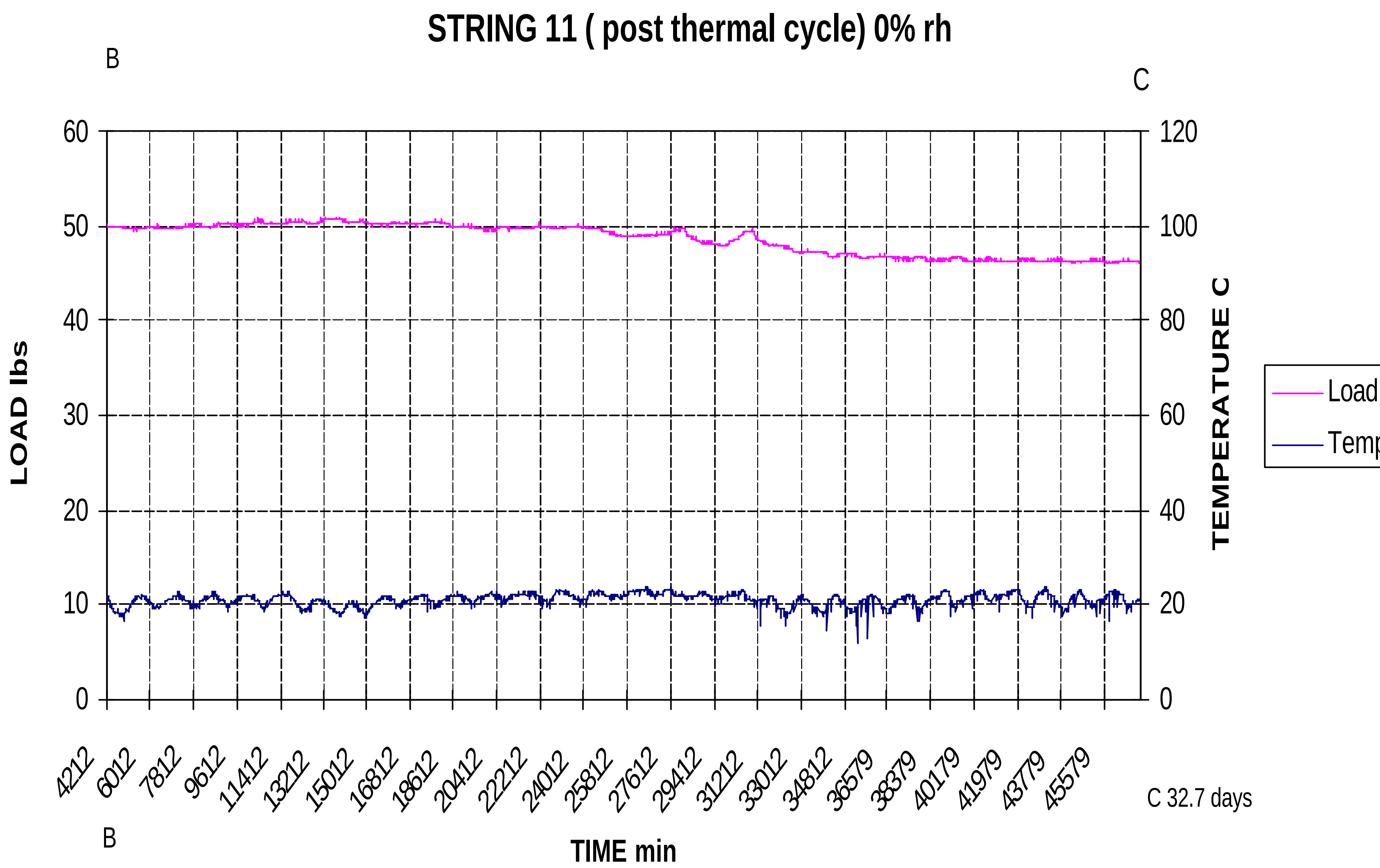


STRING 11 (post thermal cycle) 0% rh
B
C
LOAD lbs
TEMPERATURE C
60
50
40
30
20
10
0
120
100
80
60
40
20
0
Load
Temp
4212
6012
7812
9612
11412
13212
15012
16812
18612
20412
22212
24012
25812
27612
29412
31212
33012
34812
36579
38379
40179
41979
43779
45579
C 32.7 days
B
TIME min

What is an Adequate Kevlar Tension for the BDA

- Two separate analytical models were developed for the BDA using the new materials characteristics measured
- This models were used to extrapolate the performance of the Kevlar suspension to lower temperatures (about 2K)
- In addition we had a great deal of data from tests indicating how much tension we need cold
  - This testing indicated that we conservatively need >15 lbs cold after taking into account the effect of vibration

---

- By combination of analysis and test, we convinced ourselves that an initial Kevlar tension of 50 lbs is adequate for the SPIRE BDA design

---

The Need for Testing the BDAs at Lower Temperatures

- Because of the surprises found during the tiger team activities, we are convinced that we need to conduct some lower-temperature vibration tests
  - To confirm no anomalies in the transition between LN2 temperatures and true operating temperatures at launch
- Given all the lessons of the tiger team, we believe that a simple low level sine sweep is a good way to provide confidence in adequate Kevlar tension
- Although we have not finalized our plans for this test, the current thinking is that a mode-frequency test will provide a great deal of confidence that we have adequate Kevlar tension at 2K

- We need to do some testing at about 2K to have adequate confidence that we understand the BDA at operational temperatures

---

Summary

- **A high-level summary indicates the need for:**
  - **Modeling the performance with correct CTE and stiffness. This will result in the need for higher initial tension**
  - **Given the need for higher tension, it is critical to test for maximum tension up to breakage, because effect such as human factors, and launch vibration can increase tension**
    - Note that ambient temperature vibration tests will push this limit, in those conditions, humidity needs to be considered because it will add tension
  - **Conducting full conditioning of Kevlar, under full tension and in the actual unit being assembled**
    - Especially true for ensuring low long-term stress relaxation
  - **Testing performance cold – down to full operating temperature**

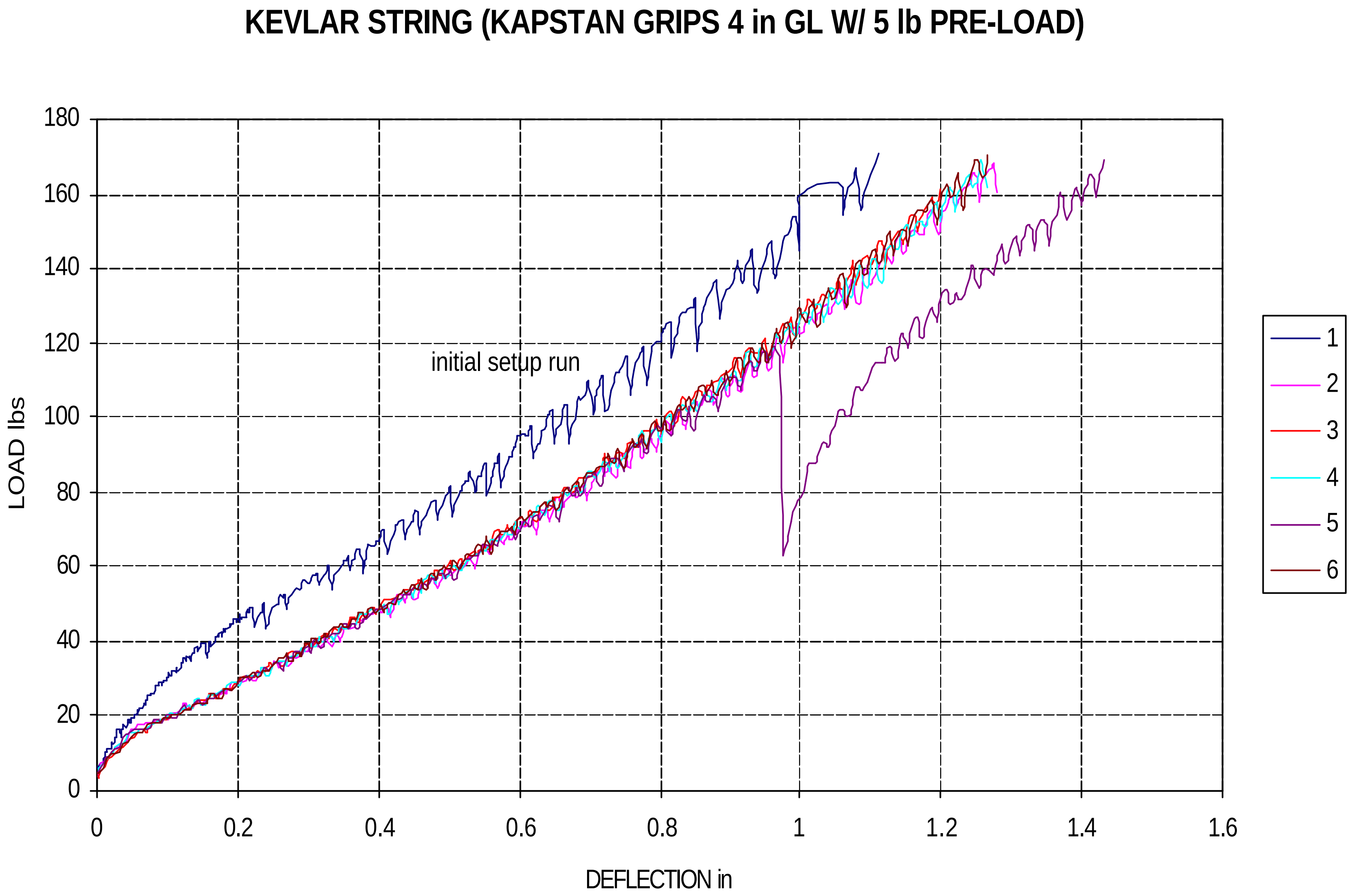
Note that conducting tests materials characterization is tricky, and it is easy to be fooled by flawed results

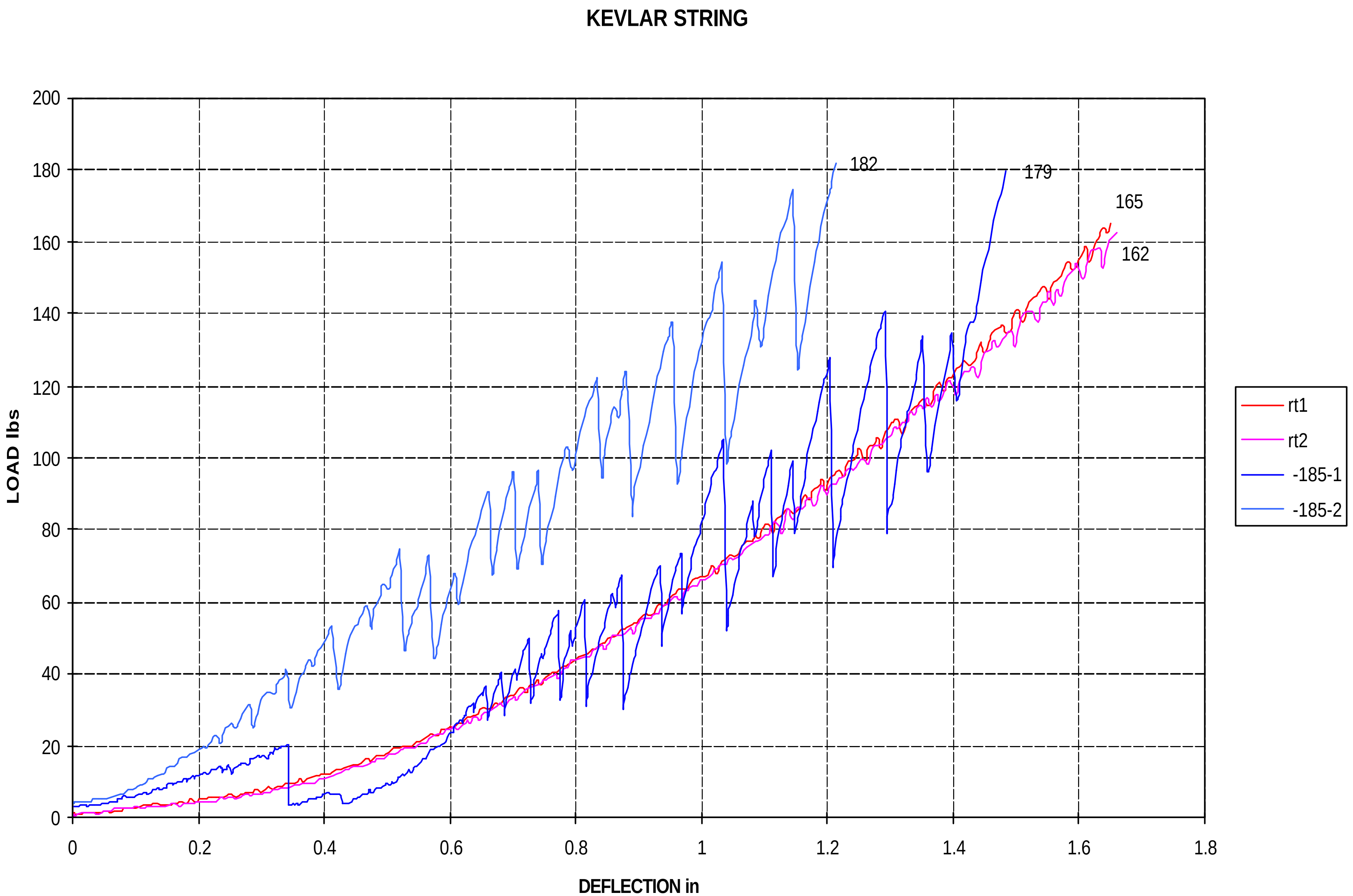
Kevlar test data

March 19, 2003

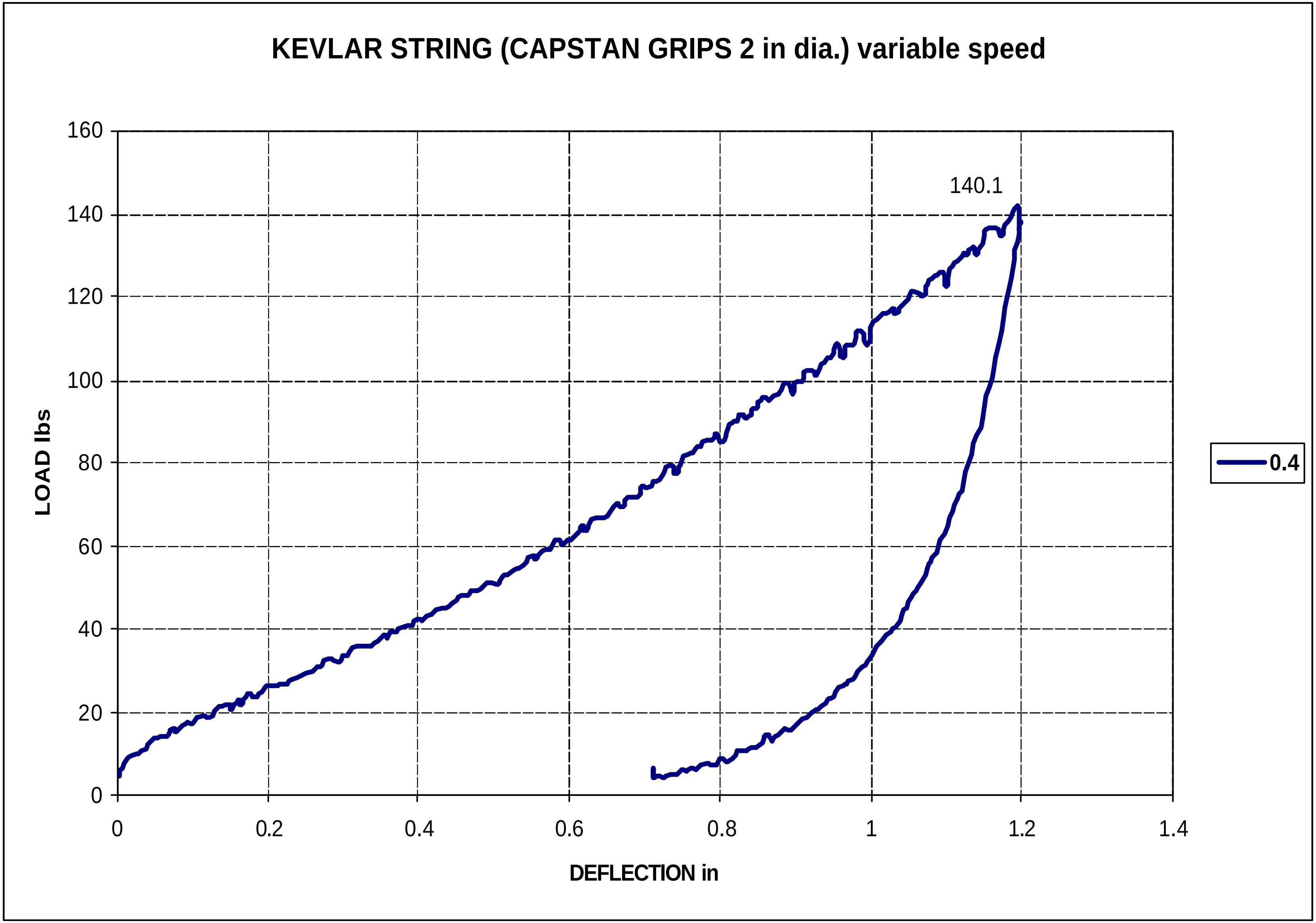
Kevlar characteristics

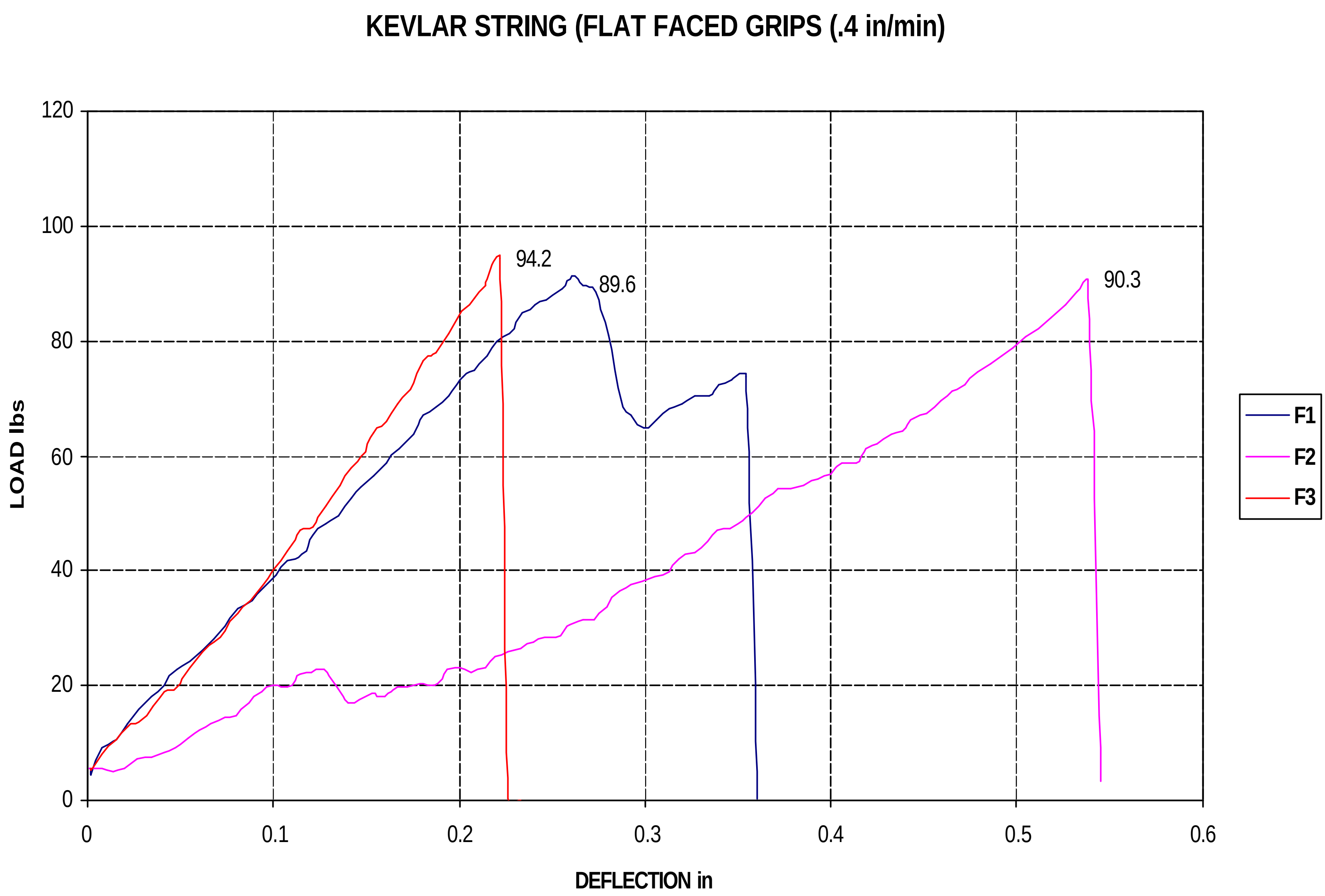
- Kevlar 29 type 964
- Braided 400 denier
- 12 carrier braid
- Average area = 0.0006 in^2

