NSTX

OH Preload System and Bellville Springs

NSTXU-CALC-133-04-00

Rev 0

October 2010

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Peter H. Titus, Branch Head, Engineering Analysis Division

PPPL Calculation Form

Calculation # **NSTX-CALC-133-04** Revision # **00** ___ WP #, if any (ENG-032) **1672**

Purpose of Calculation: (Define why the calculation is being performed.)

NSTX update requires the center column OH coil assembly to remain steady in its proper position during the applications of the TF and OH coils currents. The OH should remain steady since the cooling mechanisms could experience the unnecessary stresses. To accomplish this, a compressive force (pre load) on the upper surface of the OH coil is necessary. For these analyses a force of about 20,000. lbs total, was estimated to accomplish this task.

It was also calculated that during the maximum currents applications, the involved coils grow due to the following thermal expansions: TF coil expands 8.4 mm, while the OH coil 6.0 mm, and, may not occur at the same time. Therefore, a mechanical OH coil pre load system is required to regulate these variations?

This is best accomplished by creating a disk springs stacks regulating system as is shown in the enclosed analyses.

References (List any source of design information including computer program titles and revision levels.)

Basic disk spring equations according to the SCHNORR catalogue were programmed in XL. This file is included in this package as a reference, and also, as a tool that can be used by anyone.

A commercial code WFED4 from HEXAGON software was also purchased and is available now at PPPL (see P. Rogoff)

All calculations were performed with both packages and the results closely agree!

Assumptions (Identify all assumptions made as part of this calculation.)

The disk spring must be made from the Stainless Steel grade 301. (low permeability). Used modulus of elasticity was 206,000. MPa and mue =0.3.

Calculation (Calculation is either documented here or attached)

See the enclosed Executive Summary and the Power Point data (4 files – Summary, TfcoldOHhot, TfhotOHcold, & TfhotOHhot)

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

A designed system of disk springs stack will accomplish the original goal of maintaining a minimum compressive force of 20,000. Lbs. on the OH coil upper surface.

Cognizant Engineer's printed name, signature, and date

Prepared by P.Rogoff 10/15/2010 Peter Titus

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Date: 2011.05.09 10:49:29 -04'00'

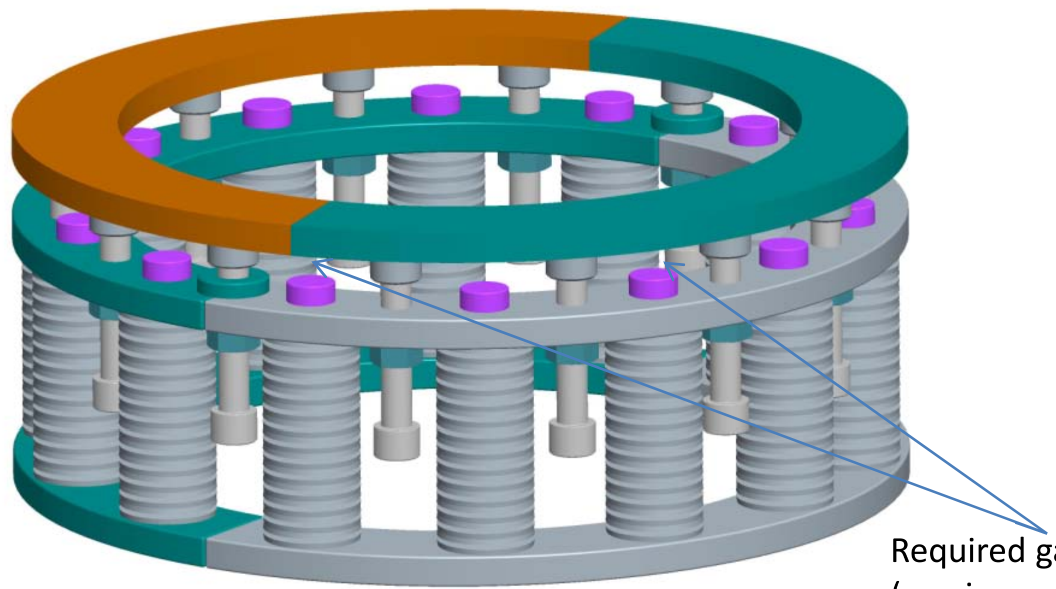
I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Verified by testing (see presentation summary) – from 3/23/2011 Power Point presentation [Bellville_Test.pptx)

Checker's printed name, signature, and date: Tom Kokub Thomas Kozub

Digitally signed by Thomas Kozub
DN: cn=Thomas Kozub, o=Engineering, ou=FOB, email=takozub@pppl.gov, c=US
Date: 2011.04.04 13:13:20 -04'00'

OH Coil Pre Load System



Required gap = 23.87 mm
(maximum permitted compression
on the stack. Protects overloading
of permitted spring stresses.)

Spring dimensions:
26 disk springs/stack
Di = 30.5 mm
De =60.0 mm
t = 3.5 mm
Lo =5.0 mm
E = 206,000. Mpa
mu = 0.3

Required 14 stack to maintain
a minimum of 20,000. lbs.
total load on the OH coil

Note: Spring should be made from SS 301 material
Depending on Stainless Steel conditions
modulus of elasticity may be slightly different.
In this case, minimum load on the OH coil may
decrease by a small percentage (say 3 to 4 %)
while everything else will stay the same.

Supporting calculations:

“TFhot OHcold26_14.ppt”
“TFcoldOHhot26_14.ppt”
“TFhotOHhot26_14.ppt”
“Spring Calculations in mm.xls”

Performance Summary

And

Input to digital coil protection system

System scenario	Compression mm	Force on OH N	Force on OH lbs.*	Tensile Stress N/mm	Fatigue Cycles
Pre Load	17.87	162,512	36,520.	849.	-----
TF hot OH hot	15.47	142,268.	31,970.	731.	2 Mil. +
TF hot OH cold	9.47	89,698.	20,157.	459.	high
TF cold OH hot	23.87	211,582.	47,546.	1185.	500,000

Thermal expansions:
FT = 8.4 mm
OH= 6.0 mm

* Allowable OH launching loads.
Note: For supporting calculation see power point files for full details.

OH Coil Pre Load System
TF cold OH hot

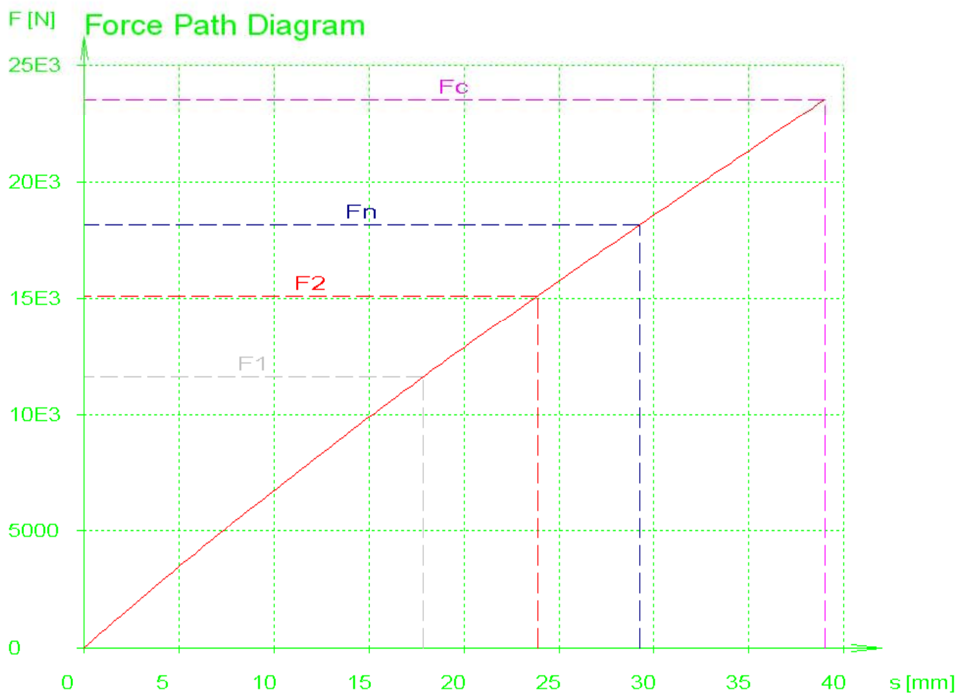
Calculations for most critical system scenario.
Pre load = 17.87 mm
OH thermal expansion = 6.0 mm
Total spring compression = 23.87 mm

Maximum obtained force on the OH coil
With 14 stacks = 15,113. x 14 = 211,582. N
(47,546. lbs.)