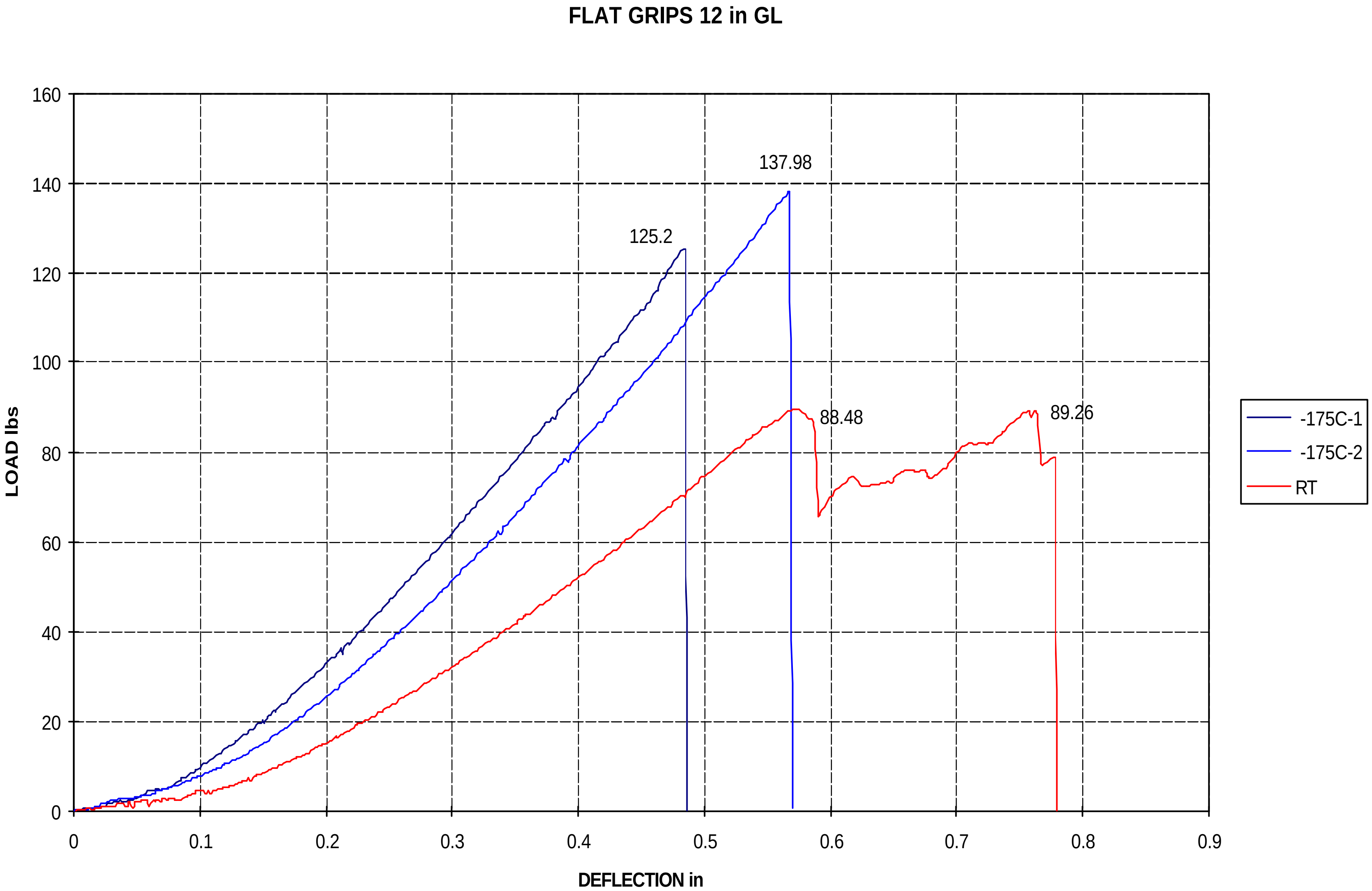

KEVLAR STRING (KAPSTAN GRIPS 4 in GL W/ 5 lb PRE-LOAD)
LOAD lbs
0
20
40
60
80
100
120
140
160
180
DEFLECTION in
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
initial setup run
1
2
3
4
5
6



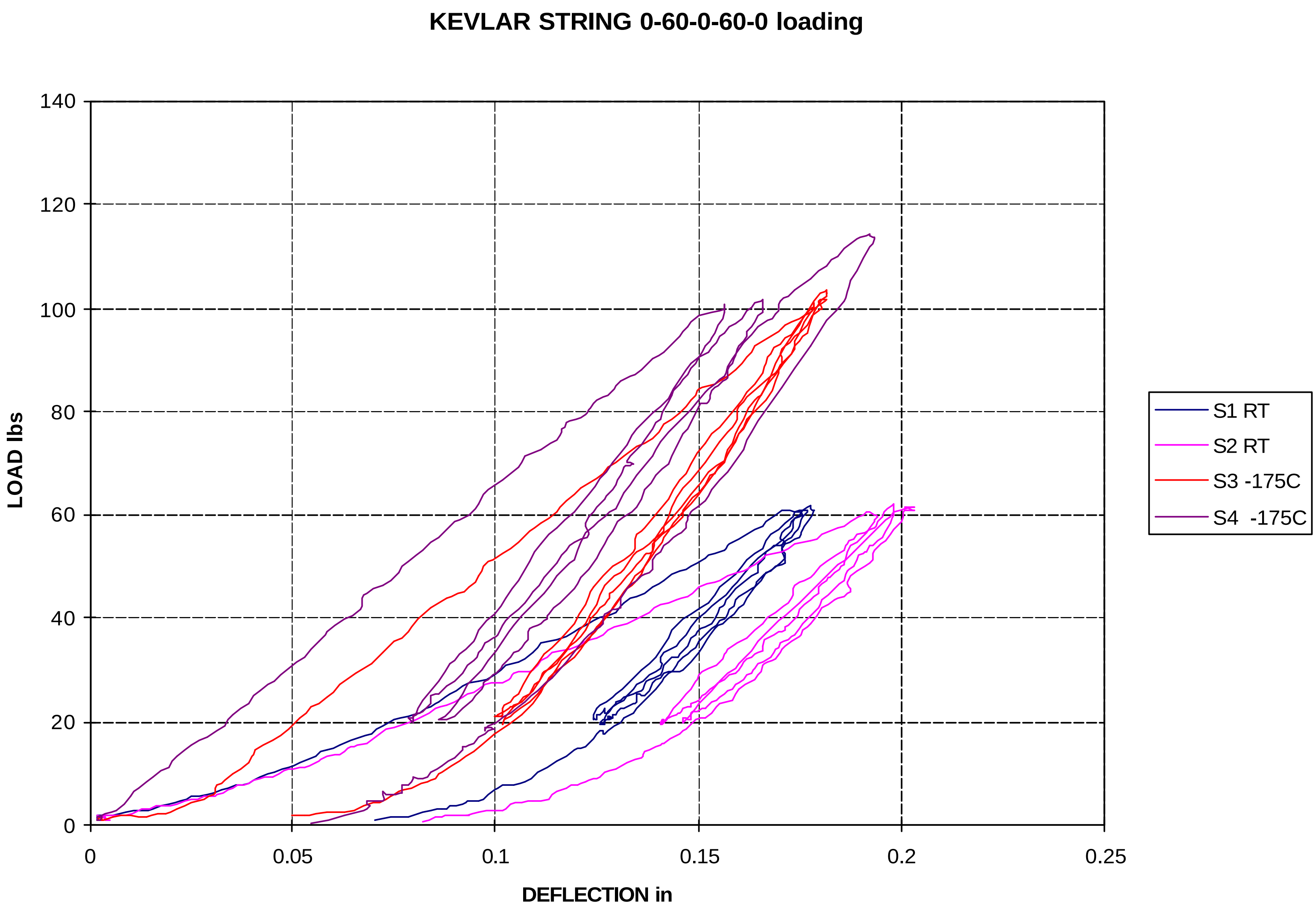
KEVLAR STRING
LOAD lbs
DEFLECTION in
0
20
40
60
80
100
120
140
160
180
200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
182
179
165
162
rt1
rt2
-185-1
-185-2


KEVLAR STRING (CAPSTAN GRIPS 2 in dia.) variable speed
LOAD lbs
DEFLECTION in
0
20
40
60
80
100
120
140
160
0
0.2
0.4
0.6
0.8
1
1.2
1.4
140.1
0.4

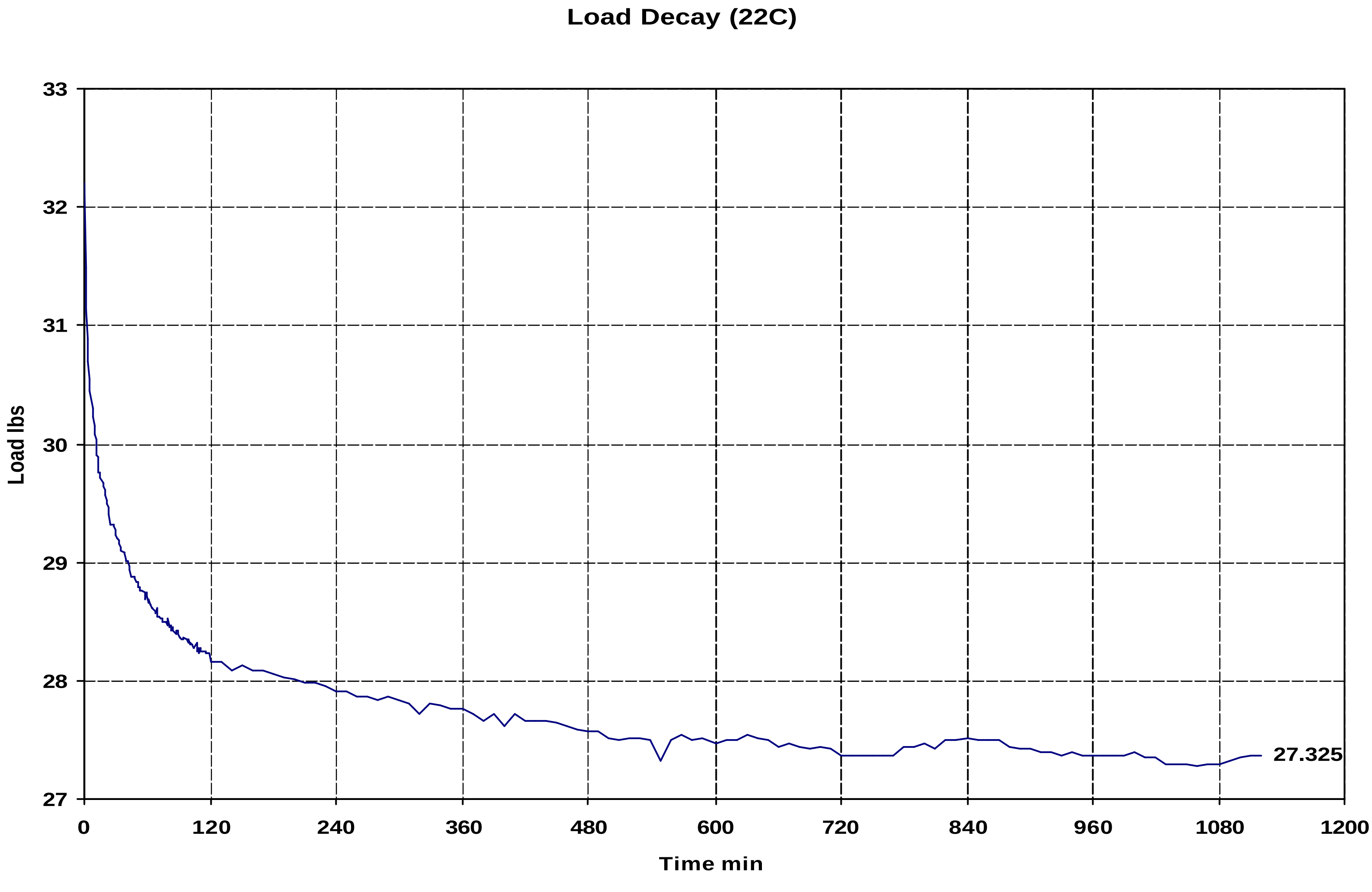

KEVLAR STRING (FLAT FACED GRIPS (.4 in/min)
LOAD lbs
DEFLECTION in
0
20
40
60
80
100
120
0
0.1
0.2
0.3
0.4
0.5
0.6
94.2
89.6
90.3
F1
F2
F3

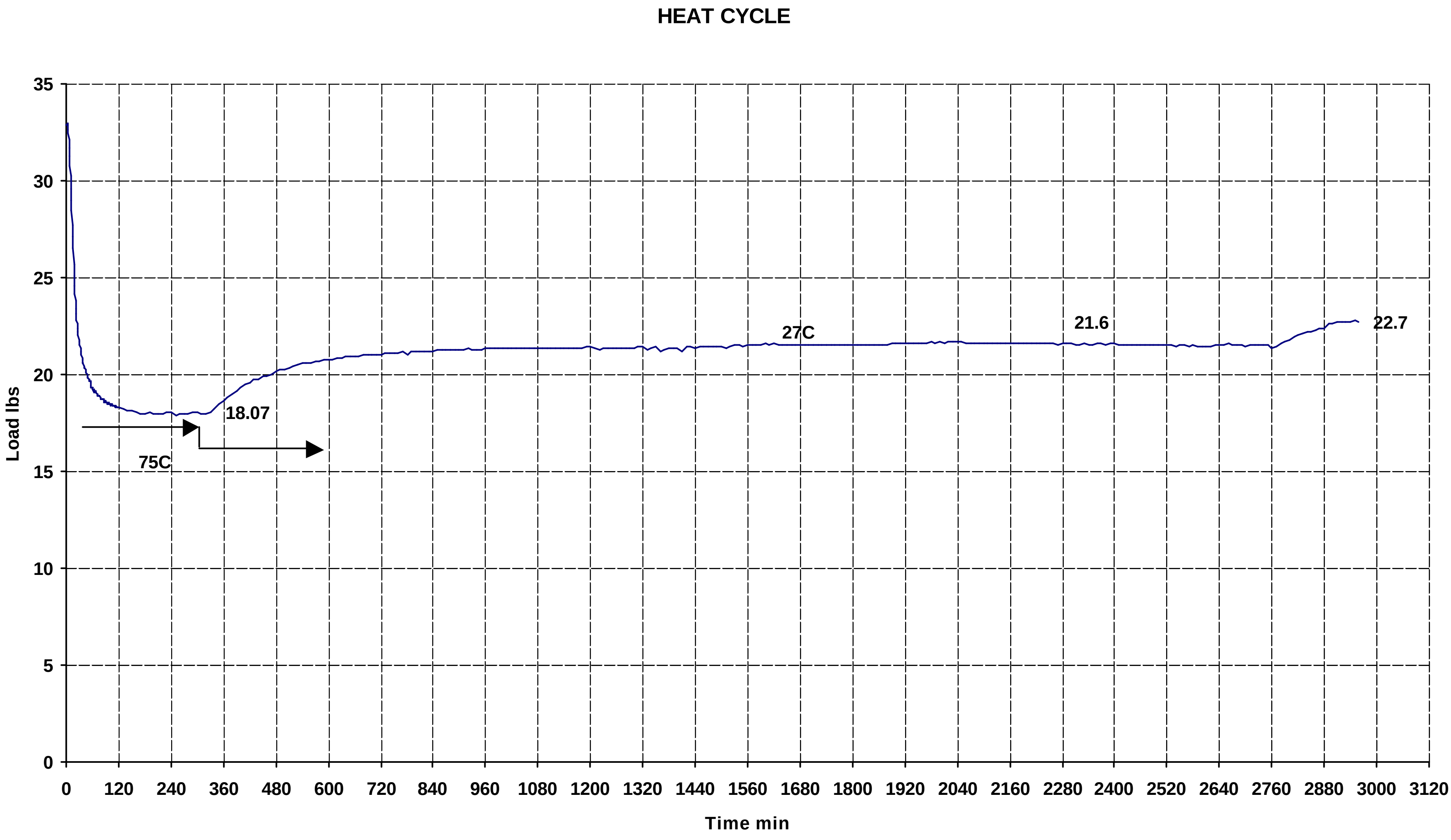


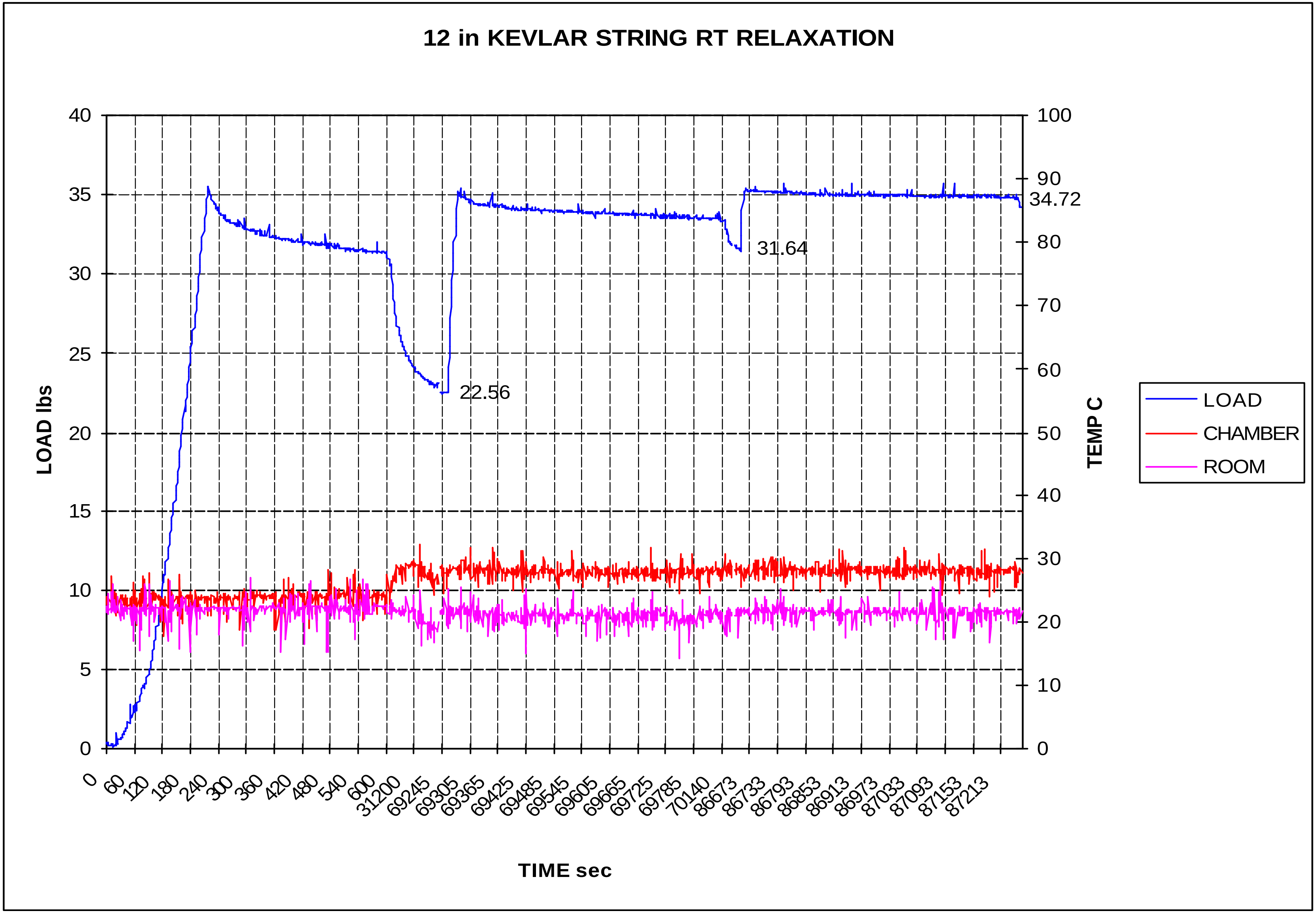
FLAT GRIPS 12 in GL
LOAD lbs
DEFLECTION in
0
20
40
60
80
100
120
140
160
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
125.2
137.98
88.48
89.26
-175C-1
-175C-2
RT



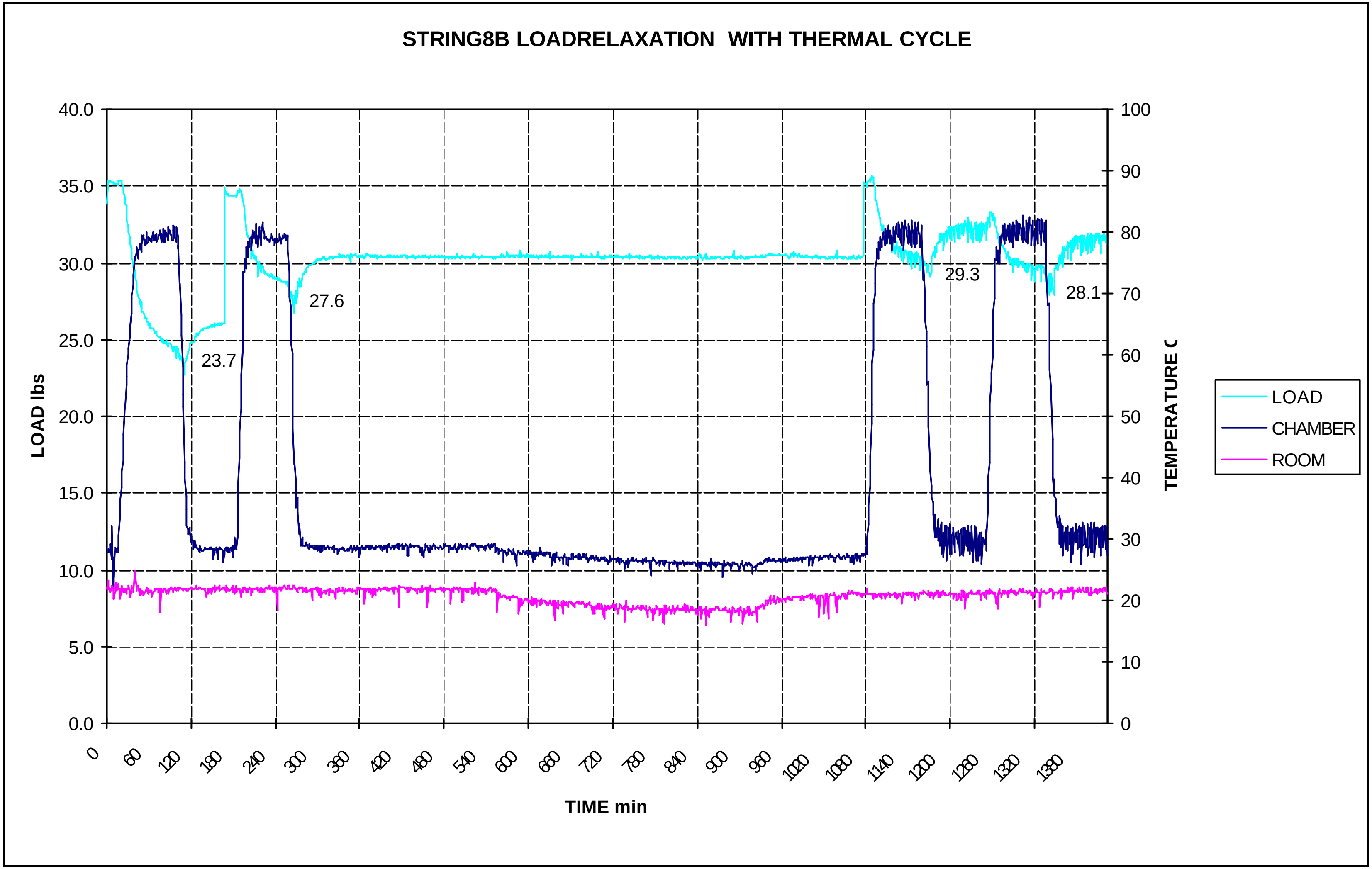
KEVLAR STRING 0-60-0-60-0 loading
LOAD lbs
DEFLECTION in
140
120
100
80
60
40
20
0
0
0.05
0.1
0.15
0.2
0.25
S1 RT
S2 RT
S3 -175C
S4 -175C


Load Decay (22C)
Load lbs
33
32
31
30
29
28
27
27.325
0
120
240
360
480
600
720
840
960
1080
1200
Time min

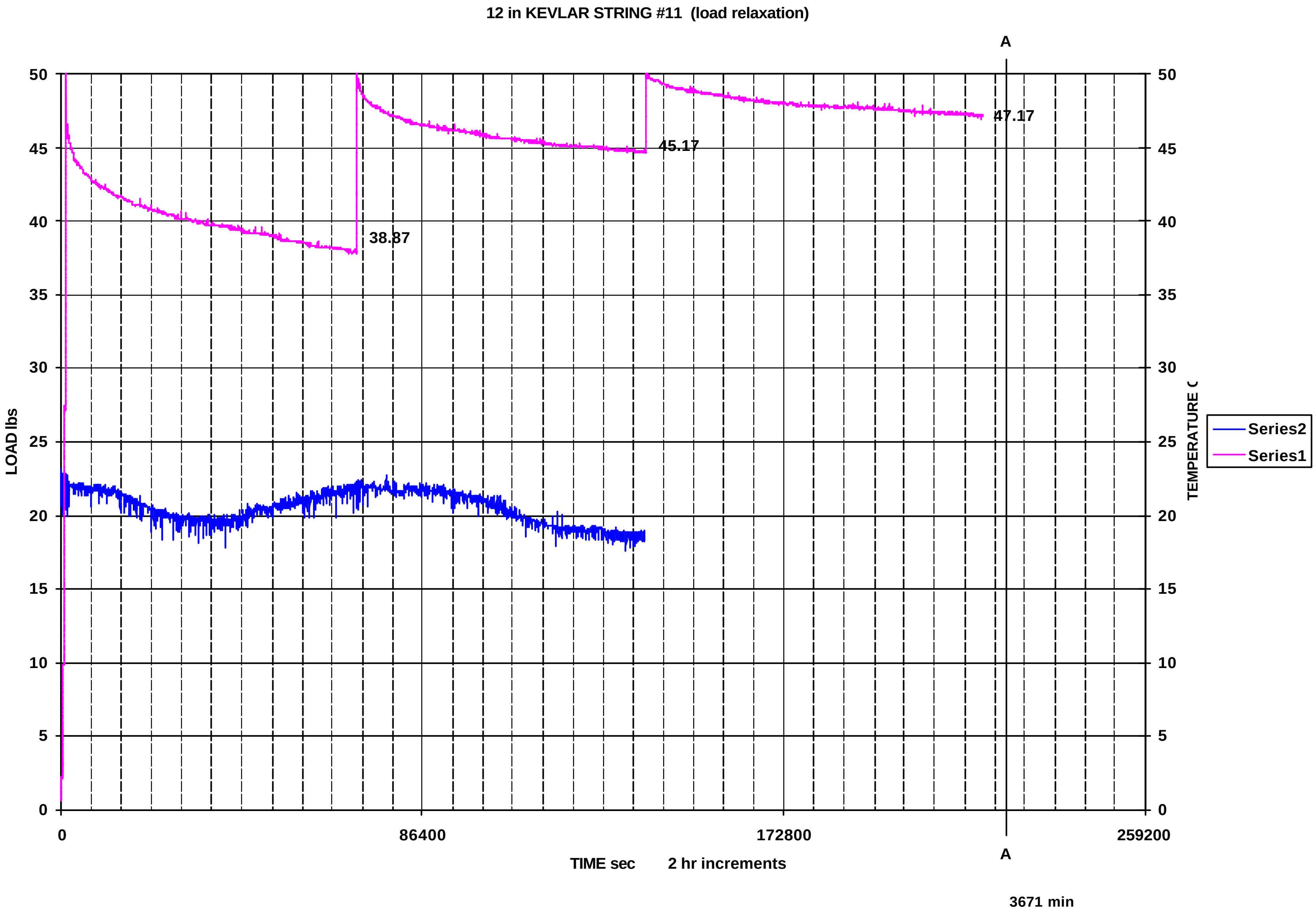

HEAT CYCLE
Load lbs
Time min
35
30
25
20
15
10
5
0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640
2760
2880
3000
3120
18.07
75C
27C
21.6
22.7



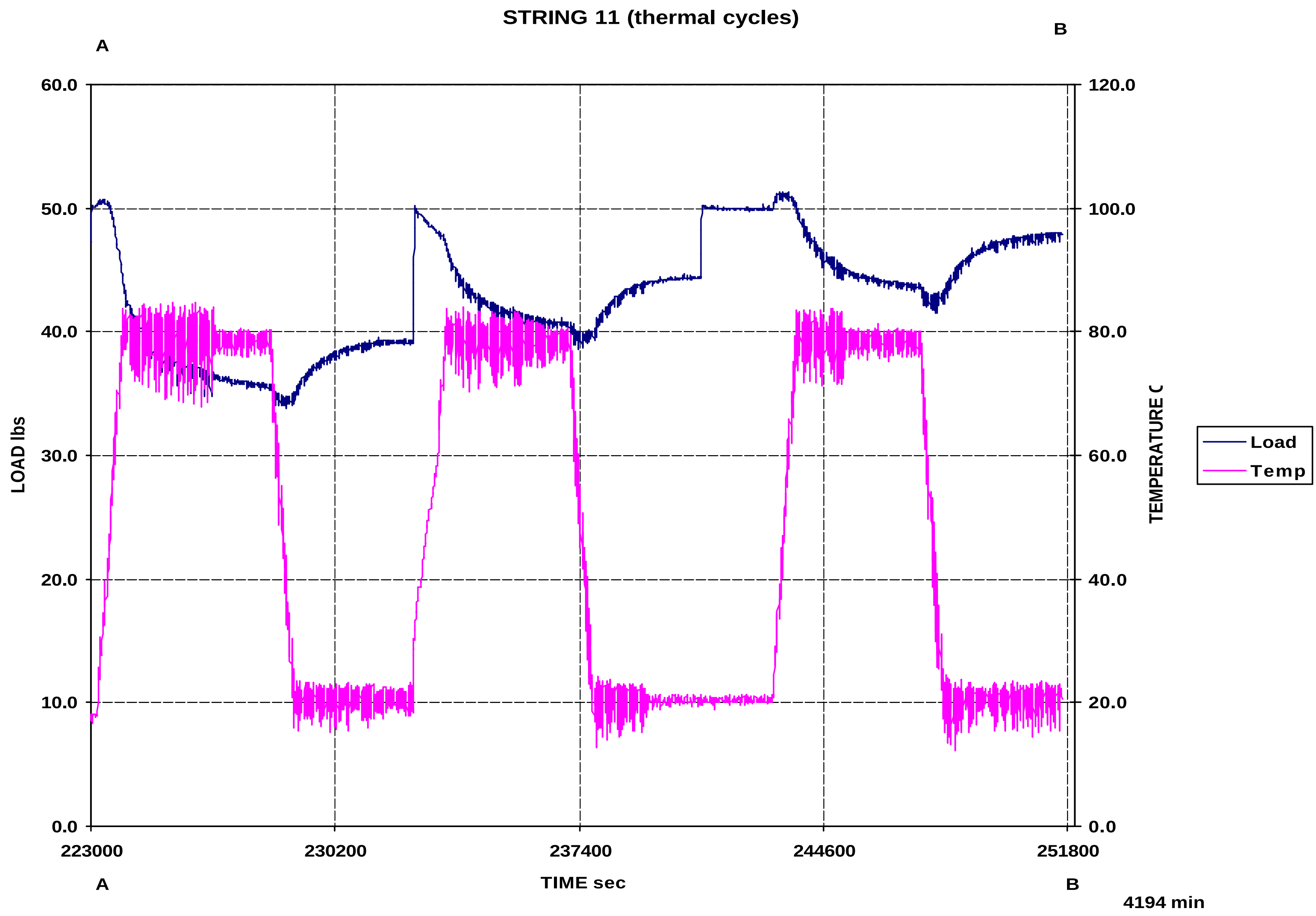
12 in KEVLAR STRING RT RELAXATION
LOAD lbs
TEMP C
TIME sec
40
35
30
25
20
15
10
5
0
100
90
80
70
60
50
40
30
20
10
0
34.72
31.64
22.56
0
60
120
180
240
300
360
420
480
540
600
31200
69245
69305
69365
69425
69485
69545
69605
69665
69725
69785
70140
86673
86733
86793
86853
86913
86973
87033
87093
87153
87213
LOAD
CHAMBER
ROOM

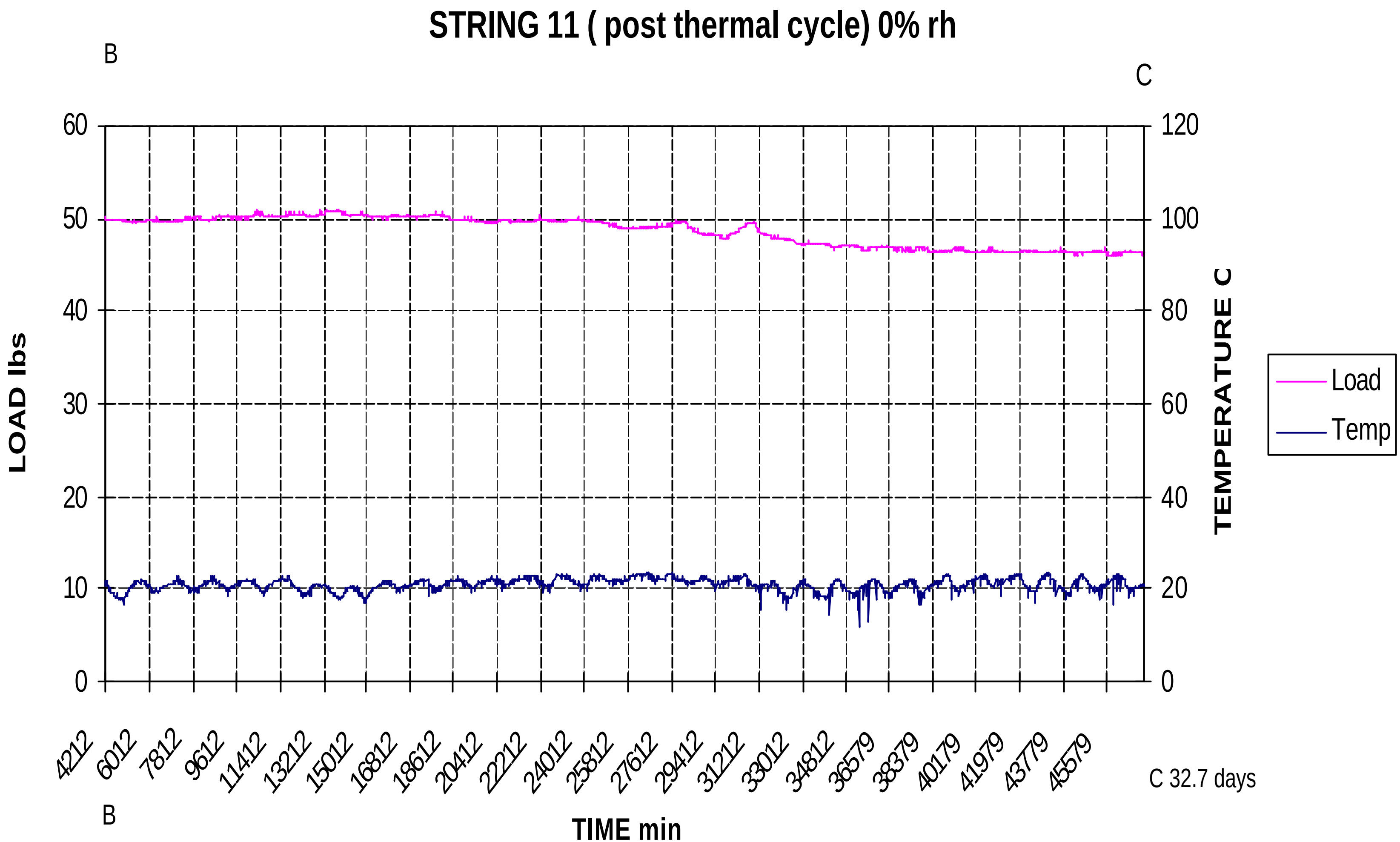


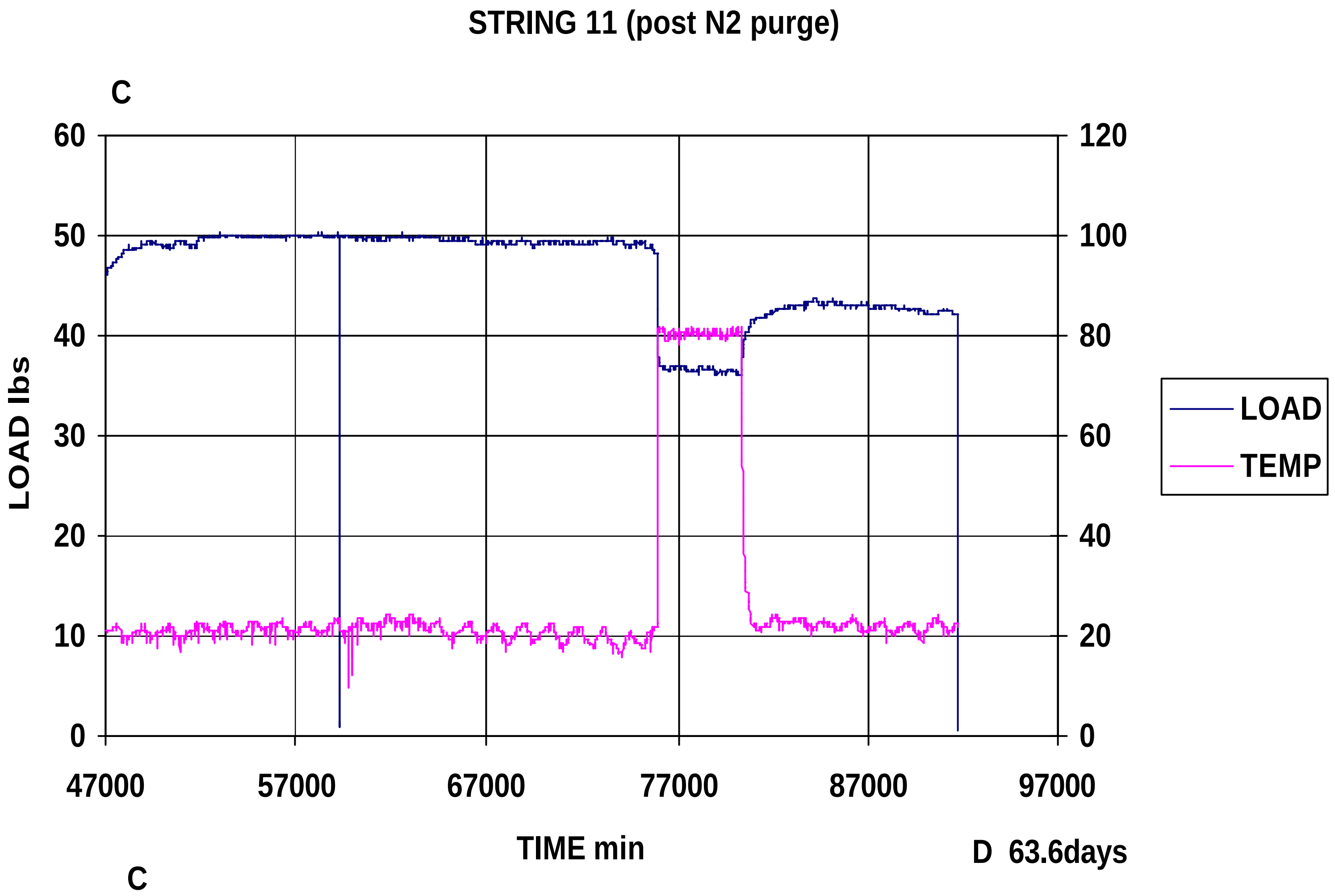
STRING8B LOADRELAXATION WITH THERMAL CYCLE
LOAD lbs
TEMPERATURE C
TIME min
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
100
90
80
70
60
50
40
30
20
10
0
0
60
120
180
240
300
360
420
480
540
600
660
720
780
840
900
960
1020
1080
1140
1200
1260
1320
1380
23.7
27.6
29.3
28.1
LOAD
CHAMBER
ROOM



12 in KEVLAR STRING #11 (load relaxation)
A
50
45
40
35
30
25
20
15
10
5
0
LOAD lbs
TEMPERATURE C
38.87
45.17
47.17
Series2
Series1
0
86400
172800
259200
A
TIME sec
2 hr increments
3671 min


STRING 11 (thermal cycles)
A
B
60.0
50.0
40.0
30.0
20.0
10.0
0.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
LOAD lbs
TEMPERATURE C
Load
Temp
223000
230200
237400
244600
251800
A
TIME sec
B
4194 min


STRING 11 (post thermal cycle) 0% rh
B
C
LOAD lbs
TEMPERATURE C
60
50
40
30
20
10
0
120
100
80
60
40
20
0
Load
Temp
4212
6012
7812
9612
11412
13212
15012
16812
18612
20412
22212
24012
25812
27612
29412
31212
33012
34812
36579
38379
40179
41979
43779
45579
C 32.7 days
B
TIME min


STRING 11 (post N2 purge)
C
60
50
40
30
20
10
0
120
100
80
60
40
20
0
LOAD lbs
LOAD
TEMP
47000
57000
67000
77000
87000
97000
TIME min
D 63.6days
C

Summary

- Kevlar CTE (unconditioned, 25^{o}C to -150^{o}C)
  - -11.9 μm/m^{o}C to -14.0 μm/m^{o}C
- Kevlar CTE (conditioned, 25^{o}C to -150^{o}C)
  - -12.0 μm/m^{o}C to –12.3 μm/m^{o}C
- Conditioning the kevlar reduces creep considerably

Kevlar Summit

L. Rodriguez
J. Martignac
CEA/DSM/DAPNIA
Service d'Astrophysique

Introduction

The aim for the CEA / SAp is to validate the Focal Plane concept, and especially the Kevlar wire suspension used inside the Bolometer Focal Plane Structure.