Life based on “Sigma II” is about 500,000 cycles.

FED4 - Disk Spring Calculation - 14 Stacks TF cold Oh Hot 2 26 Sp.fd4

File Edit View CAD Database Document OLE Help



Di = 30.5 mm
De = 60 mm
t = 3.5 mm
L0 = 5 mm

nf = 1
np = 26
Lc = 91 mm
L0 = 130 mm

Stainless Steel Required

[redacted]
E = 206000 MPa
mue = 0.3
rho= 7.85 kg/dm^3
sigma perm = 1230 MPa
(DIN 2092)

	0	1	2	n	c	
s	0.00	17.87	23.87	29.25	39.00	mm
L	130.00	112.13	106.13	100.75	91.00	mm
F	0	11608	15113	18153	23528	N
R	18566	15514	14895	14515	14245	N/mm
sigma I	0	-1554	-2029	-2434	-3121	MPa
sigma III	0	835	1085	1297	1650	MPa
si	0.00	0.69	0.92	1.13	1.50	mm
Li	5.00	4.31	4.08	5.00	0.00	mm
Fi	0	11608	15113	18153	23528	N

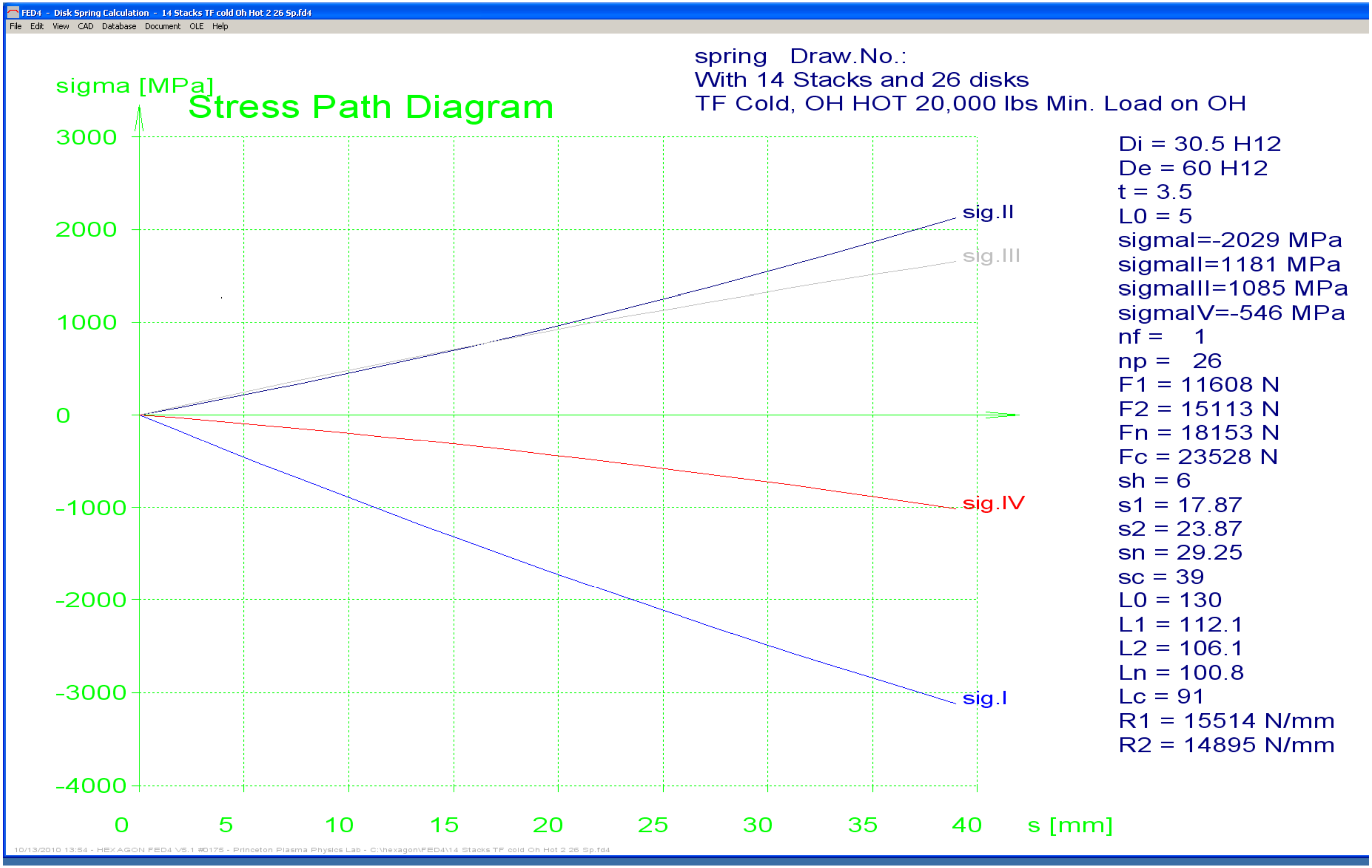
messages

- none -

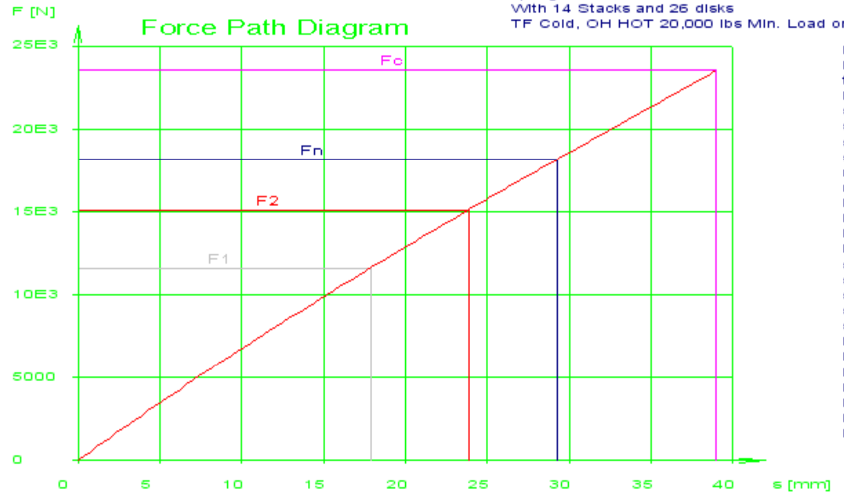
Pre Load = 17.87 mm
+OH hot = 6.0 mm
Total comp = 23.87 mm
Total Force/Stack =15113N
(Max operational force)

10/13/2010 13:19 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF cold Oh Hot 2 26 Sp.fd4

start | Microsoft PowerPoint ... | FED4 - Disk Spring C... | 1:19 PM


FED4 - Disk Spring Calculation - 14 Stacks TF cold Oh Hot 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Cold, OH HOT 20,000 lbs Min. Load on OH
sigma [MPa]
Stress Path Diagram
3000
2000
1000
0
-1000
-2000
-3000
-4000
0
5
10
15
20
25
30
35
40
s [mm]
sig.II
sig.III
sig.IV
sig.I
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-2029 MPa
sigmaII=1181 MPa
sigmaIII=1085 MPa
sigmaIV=-546 MPa
nf = 1
np = 26
F1 = 11608 N
F2 = 15113 N
Fn = 18153 N
Fc = 23528 N
sh = 6
s1 = 17.87
s2 = 23.87
sn = 29.25
sc = 39
L0 = 130
L1 = 112.1
L2 = 106.1
Ln = 100.8
Lc = 91
R1 = 15514 N/mm
R2 = 14895 N/mm
10/13/2010 13:54 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF cold Oh Hot 2 26 Sp.fd4

spring Draw.No.:
With 14 Stacks and 26 disks
TF Cold, OH HOT 20,000 lbs Min. Load on OH



Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-2029 MPa
sigmaII=1181 MPa
sigmaIII=1085 MPa
sigmaIV=-546 MPa
nf = 1
np = 26
F1 = 11608 N
F2 = 15113 N
Fn = 18153 N
Fc = 23528 N
sh = 6
s1 = 17.87
s2 = 23.87
sn = 29.25
sc = 39
L0 = 130
L1 = 112.1
L2 = 106.1
Ln = 100.8
Lc = 91
R1 = 15514 N/mm
R2 = 14895 N/mm

spring Draw.No.:
With 14 Stacks and 26 disks
TF Cold, OH HOT 20,000 lbs Min. Load on OH

SINGLE DISK SPRING			
inside diameter	Di	mm	30.5 H12
outside diameter	De	mm	60 H12
thickness	t	mm	3.5
length	L0	mm	5
weight	m	g	57.61
usable spring travel sn=0.75*h0	sin	mm	1.125
max. spring travel h0=sc	sic	mm	1.5
spring force with sn=0.75*sc	Fin	N	18153
No. of springs per package	nf		1
No. of spring packages	np		26

Length mm	Sp.travel mm	Load N	Sigma MPa
L0 = 130.00			
L1 = 112.13	s1 = 17.87	F1 = 11607.78	sigma1 = 835
	sh = 6.00	Fh = 3504.78	sigmah = 250
L2 = 106.13	s2 = 23.87	F2 = 15112.57	sigma2 = 1085
Ln = 100.75	sn = 29.25	Fn = 18152.58	sigman = 1297
Lc = 91.00	sc = 39.00	Fc = 23528.21	sigmac = 1650

	Date	Name
Compl.	08/25/2010	P. Rogoff
Check		
Stand.		

Disk Spring

Cond.	Modification	Date	Name
a	Initial Design	08/26/2010	P. R.

Princeton Plasma Physics Lab

Page

Pg.