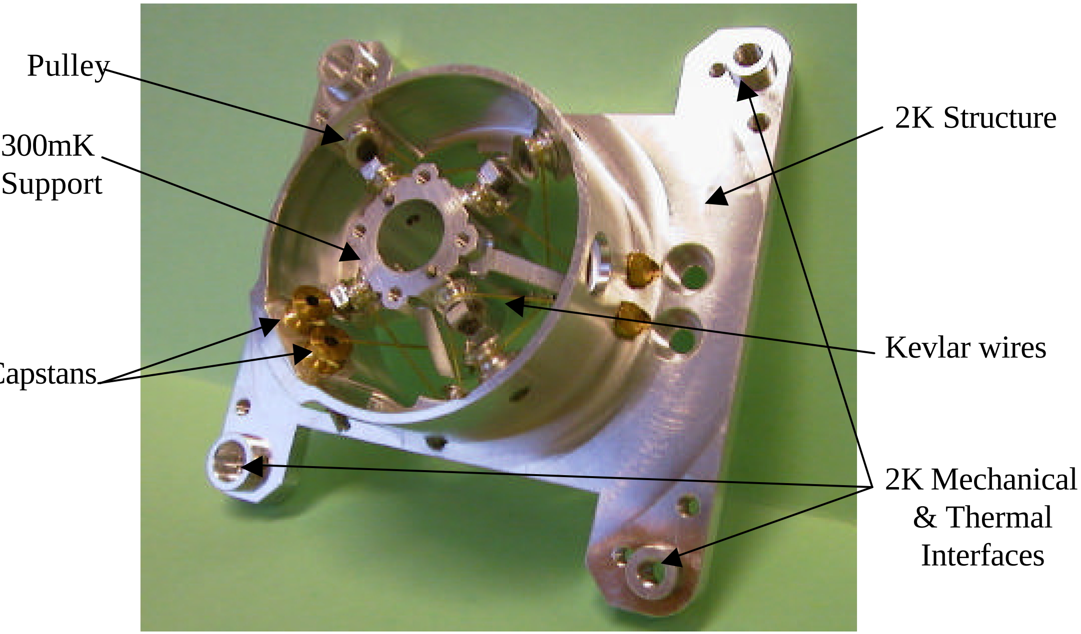
All the tests done on the Kevlar in Saclay are global measurement with BFP Structure :

- BFP Structure global stiffness measurement.
- BFP Structure warm vibration tests.

Future Tests to be done :

- Cold vibrations
- Thermal cycling (Life tests)

BFP Structure Presentation (prototype)



The BFP Structure is mainly composed by :

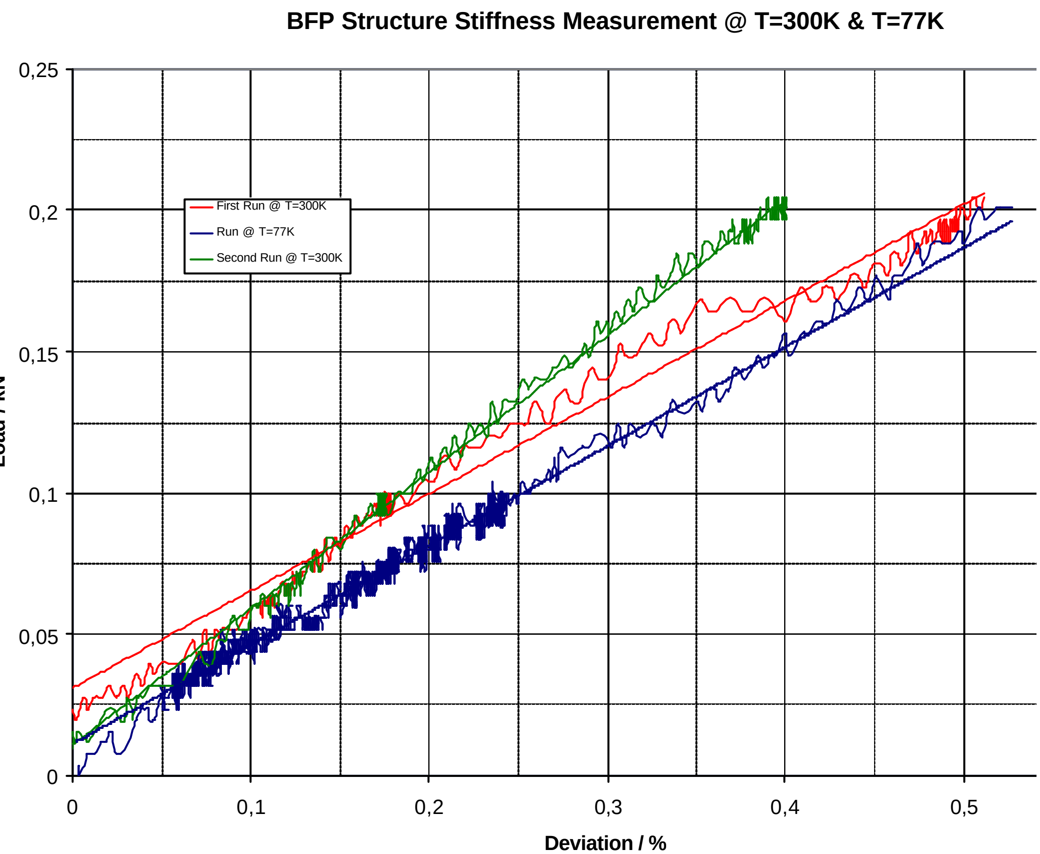
- an external structure at 2K;

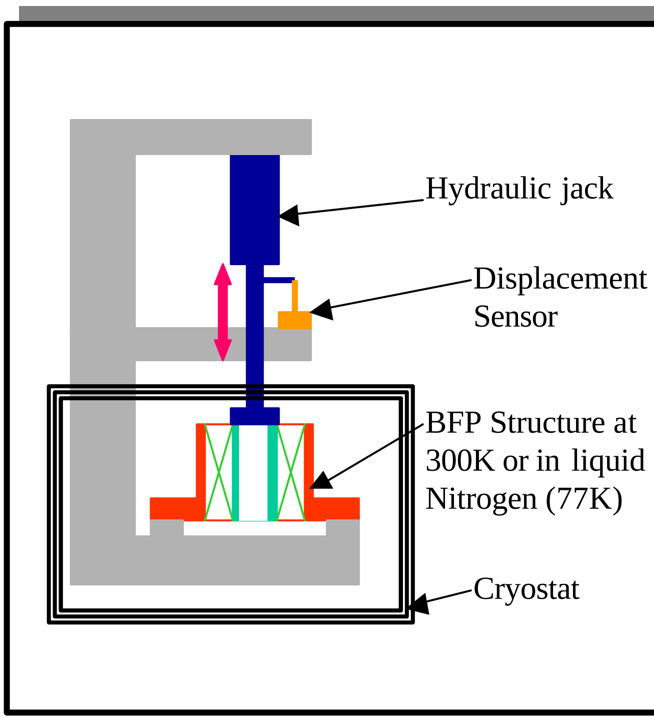
- an internal support at 300mK.

This support is suspended to the 2K structure by Kevlar wires tighten up (70 N.)with capstan set up.

Wire diameter : 0,29 mm
Max. Load : 120 N.

Global Stiffness Measurement on a prototype BFP Structure

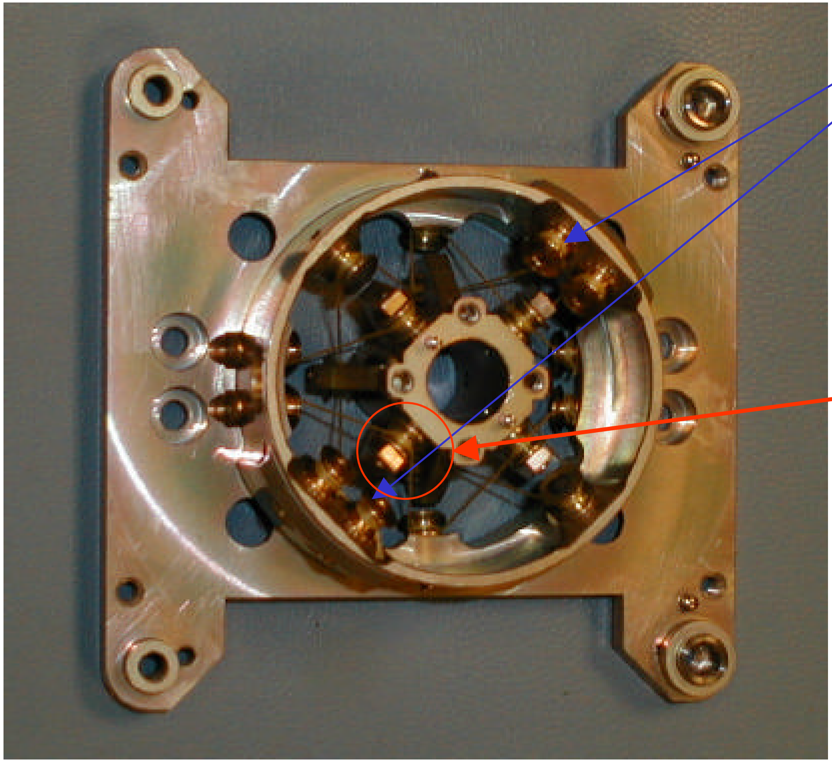




Test facility

The relative stiffness deviation between 77K and 300K is only 0,1%

Evolutions since the prototype Tests



-Additional Capstans set up in each side.

-'Dead turn' on each pulley + Glue

Goals :

-Avoid 300mK Support rotation after mounting tool release.

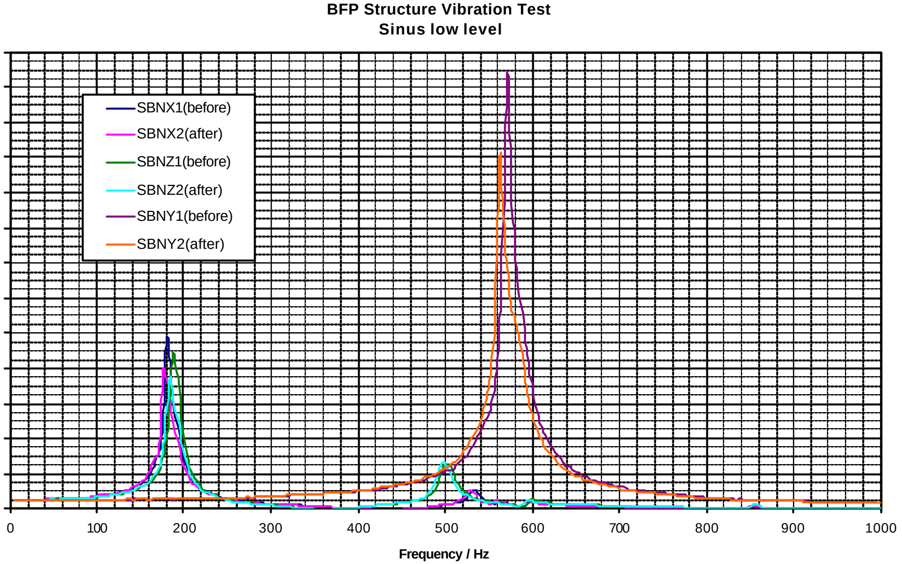
-Decrease 300mK Support displacement during vibrations tests.

BFP Structure Stabilisation

Thermal cycling : 3 cycles between 360K and 77K
Heating around 90°C during 3h. and cool down in liquid Nitrogen during few minutes.
Goal : Kevlar wire stabilization

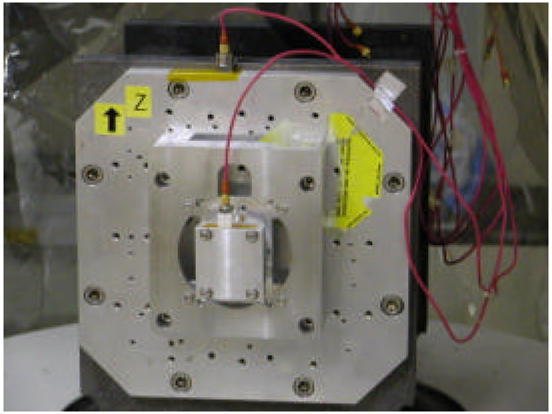
Mechanical shocks :
Manufacture of a special tool is in progress : given shocks will be done in each BFP Structure transverse direction.
Goal : Balance the Kevlar wires stretching before gluding.

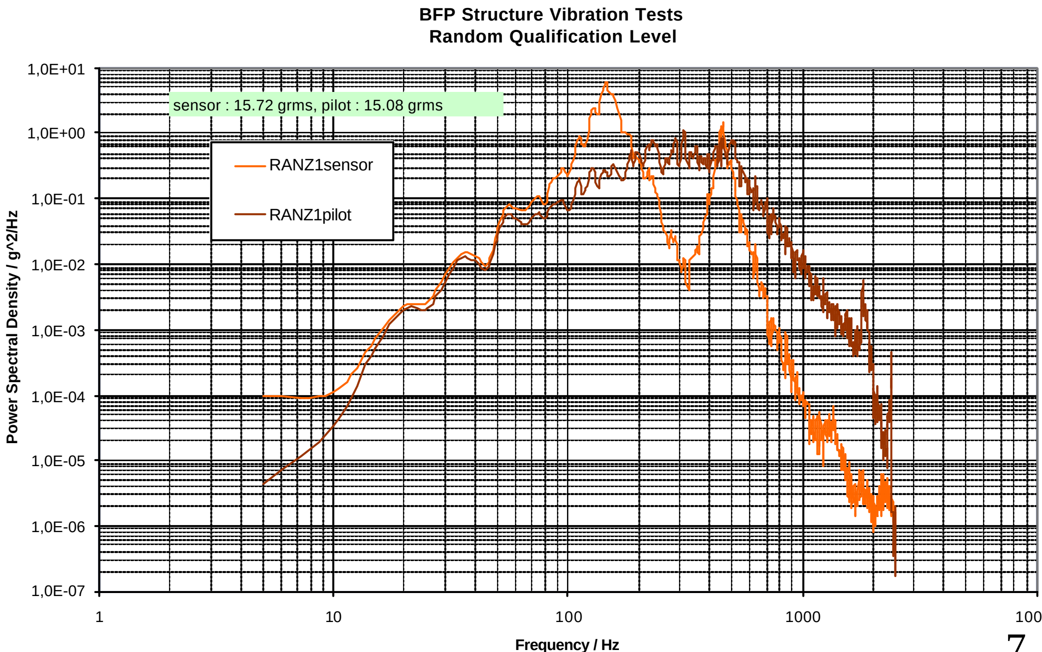
Vibration Test Results on BFP Structure



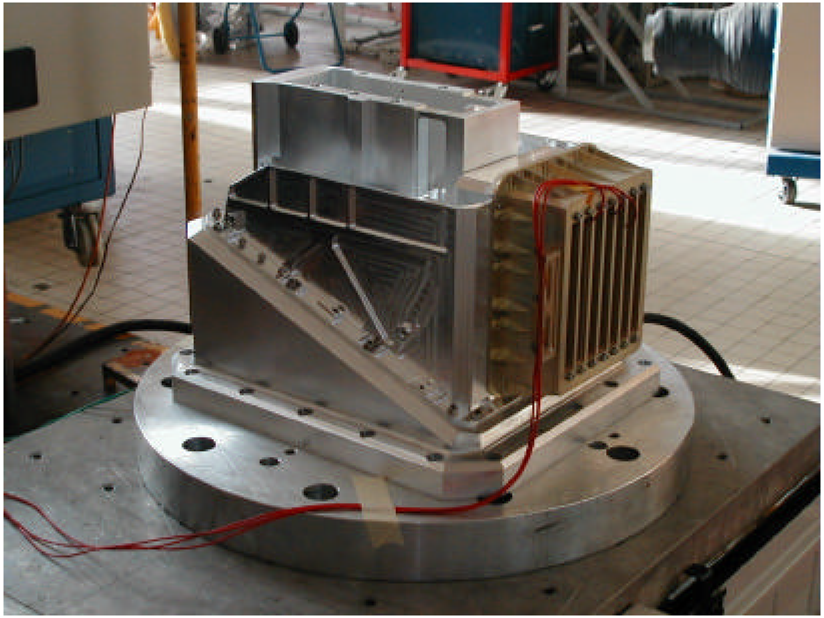
Transverse eigenfrequency : 180 Hz
Axial eigenfrequency : 560 Hz

Input levels are calculated from specifications : PACS-KT-AN-005

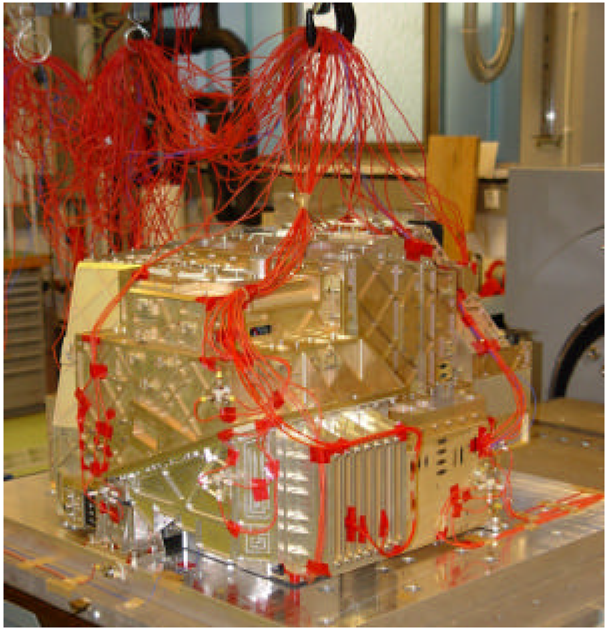




Vibration Test Results on Photometer



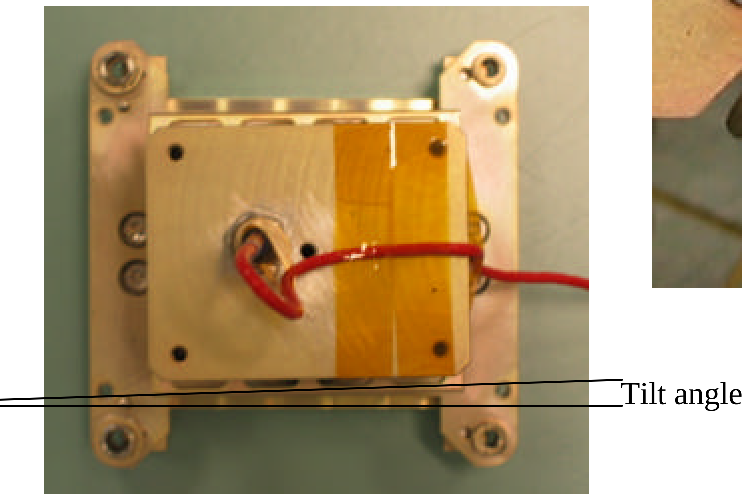
Integration & Vibration on PACS

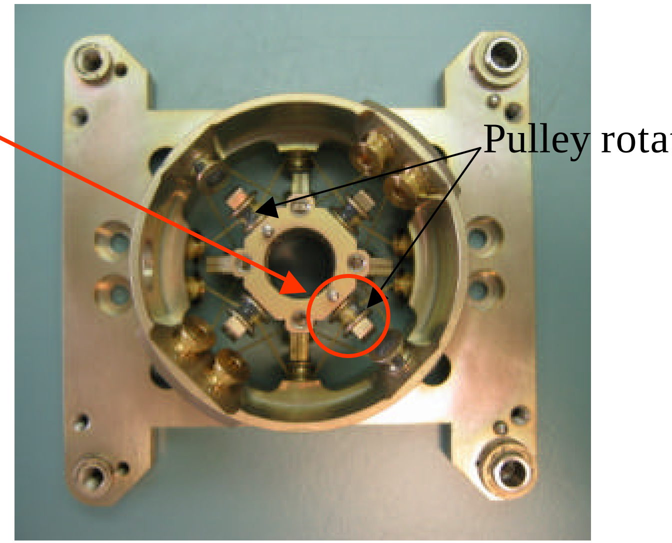


- Eigenfrequencies still the same.
  Level seen on the focal planes on PACS are lower than measured previously : 7,6 g rms instead of 78 g rms in axial direction.

- The PhFPU SM passed successfully the vibration tests (qualification levels) twice without damage.

BFP Structure Analysis





After vibrations we can observe a slight rotation of the 300mK focal plane :
Tilt angle = 0.5°

This rotation is due to the stretch relaxation between each kevlar wire.
It is foresee to solve this problem with shocks before gluding.

Future Programme

- New stiffness measurement (@ T=4K) on a BFP Structure;

- Cold vibration (@ T=4K) are foreseen with the PACS SM at CSL;
- In parallel a test facility (@ T=77K), only for the BFP Structure is under manufacture at Saclay;

- A test facility for Thermal cycling (Life test) between 4K and 300K is now operational in Saclay.

Conclusion

Our goal now is to verify that the behaviour of our BFP Structure under cold vibrations is fully compatible with requirements.

Today we demonstrated that :

- The global BFP Structure stiffness changes only by 0,1% between 300K and 77K .
- The Kevlar wires still ‘alive’ after warm vibration tests.

The future measurements should qualify :

- The Kevlar wires behaviour at T=77K.
- The Kevlar wires stability after 20 thermal cycles between 300K and 4K.

SPIRE & PACS Sorption Coolers EXPERIMENTAL CHARACTERISATION OF KEVLAR 29 CORDS

SBT internal ref : SBT/CT/2001-70

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SPIRE Approval			
PACS Approval			
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Project Approval	J.L Augueres - SAp HSO project manager	N/A	
Project Approval	L. Duband - Cooler project manager		

Service des Basses Températures (SBT)
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Document Status

Issue	Revision	Date	Nb of pages	Modifications
0	0	01/03/2001		First draft – previously referenced as a Technical Note Series TNS4
0	1	15/11/2001		Various addition (under ref. TNS4)
1	0	20/11/2001		Renamed as project technical note
1	1	04/09/2002		Various addition : § 5.1 : Chemical analysis § 5.3.1 : adjustement of cord tension
1	2	23/9/2002		& 5.10 : low temperature cycling added
1	3	20/11/2002		Adjustement of cord tension reviewed
1	4	28/2/2003		Fatigue behaviour added

CONTENTS

List of Acronyms

AD	Applicable Document		
CEA	Commissariat à l' Energie Atomique		
CDR	Critical Design Review	Revue de conception détaillée	RCD
CQM	Cryogenic Qualification Model		
ECSS	European Cooperation for Space Standardisation		
FIRST	Far Infrared and SubmillimetreTelescope		
FS	Flight spare		
HSO	Herschel Space Observatory		
N/A	Not Applicable		
PACS	Photoconductor. Array Camera and Spectrometer		
PFM	ProtoFlight Model		
PSS	Product Assurance Specification System		
RD	Reference Document		
SAp	Service d'Astrophysique		
SBT	Service des Basses Températures		
SCO	Sorption Cooler(full unit)		
SPIRE	Spectral & Photometric Imaging Receiver		

1 Scope of the document

The SPIRE/PACS sorption coolers utilise a suspension system using Kevlar cords. This material is critical to the performance of the cooler in terms of thermal efficiency, mechanical behaviour and reliability. Consequently it is important to gather as much informations as possible on the properties and behaviour of Kevlar. This is the purpose of this technical note.

2 Documents

2.1 Applicable documents

N/A

3 Kevlar general characteristics

KEVLAR® was invented by Stephanie Kwolek in the mid 60s and then introduced by DuPont in the1970s. It was the first organic fiber with sufficient tensile strength and modulus to be used in advanced composites. Originally developed as a replacement for steel in radial tires, Kevlar is now used in a wide range of applications. It is probably best known for its application in the field of bullet-resistant personal body armor. But the applications for the light weight and strength of KEVLAR® are many, and the list continues to grow.

Kevlar is an aramid, a term invented as an abbreviation for aromatic polyamide. The chemical composition of Kevlar consists of long molecular chains produced from poly-paraphenylene terephthalamide and it is more properly known as a para-aramid. The chains are highly oriented with strong interchain bonding which result in a unique combination of properties. Aramids belong to the family of nylons. Common nylons, such as nylon 6.6, do not have very good structural properties, so the para-aramid distinction is important. The aramid ring gives Kevlar thermal stability, while the para structure gives its high strength and modulus.

Like nylons, Kevlar filaments are made by extruding the precursor through a spinneret. The rod form of the para-aramid molecules and the extrusion process make Kevlar fibers anisotropic - they are stronger and stiffer in the axial direction than in the transverse direction. In comparison, graphite fibers are also anisotropic, but glass fibers are isotropic. The Kevlar precursor is very stable both chemically and thermally.

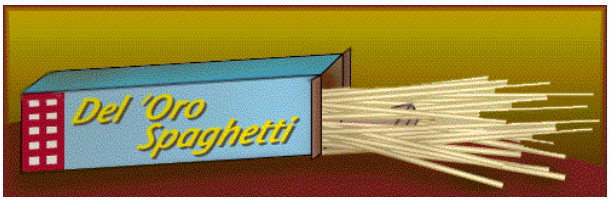
We have reproduced below a discussion by the Lawrence Berkeley National Laboratory (CA-USA) which resume some of the aspect above and deals with what makes Kevlar so strong (http://www.lbl.gov:80/MicroWorlds/Kevlar/) .

Reason #1

KEVLAR is a long chain-like molecule known as a polymer, which consists of repeating units called monomers.

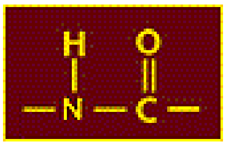
Reason #2

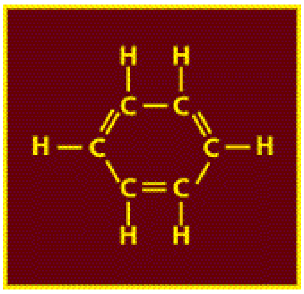
A Kevlar fiber is an array of molecules oriented parallel to each other like a package of

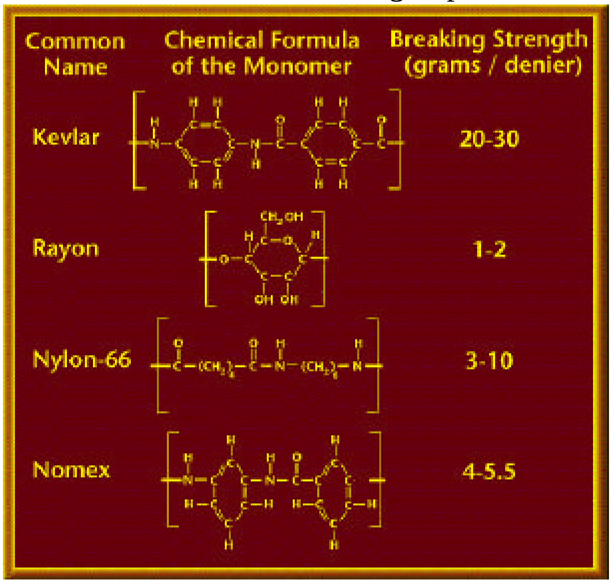


uncooked spaghetti. This orderly, untangled arrangement of molecules is described as a crystalline structure. Crystallinity is obtained by a manufacturing process known as spinning, which involves extruding the molten polymer solution through small holes. The crystallinity of the Kevlar polymer strands contributes significantly to Kevlar's unique strength and rigidity.

<u>Reason #3</u>
Kevlar is a polyaromatic amide. That is, it contains aromatic and amide groups.
Other polymers with a high breaking strength often contain one or both of these molecular groups.

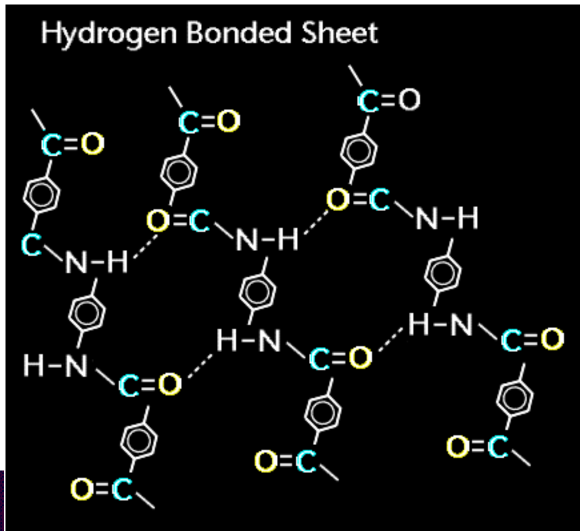




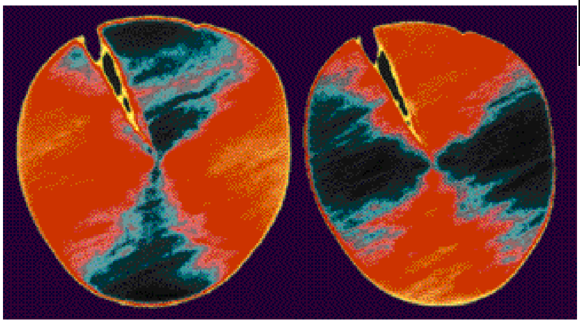


Common Name	Chemical Formula of the Monomer	Breaking Strength (grams / denier)
Kevlar		20-30
Rayon		1-2
Nylon-66		3-10
Nomex		4-5.5

<u>Reason #4</u>
The individual polymer strands of Kevlar are held together by hydrogen bonds that form between the polar amide groups on adjacent chains.



<u>Reason # 5</u>
The aromatic components of Kevlar polymers have a radial (spoke-like) orientation, which gives a high degree of symmetry and regularity to the internal structure of the fibers.



This crystalline-like regularity is the largest contributing factor in the strength of Kevlar. Only with bright synchrotron radiation could the secret strength of Kevlar be revealed.

All these features contribute to the strength of Kevlar.

Today, there are three grades of Kevlar available: Kevlar 29, Kevlar 49, and Kevlar 149. The tensile modulus and strength of Kevlar 29 is roughly comparable to that of glass (S or E), yet its density is almost half that of glass. The table below shows the differences in properties : these are general values for the fiber itself and are given for illustration purpose as the actual strength and Young's modulus of our Kevlar cords are slightly different as presented further.

Grade	Density $g.cm^3$	Young's modulus GPa	Ultimate strength MPa	Tensile elongation %
29	1.44	83	3600	4
49	1.44	131	3600 – 4100	2.8
149	1.47	186	3400	2

Kevlar has other advantages besides weight and strength. Like graphite, it has a slightly negative axial coefficient of thermal expansion, which means Kevlar laminates can be made thermally stable. Unlike graphite, Kevlar is very resistant to impact and abrasion damage. It can be used as a protective layer on graphite laminates. Kevlar can also be mixed with graphite in hybrid fabrics to provide damage resistance, increased ultimate strains, and to prevent catastrophic failure modes.
Like all good things, Kevlar also has a few disadvantages. The fibers themselves absorb moisture, so Kevlar composites are more sensitive to the environment than glass or graphite composites. Although tensile strength and modulus are high, compressive properties are relatively poor.

For our particular applications we take advantage of its hight tensile strength, its relatively high Young's modulus and its low thermal conductivity at low temperature. We have reported in the table hereafter a comparison between Nylon, stainless steel, Titanium Ta6V and Kevlar. As a first approxiamtion the goal is to maximise the resonant frequencies (proportionnal to the square root of the Young's modulus "Y") and the strength "σ", and to minimise the thermal load (proportionnal to the integrated thermal conductivity "I" between say 0.3 and 2 K).

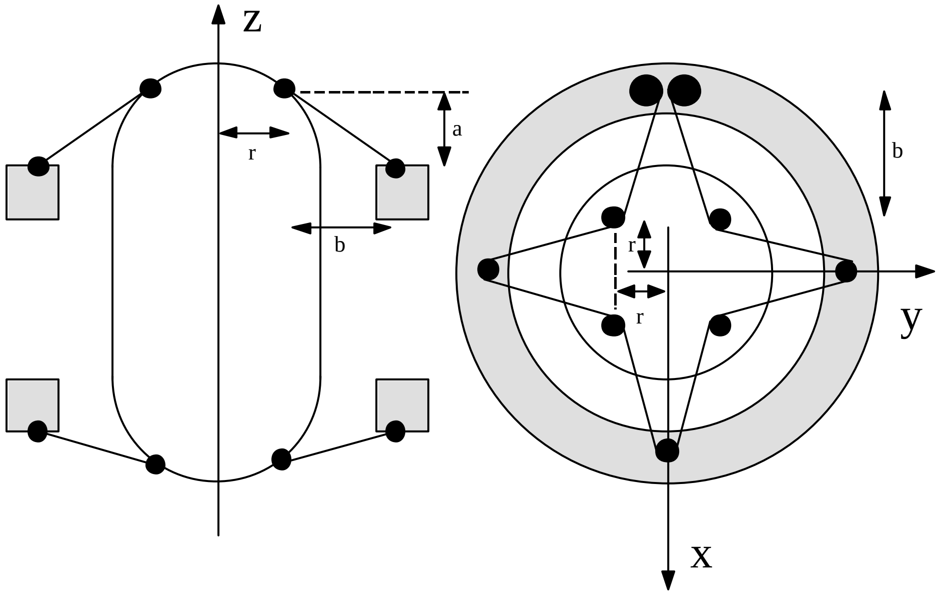
	Nylon	Stainless	Titanium Ta6V	Kevlar 29
*s (MPa)**	100	550	875	1600
*Y (MPa)**	3 000	200 000	110 000	65 000
I (W/cm)	$5.9\ 10^{-5}$	$2\ 10^{-3}$	10^{-3}	$7\ 10^{-5}$
$s.Y^{0.5}/I$	$0.9\ 10^{8}$	$1.2\ 10^{8}$	$2.9\ 10^{8}$	$58\ 10^{8}$

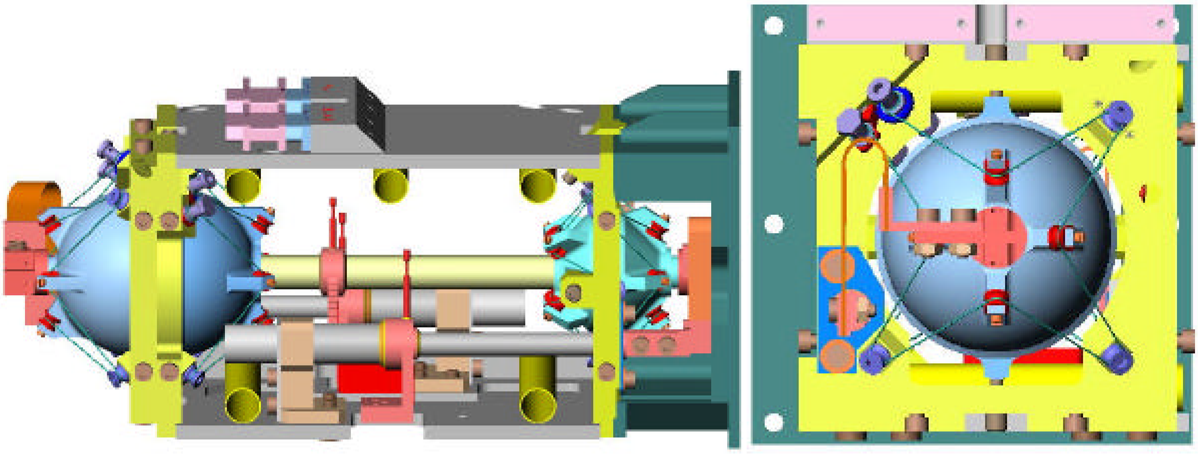
(*: mechanical properties at ambiant temperature)

These data clearly shows the benefit of Kevlar.

4 Description of support structure

The suspension system must firmly support the refrigerator during launch while minimising the parasitic heat load on the system. Various geometries and materials can be used. The selected geometry for the support structure shall take advantage of the available space and symetry. For most coolers we have developed this space has been a square or rectangular box, and thus a geometry with four attachment points has been used as detailed hereafter.





The 4 "attachment points" are actually pulleys : the support system for each element of the refrigerator consists of 2 separate Kevlar cords, one on each end of the suspended object, each wound around pulleys and ending its course by being wound around a capstan. Such a design allows for easy adjustment and balancing of the tension in different parts of the cords and in addition is far less sensitive to any creep (as compared to a support system using 8 separate cords). The capstan serves as an excellent device to attach the end of the cord and maintain tension. It is important that the support system is not weakened by bad attachment of the end of the cord (see & 4.3).

The support system is vulnerable to some potential difficulties :

- the weakening of Kevlar cord when it goes around a pulley. Kevlar, because of its anisotropic molecular chain structure, is strong in the longitudinal but weak in the transverse directions. A minimum pulley diameter is necessary in order not to weaken the cords. In addition a way to tension and lock the end cord must be developed

- the creep of Kevlar cord which, again, has the danger of significantly reducing tension in the cord

- the negative longitudinal thermal expansion of Kevlar (it expands longitudinally when it cools down). Such expansion lowers the tension of the cord and might loosen it up all together

In addition to these aspects we have performed additionnal experimental studies on the cords such as the fatigue behaviour, the effect of baking, etc…

5 Specific features

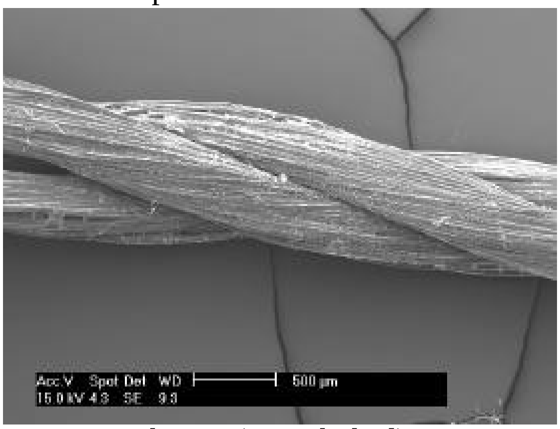
5.1 Kevlar type

The Kevlar cords we use are made of Kevlar 29. The bulk material comes from Dupont de Nemours and is then shaped by Cousin, a company located in the north of France (Cousin filterie, 8 rue Abbé Bonpain, BP 6 Wervicq Sud, 59558 Comines Cedex). Two types of cords are used :

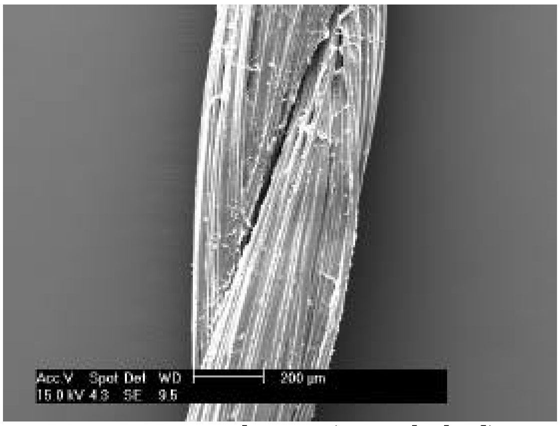
- Kevlar 11 – diameter 0.5 mm, 3 strands, with a breaking strength 30 to 40 DaN (best case)
- Kevlar 34 – diameter 0.29 mm, 2 strand, with a breaking strength 10 to 15 DaN (best case)

Note : it is not easy to measure the actual breaking strength of a cord, which explains the range of values

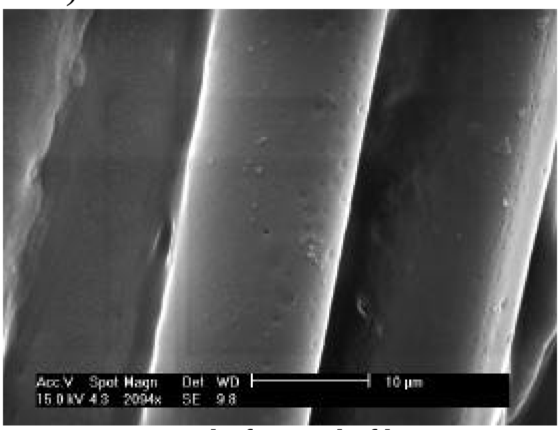
The following pictures below, taken with a scanning electron microscope (Philips XL30), show the aspect of both cords.