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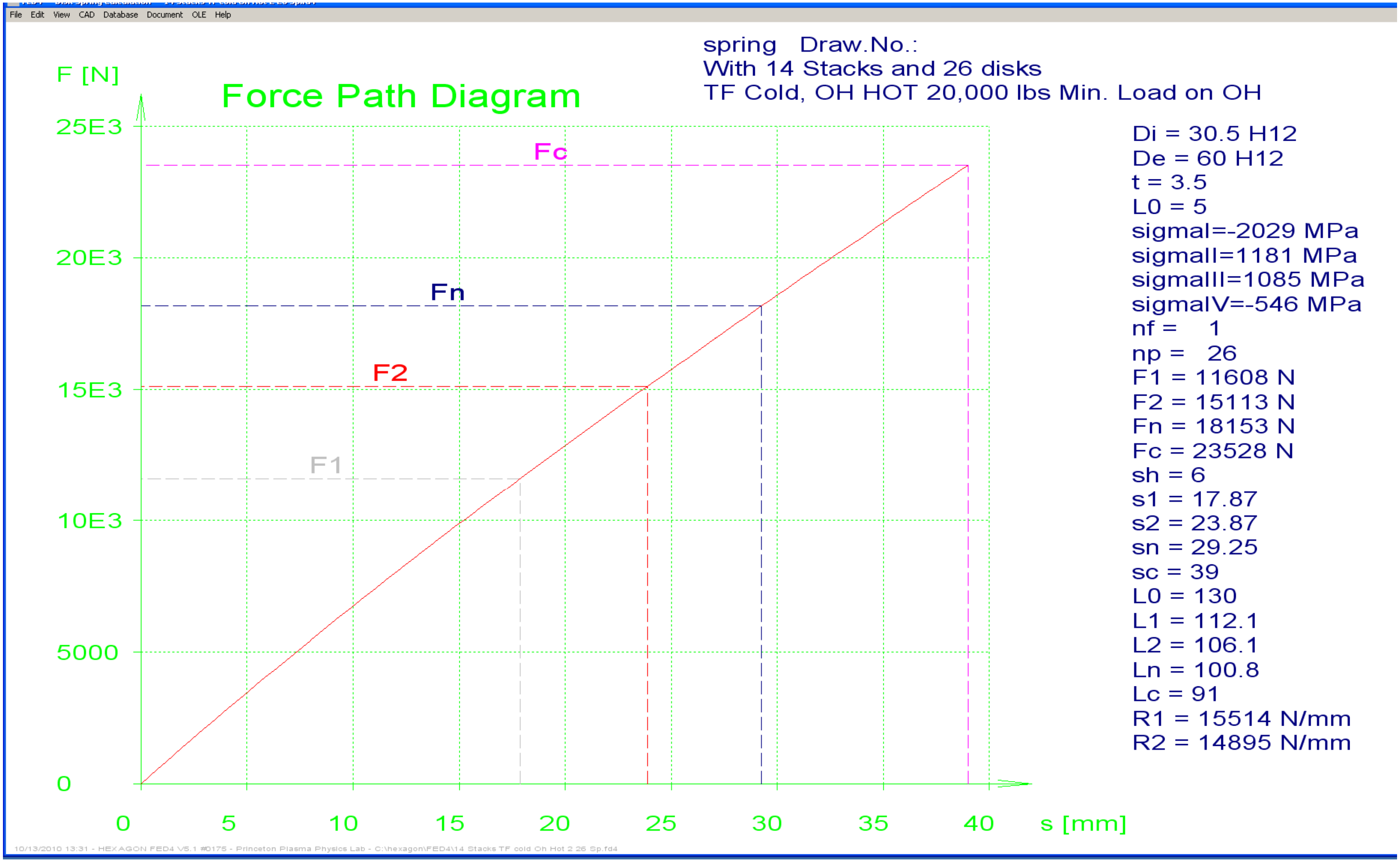
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Cold, OH HOT 20,000 lbs Min. Load on OH
F [N]
Force Path Diagram
25E3
20E3
15E3
10E3
5000
0
Fc
Fn
F2
F1
0
5
10
15
20
25
30
35
40
s [mm]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-2029 MPa
sigmaII=1181 MPa
sigmaIII=1085 MPa
sigmaV=-546 MPa
nf = 1
np = 26
F1 = 11608 N
F2 = 15113 N
Fn = 18153 N
Fc = 23528 N
sh = 6
s1 = 17.87
s2 = 23.87
sn = 29.25
sc = 39
L0 = 130
L1 = 112.1
L2 = 106.1
Ln = 100.8
Lc = 91
R1 = 15514 N/mm
R2 = 14895 N/mm
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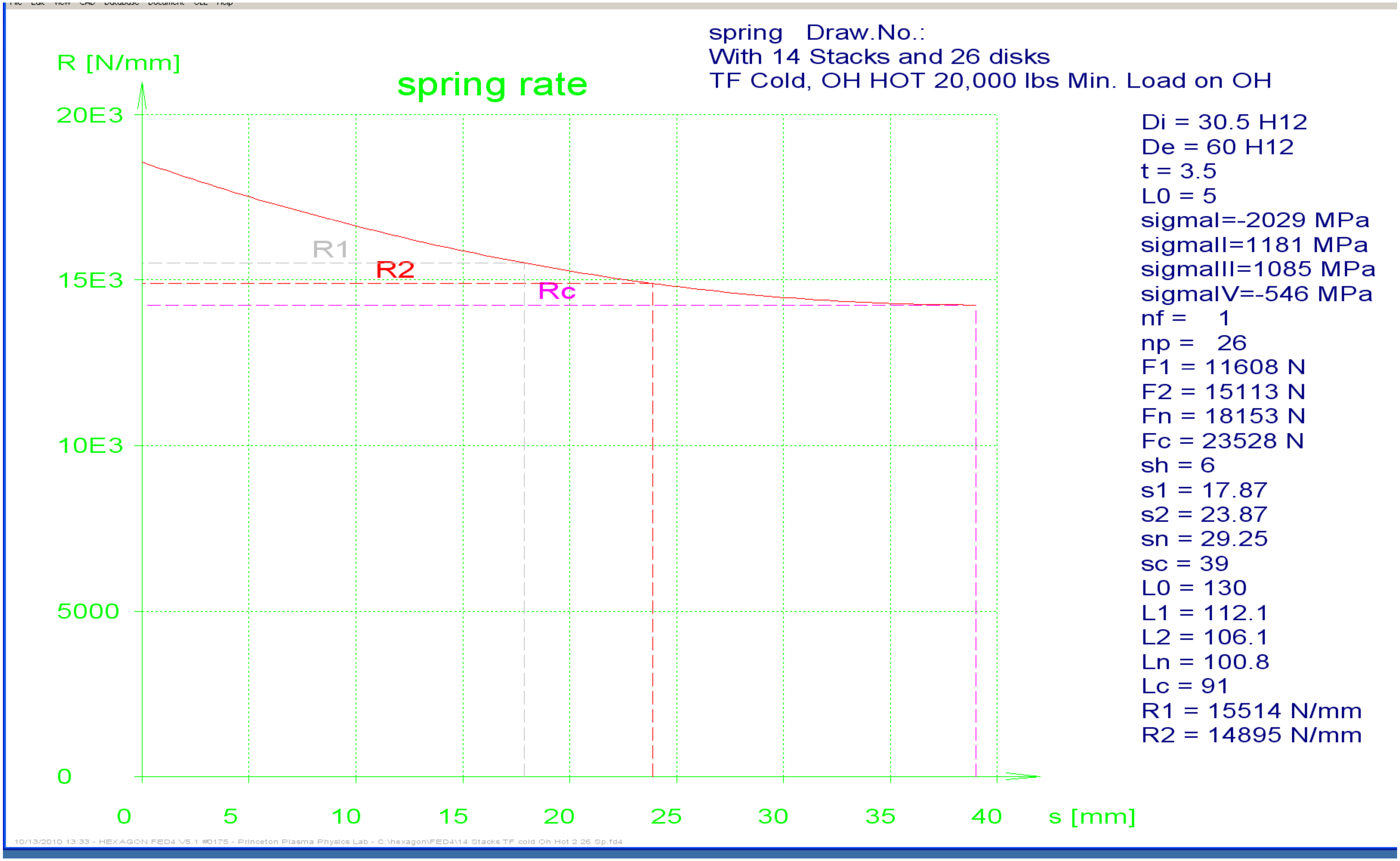
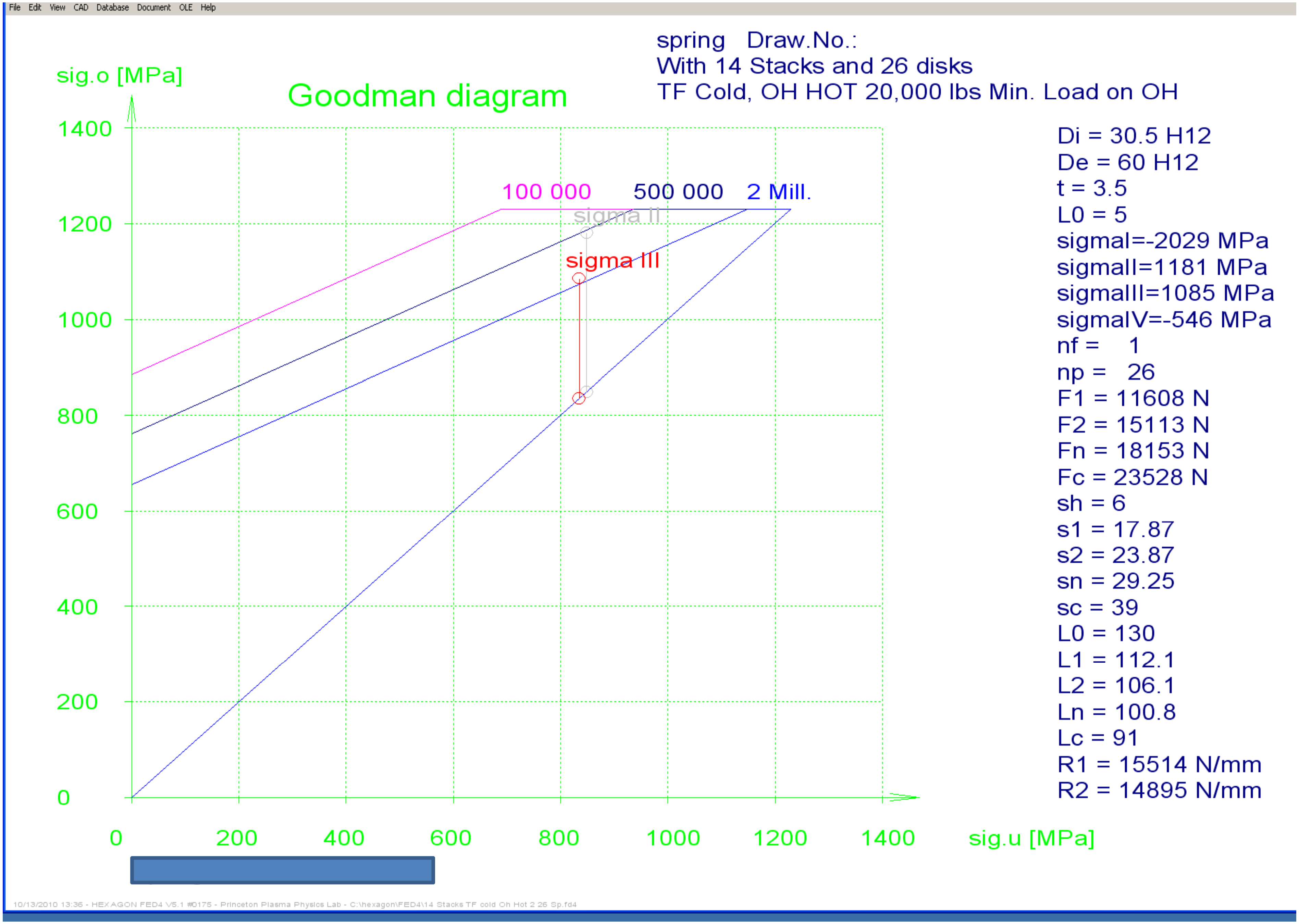
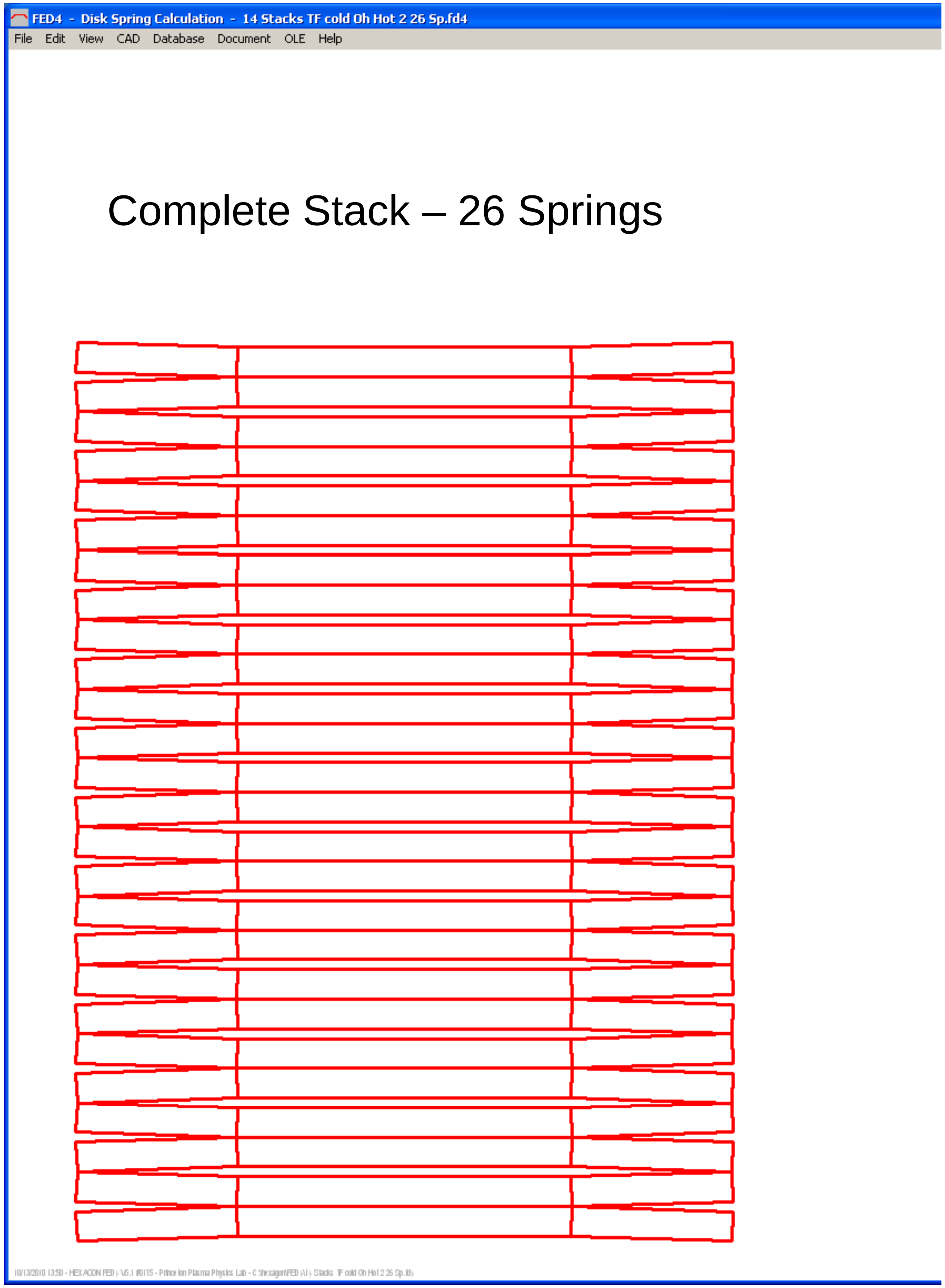

spring Draw.No.:
With 14 Stacks and 26 disks
TF Cold, OH HOT 20,000 lbs Min. Load on OH
spring rate
R [N/mm]
20E3
15E3
10E3
5000
0
R1
R2
Rc
0
5
10
15
20
25
30
35
40
s [mm]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-2029 MPa
sigmaII=1181 MPa
sigmaIII=1085 MPa
sigmaIV=-546 MPa
nf = 1
np = 26
F1 = 11608 N
F2 = 15113 N
Fn = 18153 N
Fc = 23528 N
sh = 6
s1 = 17.87
s2 = 23.87
sn = 29.25
sc = 39
L0 = 130
L1 = 112.1
L2 = 106.1
Ln = 100.8
Lc = 91
R1 = 15514 N/mm
R2 = 14895 N/mm
10/13/2010 13:33 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF cold Oh Hot 2 26 Sp.fd4


File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Cold, OH HOT 20,000 lbs Min. Load on OH
Goodman diagram
sig.o [MPa]
1400
1200
1000
800
600
400
200
0
100 000
500 000
2 Mill.
sigma II
sigma III
0
200
400
600
800
1000
1200
1400
sig.u [MPa]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-2029 MPa
sigmaII=1181 MPa
sigmaIII=1085 MPa
sigmaIV=-546 MPa
nf = 1
np = 26
F1 = 11608 N
F2 = 15113 N
Fn = 18153 N
Fc = 23528 N
sh = 6
s1 = 17.87
s2 = 23.87
sn = 29.25
sc = 39
L0 = 130
L1 = 112.1
L2 = 106.1
Ln = 100.8
Lc = 91
R1 = 15514 N/mm
R2 = 14895 N/mm
10/13/2010 13:36 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF cold Oh Hot 2 26 Sp.fd4

Complete Stack – 26 Springs



This is provided as a check of above "HEXAGON" calculations.

	A	B	C	D
3				
4		Calcs Based on the SCHNORR data formulas.		
5				
6		Note: These calculations are for SCHNORR #15900		
7				
8				
9		De - Ouside diameter	60	mm
10		Di - Inside diameter	30.5	mm
11				
12		pi	3.14	
13		1/pi	0.3185	
14		3/pi	0.9554	
15		6/pi	1.9108	
16				
17		del=De/Di Schnorr Formula #2	1.9672	
18				
19		Indel=ln(De/Di)	0.6766	
20				
21		del-1	0.9672	
22		del+1	2.9672	
23				
24				
25				
26		(del-1/del)^2	0.2417	
27		(del+1)/(del-1)	3.0678	
28		(2/Indel)	2.9559	
29				
30				
31		K1 =1/pi(((del-1/del)^2))/((del+1)/((del-1)-(2/Indel))) Formula #3	0.6879	
32				
33		K2=6/pi(((del-1)/(Indel))-1)))/(Indel) Formula #4	1.2129	
34				
35		K3=3/pi(del-1/Indel) Formula #5	1.3657	
36				
37		K4=1 since thikness is less than 6 mm Formula #6 (see chapter	1	
38				
39				
40		FORCE and STRESS Calculations		
41				
42				
43				
44		lo= total height	5.004	mm
45		ho= lo-t	1.499	mm
46		t=average spring thickness	3.505	mm

Calculations based on the "SCHNORR" catalogue equations for a single disk at maximum compression.
s = .918 mm

Stack compression
In this case:
s = 23.87 mm.

Or (.918x26) =
23.87 mm
Force = 15164 N

See Slide #2

s= deflection of the single spring (from 75% of ho))	0.918	mm
E= modulus for steel	206000	N/mm^2
mu= Poisson's ratio	0.3	
1-mu^2	0.91	
4E/(1-mu^2)	905494.505	
t^4/(K1*de^2)	0.06094519	
s/t	0.26191155	
ho/t	0.42767475	
s/2t	0.13095578	
Formula #8a	15164.64	N
Formula #9 Stresses at the center of rotation (point OM)	-1124.08	N/mm^2
(should be less then -1600N/mm^2)		
t^2/(K1*de^2)	0.00496093	
formula #10 Stress at point (I)	-2030.27	N/mm^2
formula #11 Stress at point (II)	1183.42482	N/mm^2
formula #12 Stress at point (III)	1086.30	N/mm^2
1/del	0.50833333	
(K2-2K3)	-1.5185995	
(ho/t-s/2t)	0.29671897	
Formula #13 Stress at point (IV)	-547.32	N/mm^2
t^3/(K1*de^2)	0.01738807	
Formula #14 Spring Rate (dF/ds)	14953.84	N/mm
Formula #15 Spring Work (Integral from 0 to s, of F*ds)	7218.36	N-mm
2E/(1-mu^2)	452747.253	
t^5/(K1*de^2)	0.2136129	
Basic requirements for a good Disk spring design		
For the above basic equations to work		
This Spring is linear because ho/t=.428 (since for ho/t<0.4 are lii	slightly non-LINEAR	
del=De/Di=2.3923 and it should be between 1.75 and 2.5	O.K.	
Outside diameter De, Inside diameter Di		

ho/t=(lo-t)/t=.428 and it should be between 0.4 to 1.3 O.K.

ho=lo-t cone height, t=disk thickness

De/t=17.12 and it should be between 16. and 40. O.K.

Conclusion: This spring under the constant load of 3790.0 N is O.K.

Basic machine operation requirements:

1) TF coil inner leg maximum thermal expansion was calculated at 8.4mm

2) OH coil requires a preload of 20,000.0 lbs total or 7,413.3 N (12 St) per stack. Must calculate the required deflection (s) for the preload force?