Kevlar 11 (80°C baked)



Kevlar 34 (80°C baked)

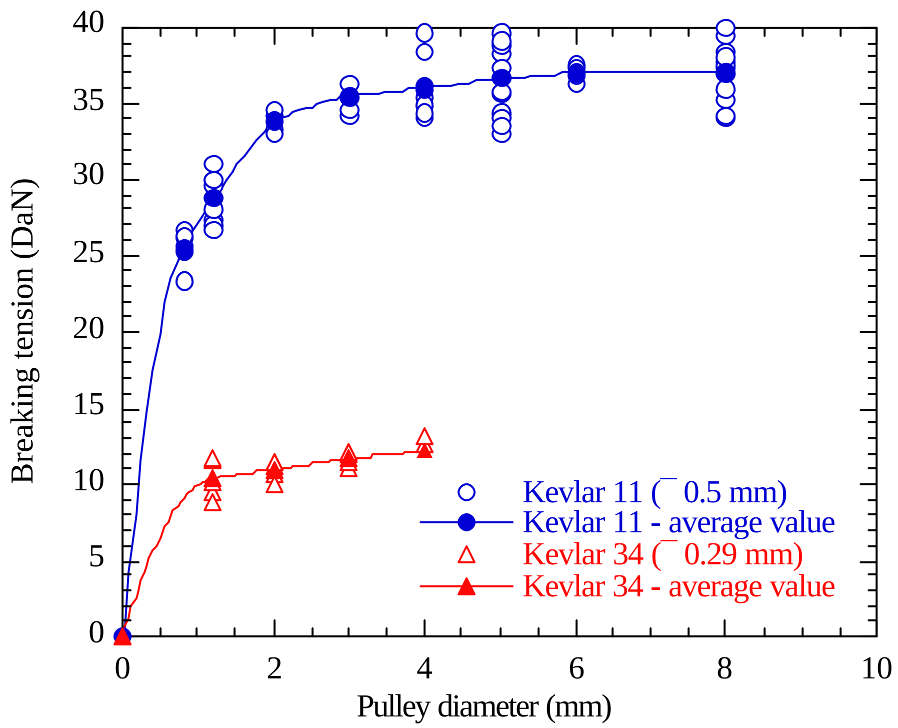


Detail of a single fiber

A material analysis has been performed on the Kevlar 34 by the “Société d’Etudes et de Services pour l’Analyse des Matériaux” (SESAM), to determine the nature of the material used for the “coating/bonding” of the Kevlar cords. The analysis was done using an infrared spectrometric method (Fourier transform in ATR (Réflexion Totale Atténuée)). The results indicate this coating is made of silicone of type poly (diméthylsiloxane).

5.2 Pulley diameter

The first question is what pulley diameter is required to obtain the full rated strength of the cords. A simple experimental set-up has been developed, which allow to pull on a cord wound around various pulleys of different diameter, while a force transducer measure the tension. The results of these measurements, carried out at room temperature for both cords (0.5 and 0.29 mm diameter), are presented on the curve hereafter.

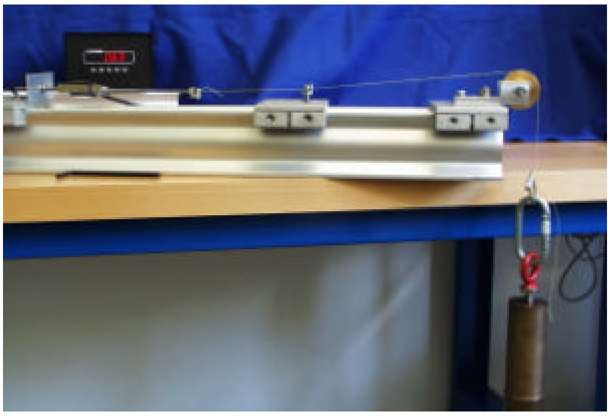


Influence of pulley diameter on the breaking strength

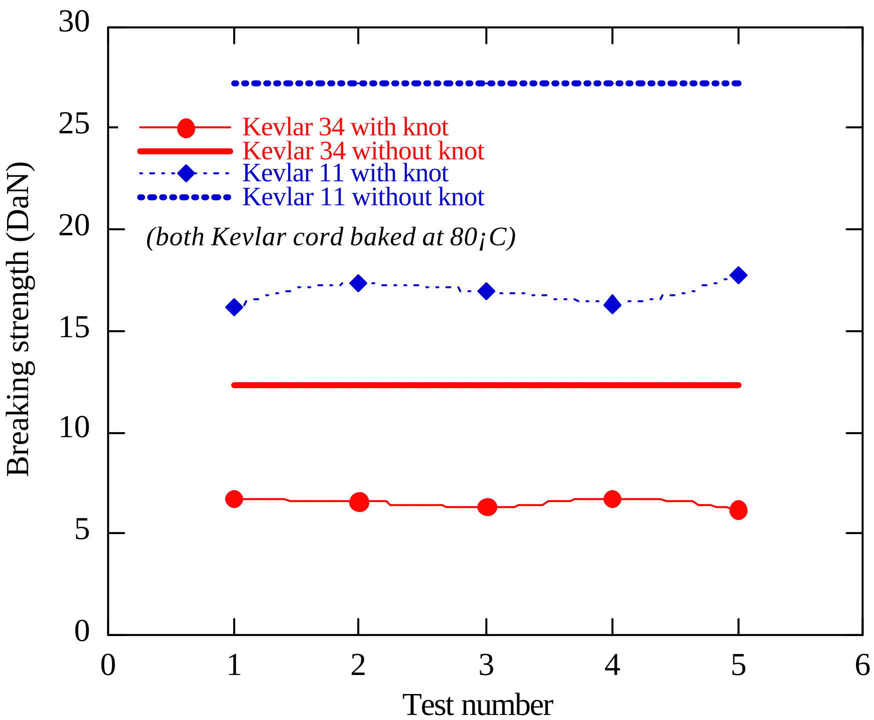
These tests show that for both cords, pulleys of diameter = 3 mm are adequate to realize the full rated strength. In our design we have settled for 4 mm diameter pulleys and capstan.

5.3 Tensioning and locking

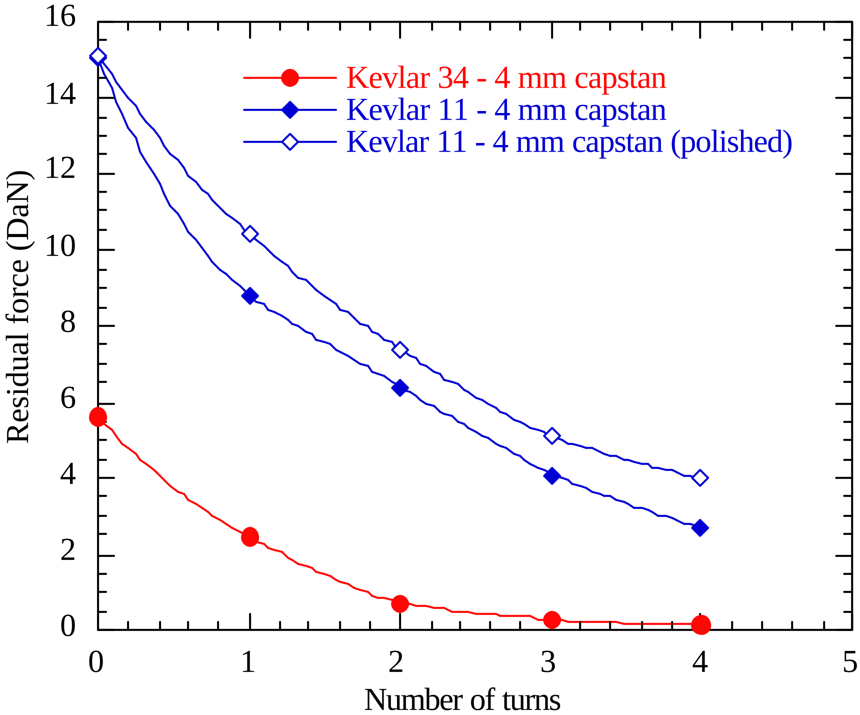
The Kevlar weakness in transverse directions requires a specific way to lock the end cord. Any direct knot on the cord must be avoided. As an illustration tests have been performed on both Kevlar cord (80°C baked) on the influence of a simple knot on the breaking strength. These results, presented on the following figure, clearly show the knot decreases the breaking strength by a factor of roughly 50% (as expected this factor increases as the cord diameter increases, because while the fiber itself remains the same the radius of curvature of the cord at the knot becomes larger with the cord diameter – *the best knots on climbing ropes can allow 80% of the breaking strength*).



To get around this problem the idea is to come up with a solution where the remaining tension in the cord is low enough it is acceptable to sollicitate the kevlar in the transverse direction. The method we have chosen is to make a few turn around a capstan before locking the cord. The figures hereafter deal with this aspect. The first experiment is simple : the cord is permanently loaded on one side, then goes around a capstan by "n" turns and is attached to a force transducer on the other side The first figure shows how the remaining tension is affected as a function of the number of turns around the capstan.

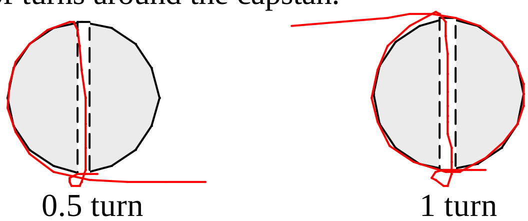


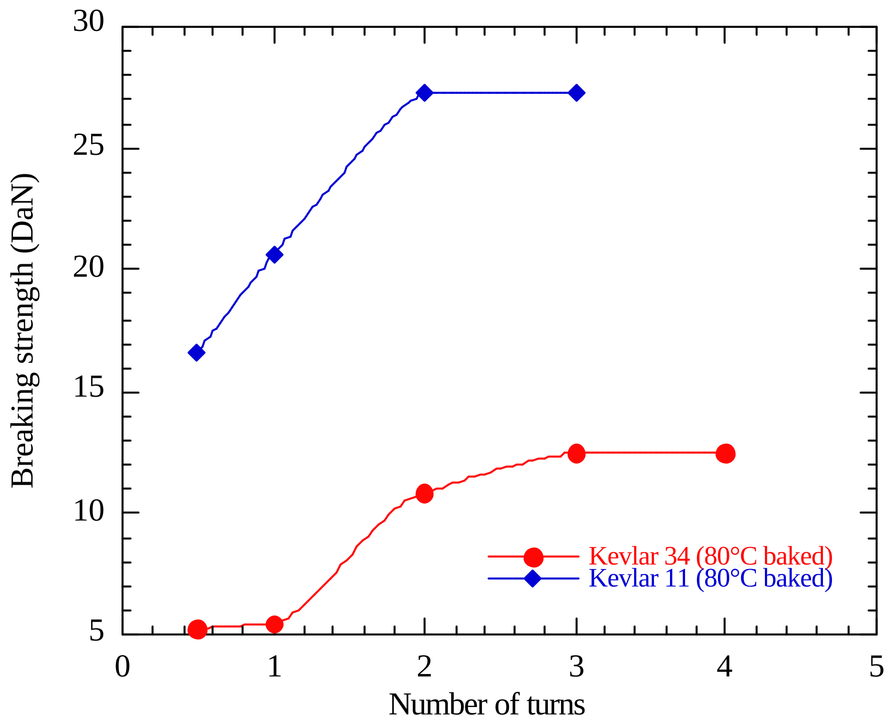
Effect of a knot on the breaking strength



Cord permanently loaded on one side - Remaining force in cord other side after "n" turns around capstan

The second experiment is somewhat similar : the capstan we use features a hole, in which one end of the cord is inserted and locked (knot), while the other end is wound around by "n" turns (see next figure). The curve hereafter shows the breaking strength of this arrangement as a function of the number of turns around the capstan.





Breaking strength as a function of the number of turns around the capstan

These results show that a cord arrangement featuring 3 turns around the capstan allows to lower the remaining tension at the end cord to a level such Kevlar can be sollicitate in the transverse direction (knot).
Note that one can argue the tension at the end cord may slowly increases along time as the cord can slip around the capstan and the "force may propagate". To try to address this potential problem we have performed tests where we left one end of the cord loaded while we measured the tension at the other end (after 3 turns around the capstan) : after 4 days the value remained unchanged. This aspect is further discussed in paragraph 4.8.

From the previous results the technique we use to lock the kevlar cord is displayed in the following set of pictures. Note that this technique is feasible both ways (it must be) : cord starting from the capstan or ending at the capstan.
For the Kevlar 11 (0.5 mm diameter) a knot is not required at the end cord (as shown on the pictures) but we decided to have the same attachment method for both cords – the knot has been added to avoid for the smaller cord (0.29 mm) that the cords which are wound up each other could get into the hole in the capstan. This could then result in a loss of friction between the two cords and consequently a loss of locking (the hole in the capstan is 1 mm diameter first for convenience and second to be able to round the hole edges – indeed 3 x 0.29 mm < 1 mm).

Cord begining its course at capstan			
			
1	*2*	*3*	*4*

Cord ending its course at capstan			
			
1	*2*	*3*	*4*

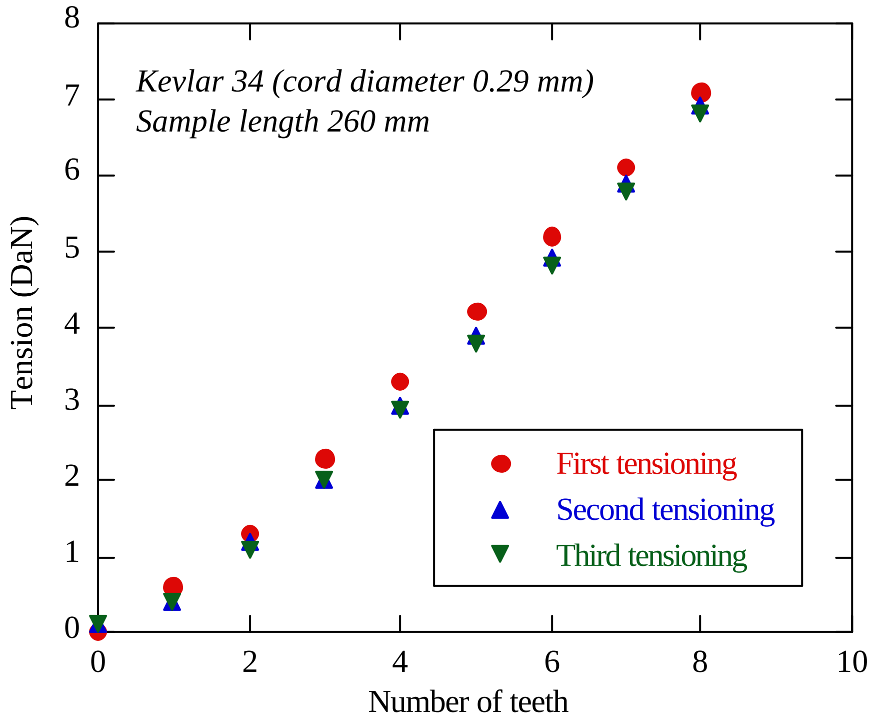
Attachment technique (shown scale X10 approximately)

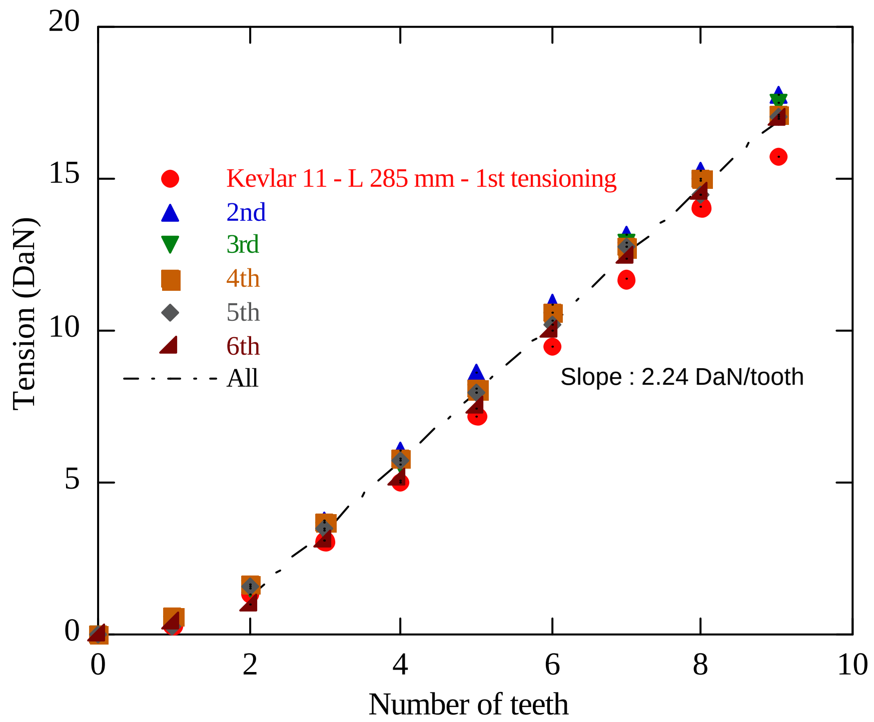
Actual capstan size- Cord 0.29 mm shown

5.3.1 Adjustement of cord tension

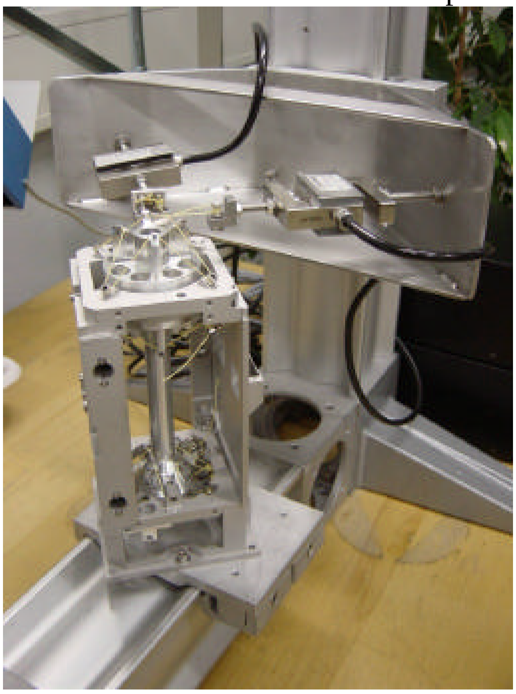
The suspensions system of the HSO sorption coolers features capstans equipped with ratchets. During tensioning the ratchet prevents the cord to unwind and allows to lock the capstan once the desired tension has been set. In addition the ractchet is actually used to adjust the tension in the cord. This is shown on the following curves. In the first set we have reported for both cords the evolution of tension as a function of the rotation of the capstan in terms of teeth on the ratchet – measured for a representative straight lentgh of cord.