3) OH coil thermal expansion was calculated at 6.0mm

So, the total each spring stack travel is = 8.4+6.0+calculated from minimum preload

For Fatigue predictions, using fatigue life diagrams for disk springs, one requires the Pre and Maximum loads stresses at points II or III (depending on del and ho/t).

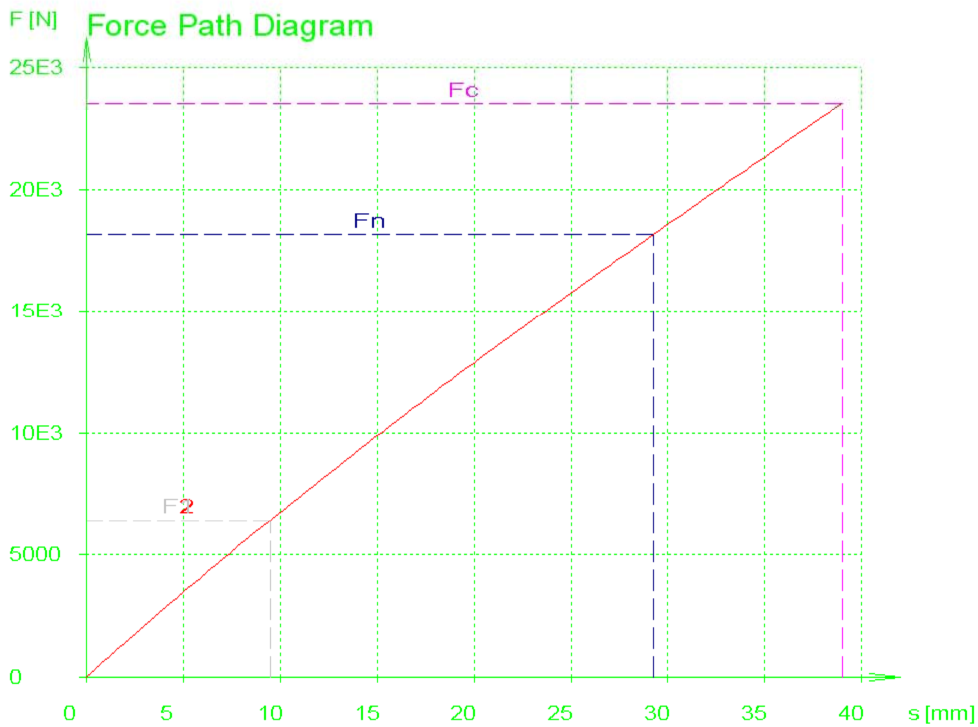
OH Coil Pre Load System
TF hot OH cold

Calculations for the least critical system scenario.
From Pre Load of 17.87 mm
8.4 mm of compression are released due to the
TF coil thermal expansion = 8.4 mm
Therefore, the total compression on the
Spring stack is = 9.47 mm

For a single spring s = .364 mm
For the stack = .3642 x 26 = 9.47 mm
Maximum obtained force on the OH coil
With 14 stacks = 6,407. x 14 = 89,698 N
(20,157. lbs.)

FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Cold 2 26 Sp.fd4

File Edit View CAD Database Document OLE Help



Di = 30.5 mm
De = 60 mm
t = 3.5 mm
L0 = 5 mm

nf = 1
np = 26
Lc = 91 mm
L0 = 130 mm

Stainless Steel Required

E = 206000 MPa
mue = 0.3
rho= 7.85 kg/dm^3
sigma perm = 1230 MPa
(DIN 2092)

	0	1	2	n	c	
s	0.00	9.47	9.47	29.25	39.00	mm
L	130.00	120.53	120.53	100.75	91.00	mm
F	0	6411	6411	18153	23528	N
R	18566	16723	16723	14515	14245	N/mm
sigma I	0	-850	-850	-2434	-3121	MPa
sigma III	0	459	459	1297	1650	MPa
si	0.00	0.36	0.36	1.13	1.50	mm
Li	5.00	4.64	4.64	5.00	0.00	mm
Fi	0	6411	6411	18153	23528	N