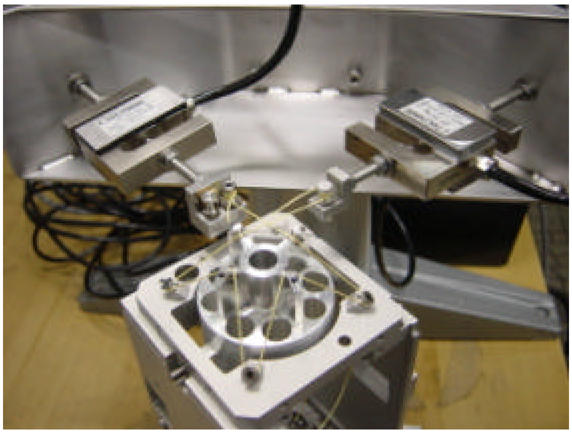


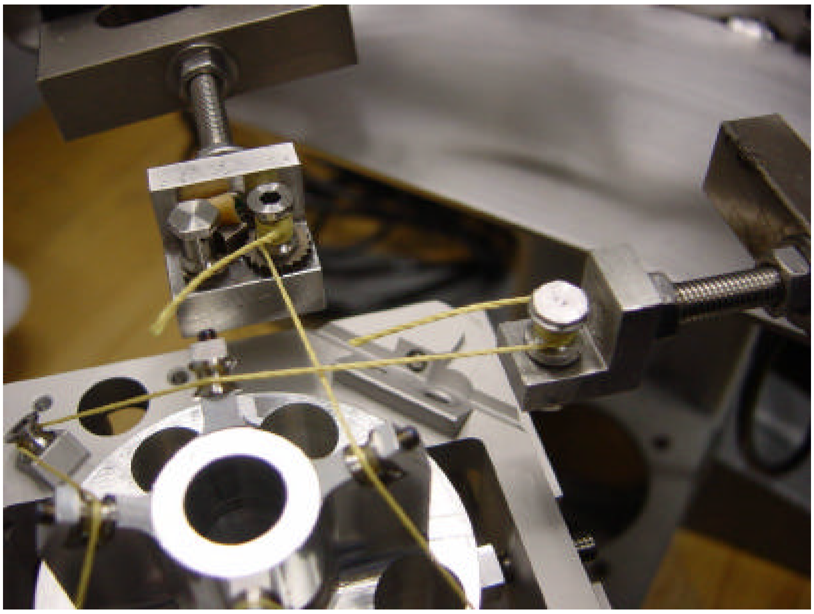
The slope of this curve is 0.9 DaN per teeth, consistent with the theoretical value of 1.05 DaN obtained using the young's modulus and capstan geometry.
Similarly for the Kevlar 11 we obtain the following result.

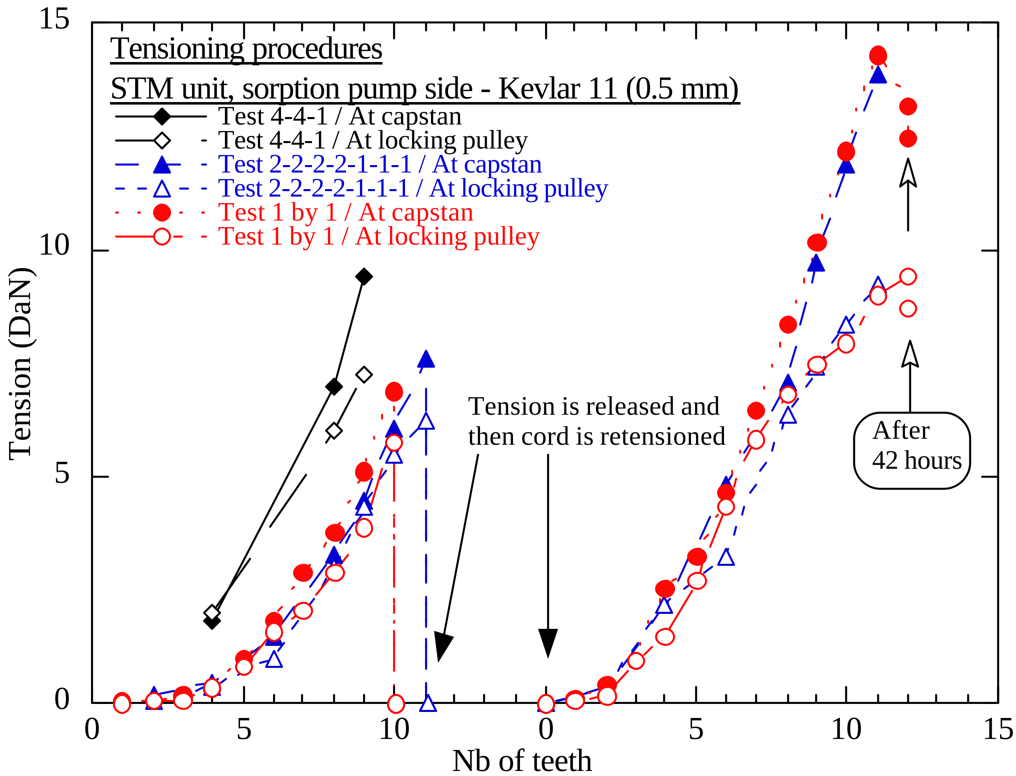


In reality the cords are wound around pulleys and end their courses by being wound around one locked and one free capstan.
A test bench has been set up using the real suspension system, a STM unit and two force transducers. The two capstans, normally mounted on the structure, have been mounted on some fixture mechanically attached to the force transducer. This set-up, shown on the following figure, is fairly representative of the real case. We have been able to measure the tension at both ends and to come up with a tensioning procedure – see following curves.

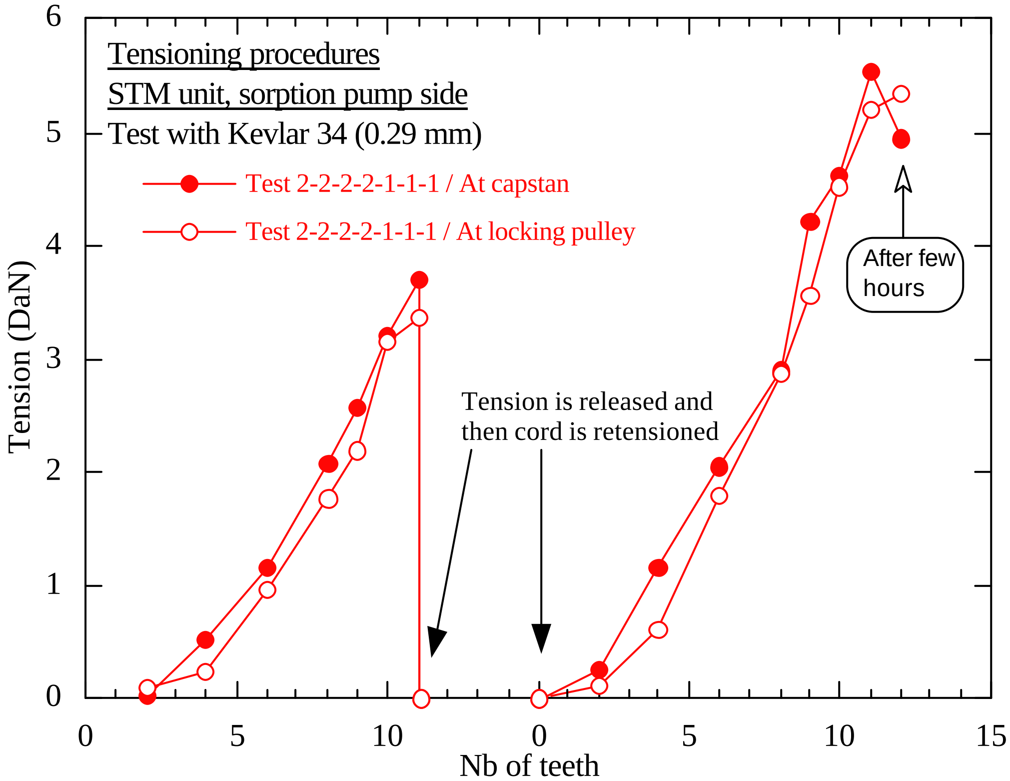


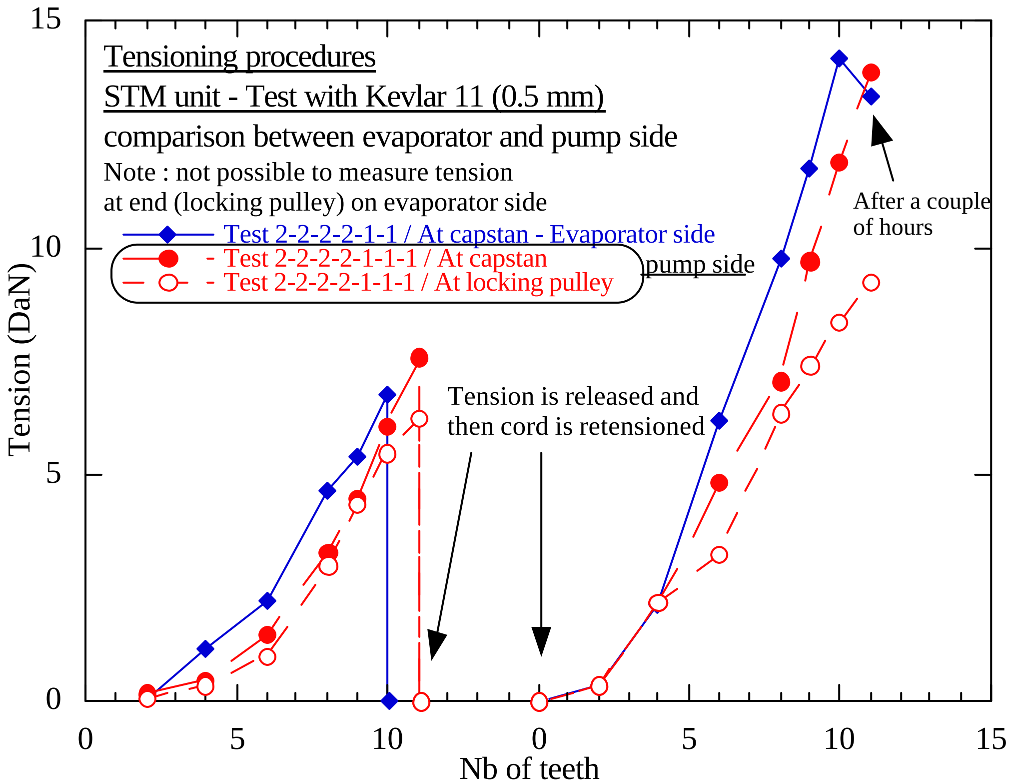






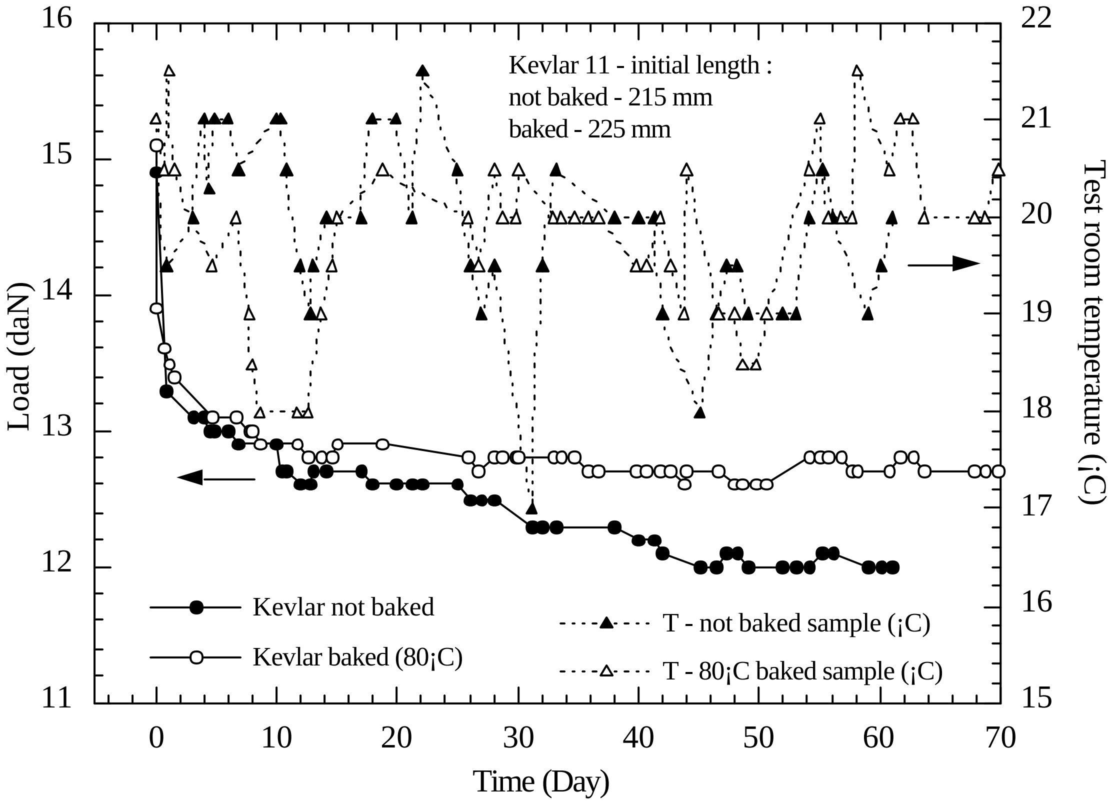
The selected procedure is displayed on the two following curves. Note that after the first tensioning the slope of the curve for the 0.5 mm cord is about 2 DaN/tooth, consistent with the previous measurements (actual length of cord is about 285 mm).

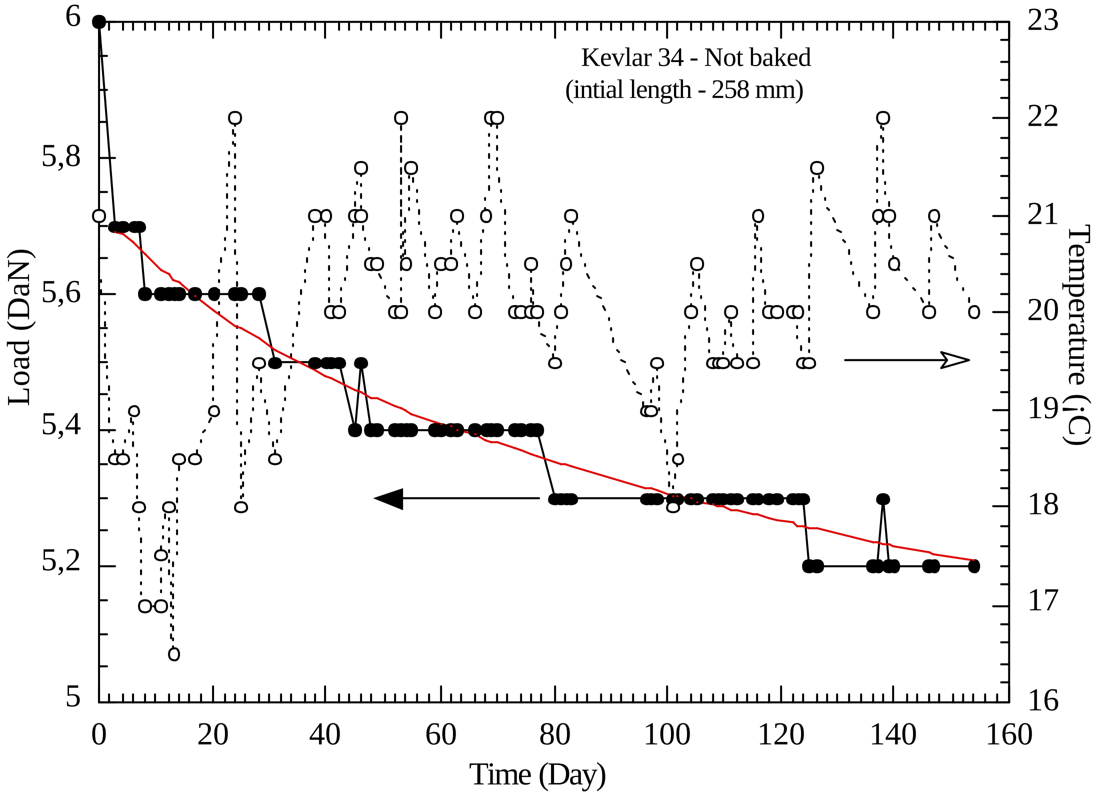

Tensioning procedures
STM unit, sorption pump side
Test with Kevlar 34 (0.29 mm)
Test 2-2-2-2-1-1-1 / At capstan
Test 2-2-2-2-1-1-1 / At locking pulley
After few hours
Tension is released and then cord is retensioned
Tension (DaN)
Nb of teeth
0
1
2
3
4
5
6
0
5
10
0
5
10
15


Tensioning procedures
STM unit - Test with Kevlar 11 (0.5 mm)
comparison between evaporator and pump side
Note : not possible to measure tension
at end (locking pulley) on evaporator side
Test 2-2-2-2-1-1 / At capstan - Evaporator side
- Test 2-2-2-2-1-1-1 / At capstan
- Test 2-2-2-2-1-1-1 / At locking pulley
pump side
After a couple of hours
Tension is released and then cord is retensioned
Tension (DaN)
Nb of teeth
0
5
10
15
0
5
10
0
5
10
15

5.4 Kevlar creep

Kevlar creep has the danger of significantly reducing tension in the cord. Recent measurements indicate that the creep at room temperature remains limited; the cord can be retensioned at least 1 day after the initial tensioning and there shouldn't be any problem. Nevertheless this effect is compensated by the increase in Young's modulus at low temperature (see paragraph 4.5). To further study this aspects creep measurements have been performed on the two Kevlar cords of lengths and initial loads representative of the foreseen support structure for the SPIRE/PACS cooler. The first sample are taken directly from the supplier spool as the second one are first baked at 80°C under vacuum.
These creep results, displayed on the following figures, are very important since they provide indication on the potential loss of tension over time for the support structure.





These results indicate that after a couple days a 10% decrease in tension would require the following time :

- over 40 years for the Kevlar 11 baked
- 3 to 4 years for the Kevlar 34 not baked (experiment on baked Kevlar in progress)

5.5 Young's modulus and breaking strength

A specific test set up has been developed to determine the Young's modulus of our Kevlar in real situation, i.e. tension in between two capstans as described before. The results include not only the actual Young's modulus but the slippage of the cord if any, etc....It is indeed this "overal" value which will drive the resonant frequencies.

The basic principle is simple : we measure for a known length of cord the tensioning force versus displacement. The set up features an external thermally isolated stainless steel envelope. This "cryostat" can be filled with liquid nitrogen so that the two end capstans and cord are immersed in liquid and consequently maintained at 77 K. The force transducer and displacement sensor remains at ambiant temperature.

As reported in the table hereafter there is an hysteresis between the tensioning and detensioning phase. This might be due to the braided structure (friction between single fibers). In any case the values measured are consistant with values previously measured (Kevlar cord only) and with values given by the supplier. Both cords (0.29 and 0.5 mm) exhibit the same modulus.

Remark : Kevlar 49 has a Young's modulus twice as high as Kevlar 29 and could be a better material. However we have not been able to find a supplier of braided Kevlar 49 and more importantly this difference in Young's modulus seems only true for small tension : the force versus strain for Kevlar 49 is pretty much a straight curve as for Kevlar 29 it is curved upward; consequently the Young's modulus of Kevlar 29 increases as the load increases and in fact may even exceed that of Kevlar 49 for high load. This is best shown on the curve hereafter extracted from a technical note from Dupont de Nemours.

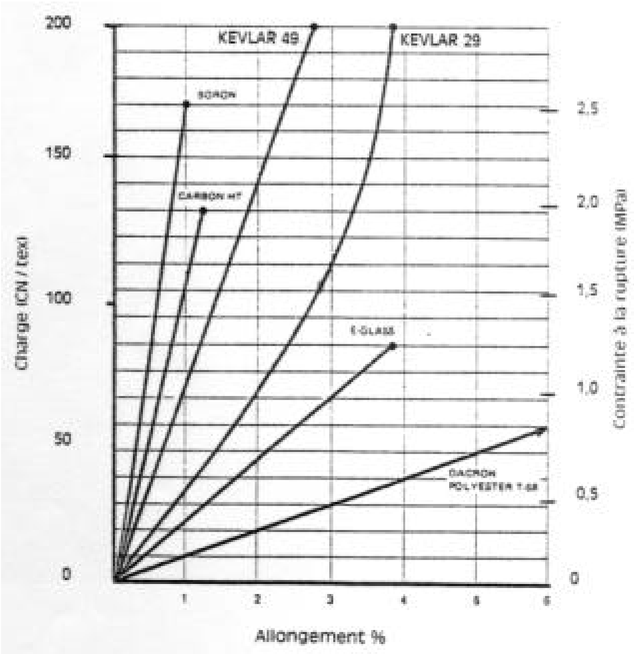
	Kevlar 29 Young's modulus	
	Tensioning phase	De- tensioning phase
Room temperature	66 GPa	91 GPa
Nitrogen temperature	108 GPa	118 GPa
Previous measurement* (other supplier) - Data for braided cord	Room temperature : 29 GPa Nitrogen temperature : 58 GPa	
Supplier data (Dupont de Nemours) (ambiant temperature)	59 GPa (fiber alone is 83 GPa)	

* : ***Thermal isolation of large loads at low temperature using Kevlar rope,*** L. Hui, L. Duband and A. Lange, *Cryogenics* (1993) **33** p. 643-647

The same set-up has been used to measure the breaking strength at nitrogen temperature.