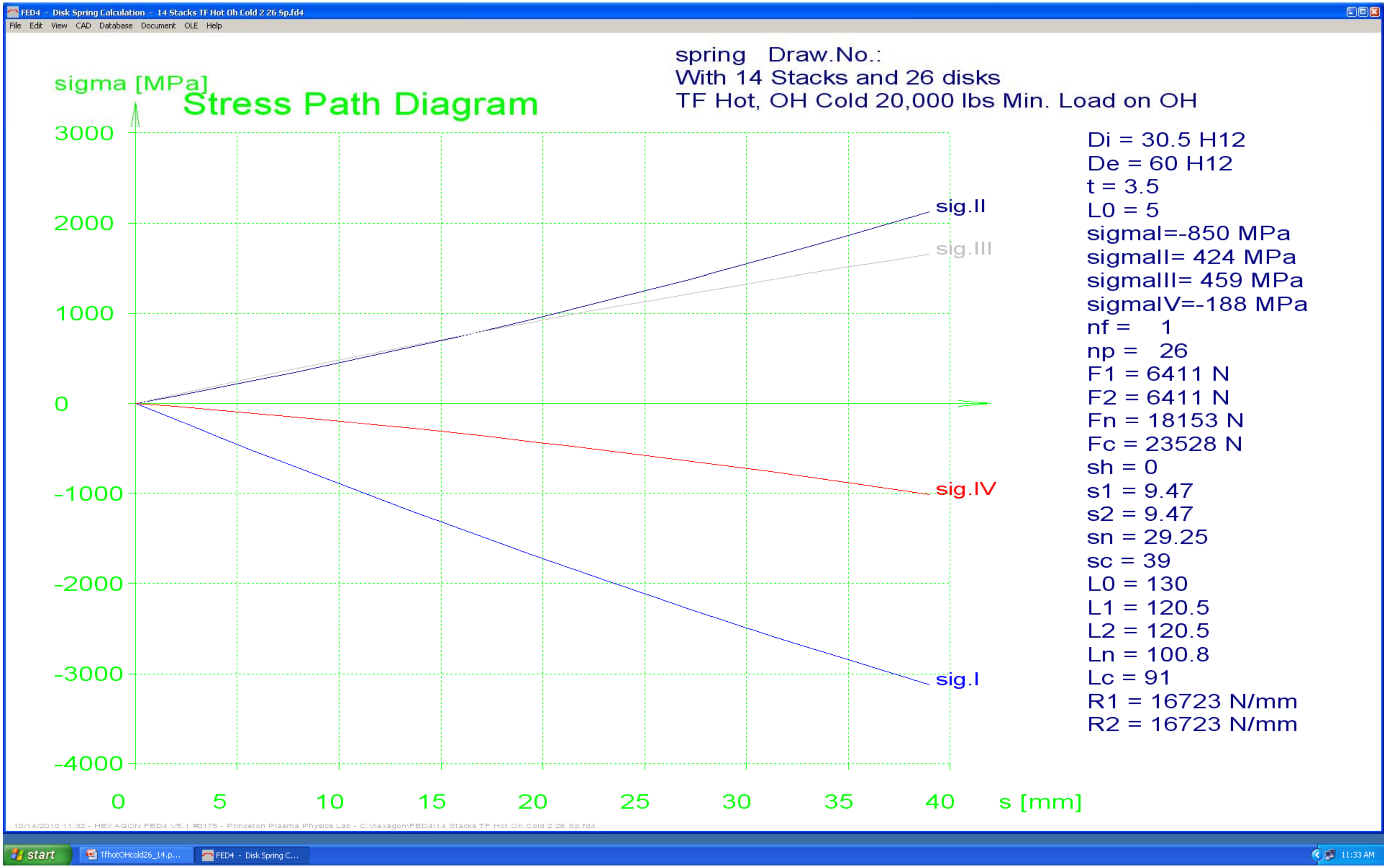
messages

- none -

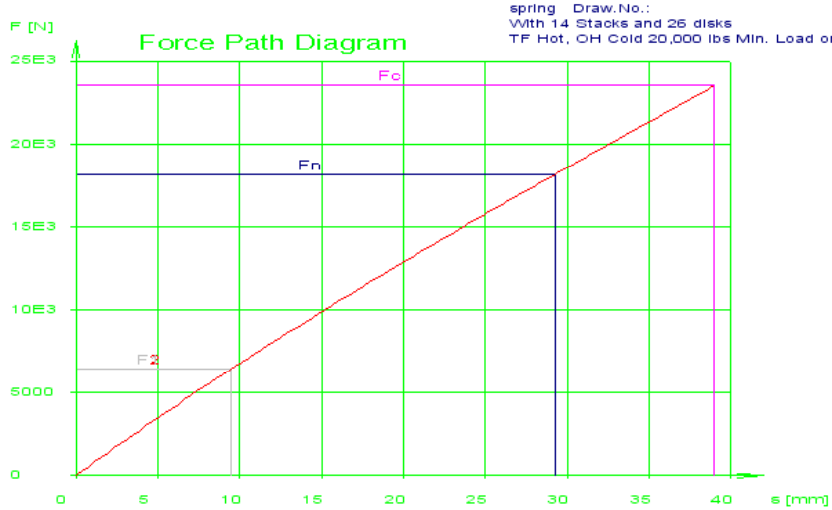
Pre Load was = 17.87 mm
-TF hot = 8.4 mm
Total compression = 9.47 mm
Total Force/Stack = 6,411. N
(1,441. lbs.)
Constant Force on OH coil
(1,441 x 14 = 20,169. lbs)

10/14/2010 11:08 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF Hot Oh Cold 2 26 Sp.fd4

start TfhotOHcold26_14.p... FED4 - Disk Spring C... 11:09 AM


FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Cold 20,000 lbs Min. Load on OH
sigma [MPa]
Stress Path Diagram
3000
2000
1000
0
-1000
-2000
-3000
-4000
0
5
10
15
20
25
30
35
40
s [mm]
sig.II
sig.III
sig.IV
sig.I
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-850 MPa
sigmaII= 424 MPa
sigmaIII= 459 MPa
sigmaIV=-188 MPa
nf = 1
np = 26
F1 = 6411 N
F2 = 6411 N
Fn = 18153 N
Fc = 23528 N
sh = 0
s1 = 9.47
s2 = 9.47
sn = 29.25
sc = 39
L0 = 130
L1 = 120.5
L2 = 120.5
Ln = 100.8
Lc = 91
R1 = 16723 N/mm
R2 = 16723 N/mm
10/14/2010 11:32 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
start
TfhotOHcold26_14.p...
FED4 - Disk Spring C...
11:33 AM

spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Cold 20,000 lbs Min. Load on OH



Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-850 MPa
sigmaII= 424 MPa
sigmaIII= 459 MPa
sigmaIV=-188 MPa
nf = 1
np = 26
F1 = 6411 N
F2 = 6411 N
Fn = 18153 N
Fc = 23528 N
sh = 0
s1 = 9.47
s2 = 9.47
sn = 29.25
sc = 39
L0 = 130
L1 = 120.5
L2 = 120.5
Ln = 100.8
Lc = 91
R1 = 16723 N/mm
R2 = 16723 N/mm

spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Cold 20,000 lbs Min. Load on OH

SINGLE DISK SPRING			
inside diameter	Di	mm	30.5 H12
outside diameter	De	mm	60 H12
thickness	t	mm	3.5
length	L0	mm	5
weight	m	g	57.61
usable spring travel sn=0.75*h0	sin	mm	1.125
max. spring travel h0=sc	sic	mm	1.5
spring force with sn=0.75*sc	Fin	N	18153
No. of springs per package	nf		1
No. of spring packages	np		26

Length mm	Sp.travel mm	Load N	Sigma MPa
L0 = 130.00			
L1 = 120.53	s1 = 9.47	F1 = 6411.21	sigma1 = 459
	sh = 0.00	Fh = 0.00	sigmah = 0
L2 = 120.53	s2 = 9.47	F2 = 6411.21	sigma2 = 459
Ln = 100.75	sn = 29.25	Fn = 18152.58	sigman = 1297
Lc = 91.00	sc = 39.00	Fc = 23528.21	sigmac = 1650

	Date	Name
Compl	08/25/2010	P. Rogoff
Check		
Stand.		