	Breaking strength
Room temperature	1600 to 1800 MPa
Nitrogen temperature	

COMING SOON



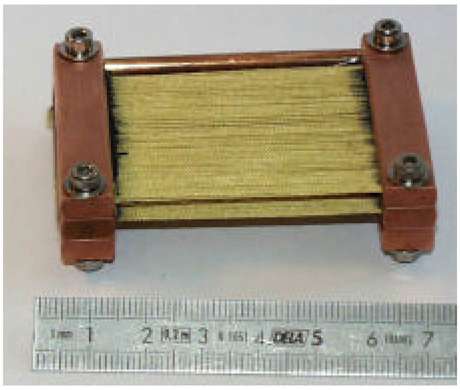
5.6 Thermal expansion

One potential difficulty is the negative longitudinal thermal expansion of Kevlar (it expands longitudinally when it cools down). Such expansion lowers the tension of the cord and might loosen it up all together. The only data we are aware of on the thermal expansion of Kevlar at cryogenic temperature is that of a Kevlar 49 epoxy-composite (60% Kevlar 49 by volume). Its fractional integral expansion in the longitudinal direction from 293K to 0K is -9 10^{-4}. We assume that this also gives a reasonable estimate of the thermal expansion of Kevlar 29 cord. (Kevlar 29 and 49 have the same coefficients of thermal expansion at room temperature). Note that the estimate of thermal expansion of Kevlar cord is further complicated by its weave structure. In any case and assuming the Young's modulus remains constant between room and low temperature (77 K) a rough calculation on the pump side for instance, taking into account the structure, sphere and Kevlar cords, shows that the initial tension of 15 DaN decreases to 11 DaN (which remains acceptable). In reality the Young's modulus increases as the temperature is lowered as discussed in the previous paragraph. Consequently not only all mechanical characteristics improves but the loss in tension is compensated since a rough calculation indicates the tension at 77 K will in fact raise to 19 DaN (however see & 5.10)

Note : we assume most of the thermal contraction/expansion and variation of mechanical properties occur between room and nitrogen temperature. This is generally the case.

5.7 Thermal conductivity

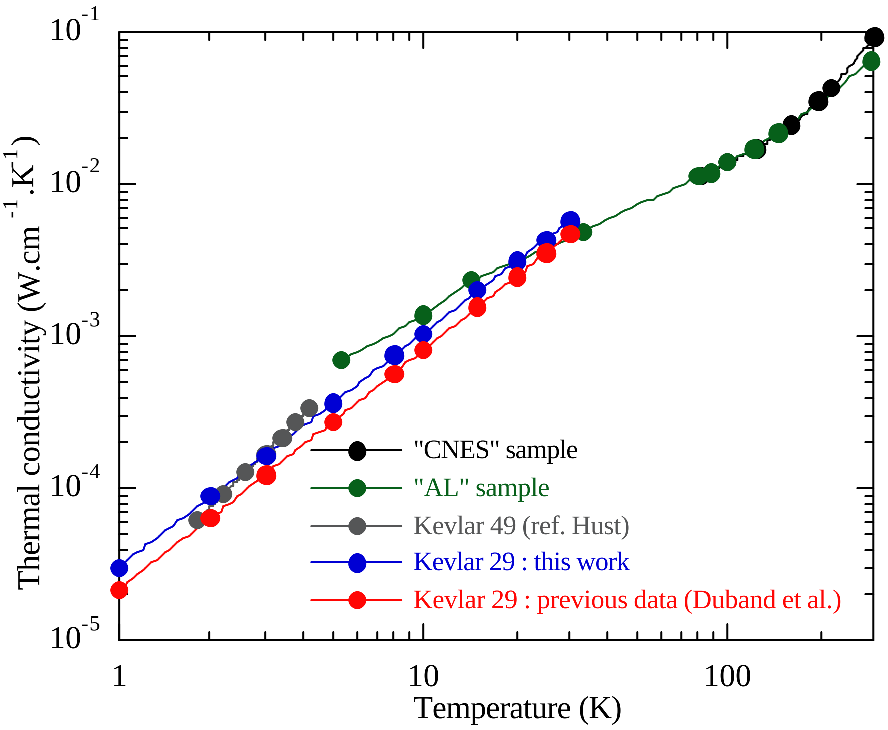
A measurement on a Kevlar 29 referenced T88 50/4 (Cousin Filterie) rated for 10 kg has been performed. Due to the very low thermal conductance, a sample made up of 240 cords 50 mm each in length has been assembled.



Yet the measurement has turned out to be very difficult and we have been unable to extend it to sub Kelvin temperature. The analysis of the results leads to

$$k = 30.3\ 10^{-6}\ T^{1.54}\ W.cm^{-1}.K^{-1}$$

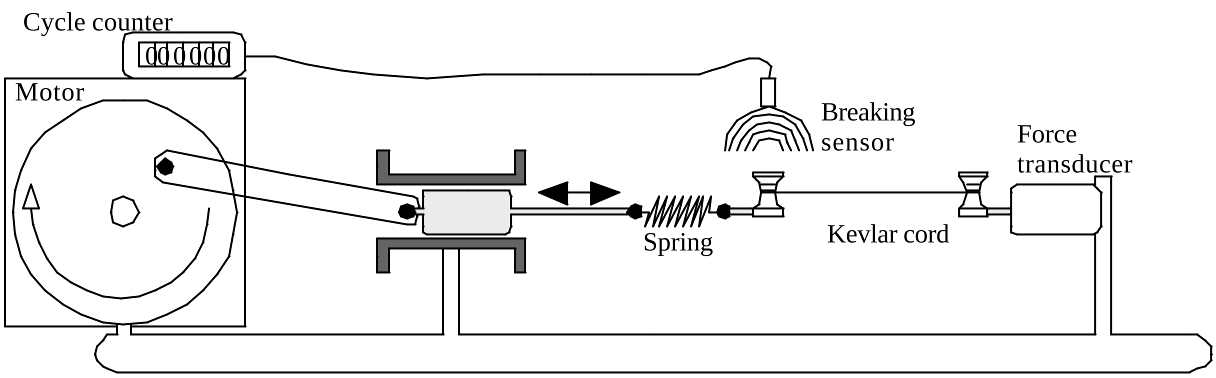
in the temperature range [3 K-20 K]. This result is similar to what has been measured before (Duband et al.) : same slope but slightly different constant (21.5 10^{-6} $T^{1.58}$). The curve hereafter displays this conductivity in the extended range [1 K – 300 K].

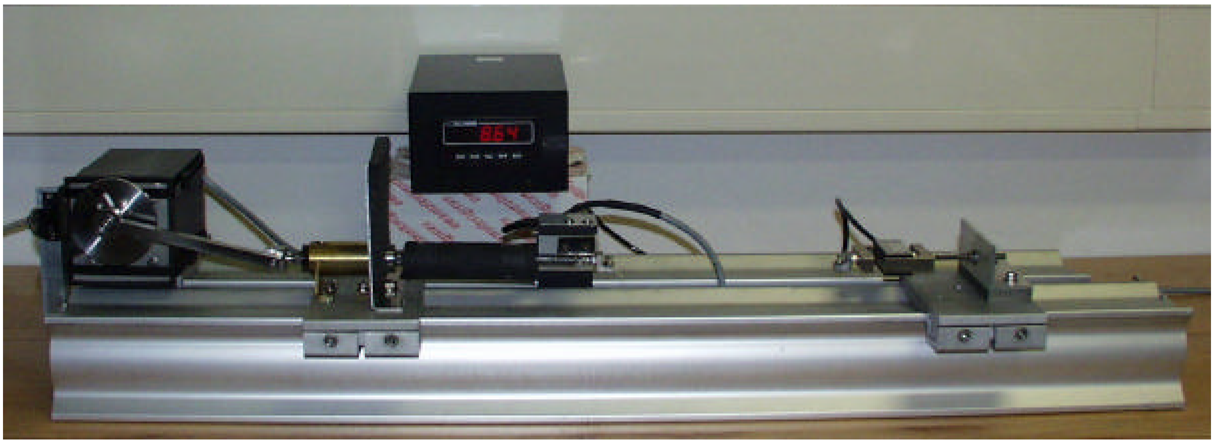


Kevlar 29 thermal conductivity

5.8 Fatigue behaviour

As for most materials, Kevlar might be subjected to fatigue behaviour. To try to address this problem we have designed an experimental set up as represented in the schematic and picture hereafter.





After pretensioning a kevlar cord at T_i this set-up allows to vary this tension between T_i ± ?T (?T is adjustable) at a frequency of 0.16 Hz (10 cycles/mn), and to count the number of cycles before rupture (if any). The objective is to guarantee that at room temperature the tensioning force we'll use in our suspension system will allow an infinite number of cycles (as seen for instance during the vibration tests).

In reality this experiment deals with two aspects, the fatigue behaviour as described above, but also the potential propagation of the tensioning force around the capstan toward the end knot (see § 1.3). The failure (if any) can then be attributed to the following :

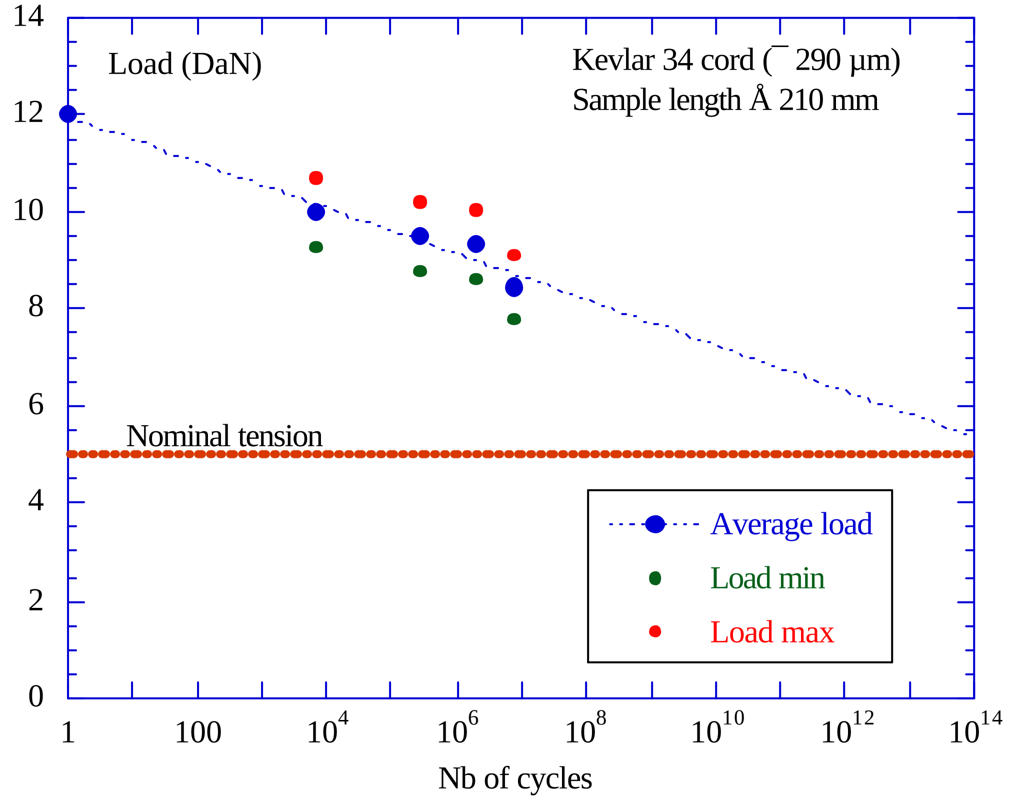
- if the variation of the tensioning force during the cycles does not change significantly, one can argue that the cord does not slip around the capstan and then that the knot is not sollicitated. The failure can be attributed to fatigue or possibly to a slight rubbing between the cord and the capstan surface (depending on where is the failure)

- if the tensioning force lowers along time, then it doesn't seem possible to discriminate between the various causes (creep, fatigue, rubbing, knot)

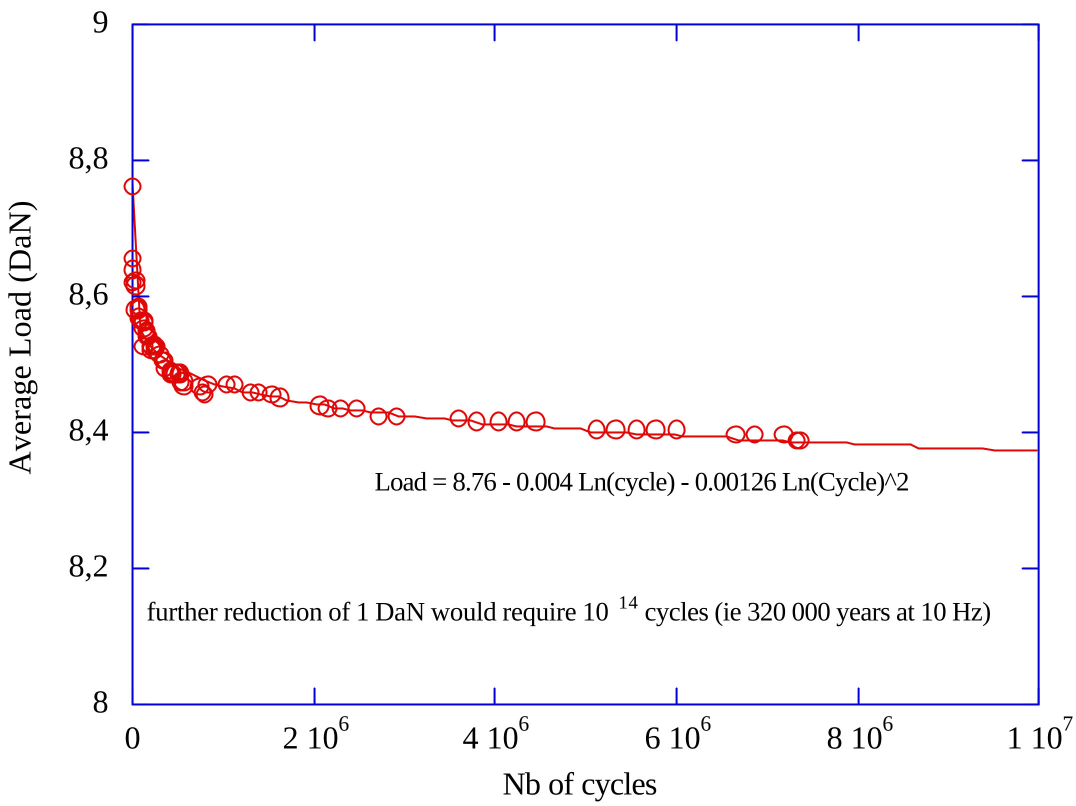
The numerical modeling performed on the overal cooler indicates that even at the resonant frequencies and under the previous specified loads (˜ 20 G rms max – new ones are down at 10 G rms) the maximum stress in the cord remains limited to 17 MPa rms (well below 1 DaN).

The curve hereafter displays the results obtained with a 0.29 mm Kevlar cord. On the first curve, each data point represents the number of cycles required before the cord breaks at the corresponding load. On the second curve the decrease in tension over time (cycle numbers) for one data point (namely the last one (on the right) on the first curve) is represented; this last curve provides data on the overall "creep" behaviour. Note that it took over 3 months for this last cord to break

On the face of it, these results indicate there shouldn't be any problem with the fatigue behaviour.



Load (DaN)
Kevlar 34 cord (¯ 290 µm)
Sample length Å 210 mm
Nominal tension
Average load
Load min
Load max
Nb of cycles



Average Load (DaN)
Load = 8.76 - 0.004 Ln(cycle) - 0.00126 Ln(Cycle)^2
further reduction of 1 DaN would require 10 14 cycles (ie 320 000 years at 10 Hz)
Nb of cycles

5.9 Effect of moisture

Kevlar is indeed sensitive to moisture. As far as we can tell the moisture has no effect on the mechanical performance (tests have been performed on baked and not baked Kevlar and except for the creep no significative difference has been found).

The following curve shows the weigth evolution with time of a piece of Kevlar before and after baking.

COMING SOON

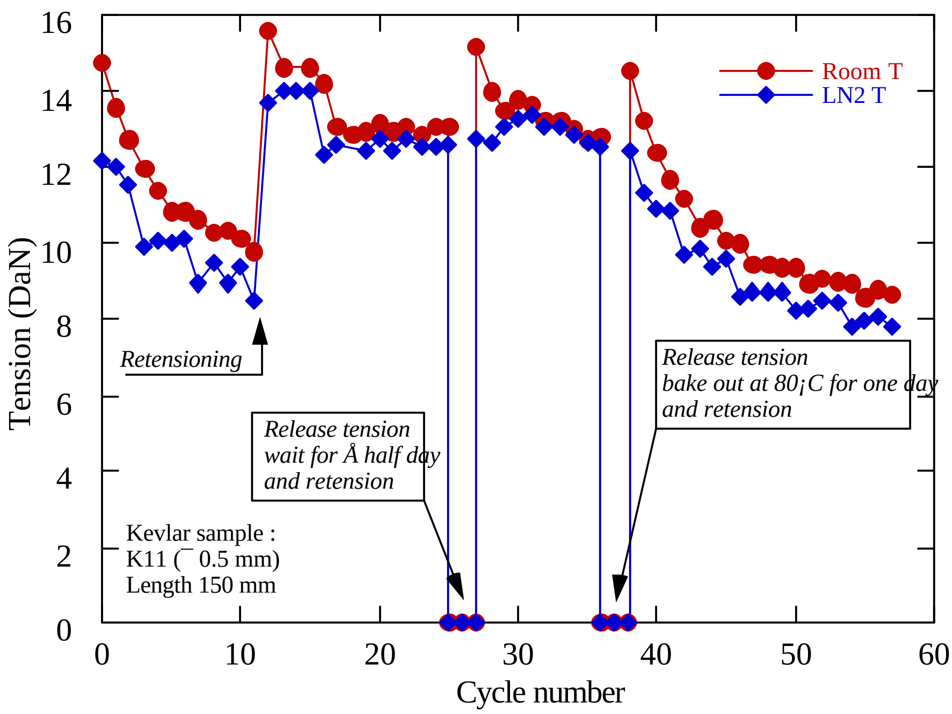
5.10 Low temperature cycling

To evaluate the effect of the thermal cycling on a pretension cord, a simple experiment has been set-up. It consists of a piece of Kevlar cord tensioned in between two pulleys, one fixed and one mobile; a force transducer is attached to the moving pulley and allows to determine the tension. The set-up is designed such the cord and the pulleys can be totally immersed in liquid nitrogen.

The cord is pretensioned at typically 16 to 17 DaN, left for a couple of hours (to allow for the cord to set itself in place) until the measured tension becomes stable (on an hour time scale).

The cord is then dipped into liquid nitrogen, the resulting tension is measured, then brought back to room temperature (tension measured) and so on. Each cycle takes about one hour.

The results as shown hereafter are unexpected and peculiar. These experiments have been repeated and have led to the same results.



The behaviour could be described as some accelerated creep. Couple points should be noted :

- after 10 cycles, the decrease in tension slows down, and at this point if the cord is retensioned the loss in tension during the following cycles is reduced and the tension becomes roughly stable.
- after many cycles (> 10), if the tension is dropped down to zero and then reset to its initial value (14 to 15 DaN), again the tension remains stable during the subsequent cycles
- the tension is smaller at nitrogen temperature compare to room temperature – unexpected (see & 5.6)

From these results one could assume the Kevlar cord requires some training. Unfortunately as displayed in the previous curve, after about 25 cycles the tension has been released, the cord has been baked out at 80°C for one day and then retensioned back to 15 DaN – the subsequent thermal cycles lead to a similar behaviour as during the initial cycling phase.

This problem is currently under investigation.
The only solution we have at present is to evaluate the number of thermal cycles / baking the cooler will go through, and hopefully guarantee the tension will only drop to some "reasonable" value. It is important to note that the resonant frequencies and the strength of the Kevlar suspension system are independent of the tension as long as this tension remains above a couple of DaN. From our experience this lower limit can be set at 5 DaN.
A low tension will only impact the positioning of the cooler heart : under large vibrations it can slightly move (see HSO-SBT-MoM-060 and 061 (Vtests on STM units)) and induce stresses on the heat switches straps and/or thermal bus to the detectors.