Disk Spring

Page

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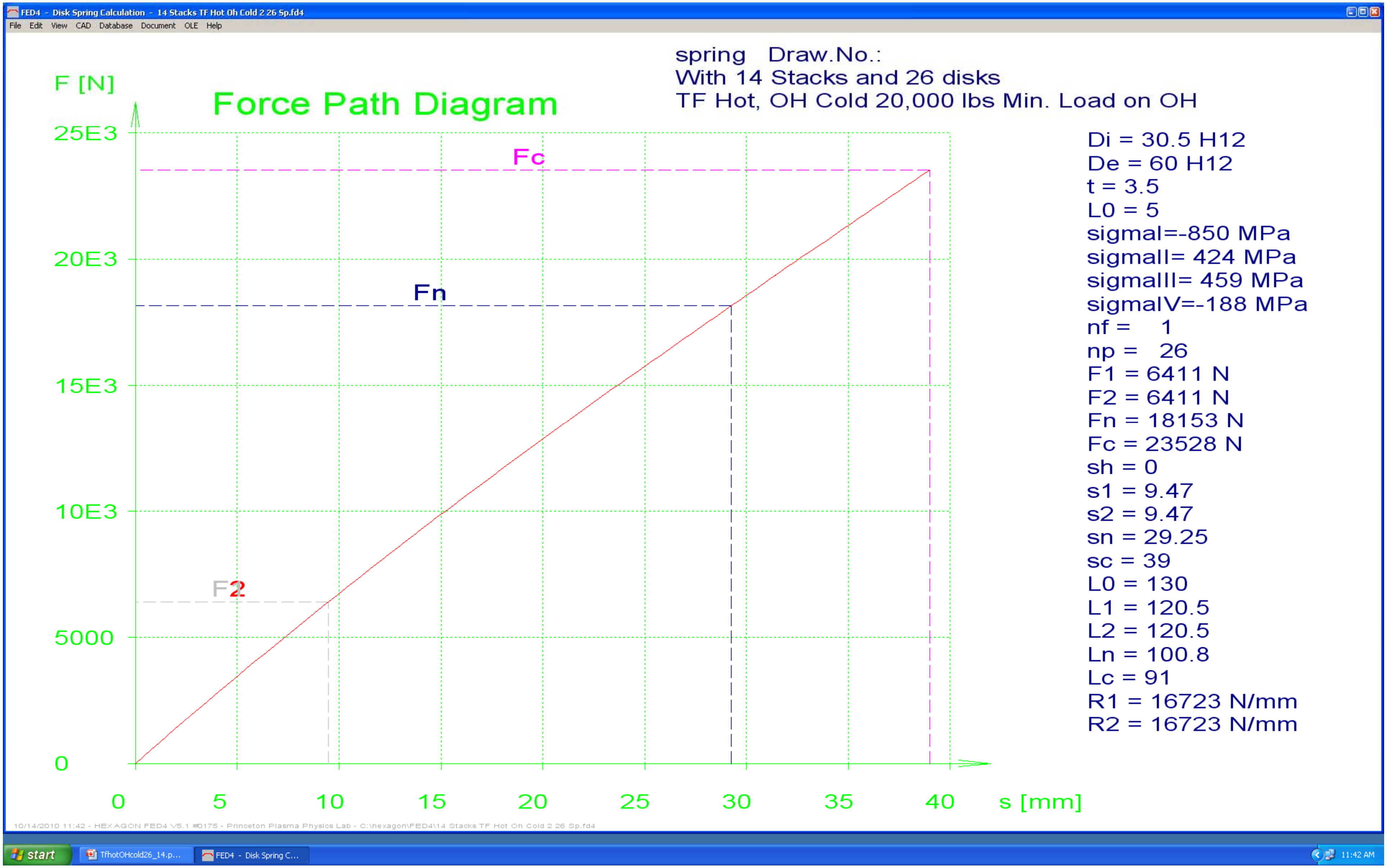
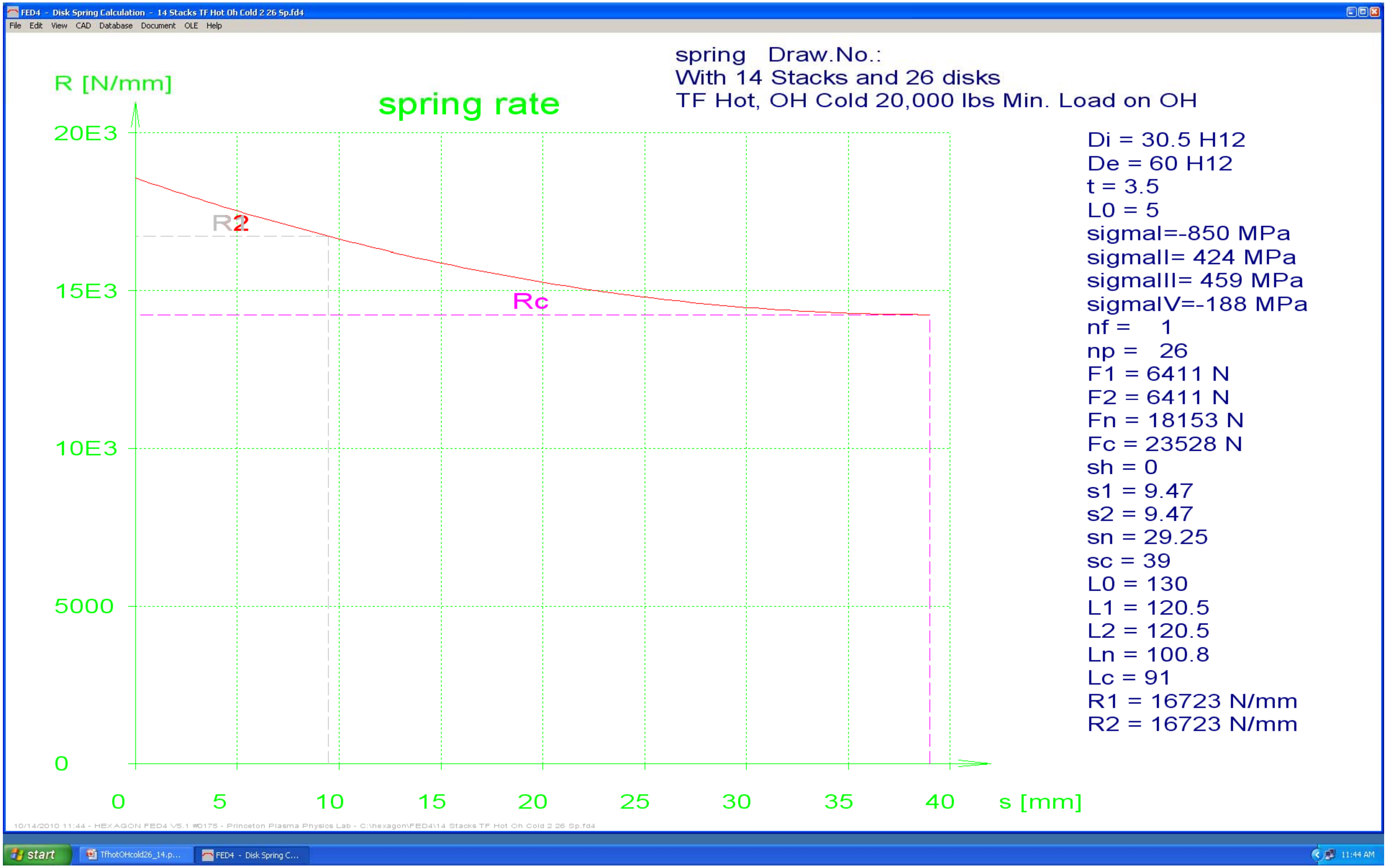
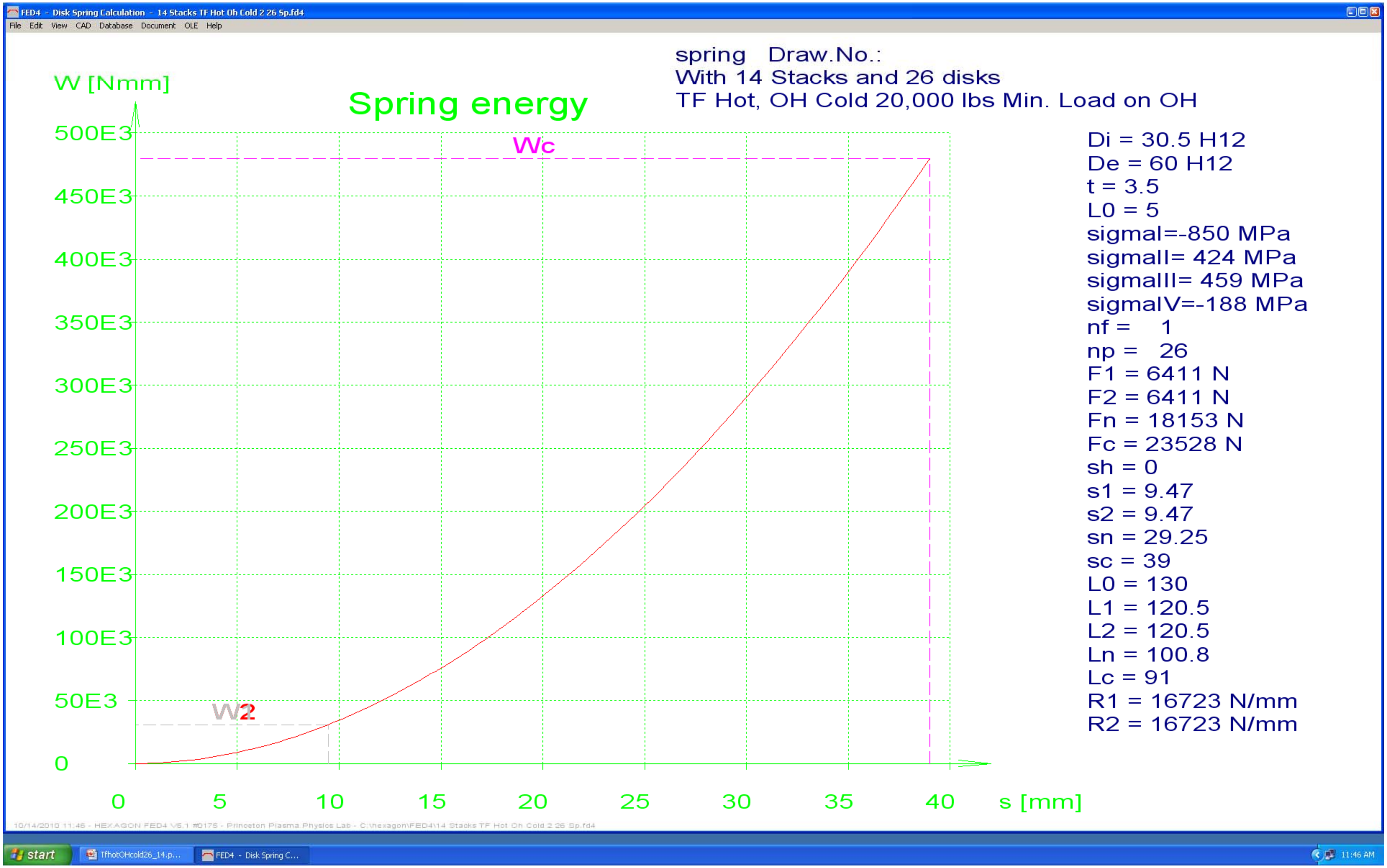
Cond. Modification Date Name

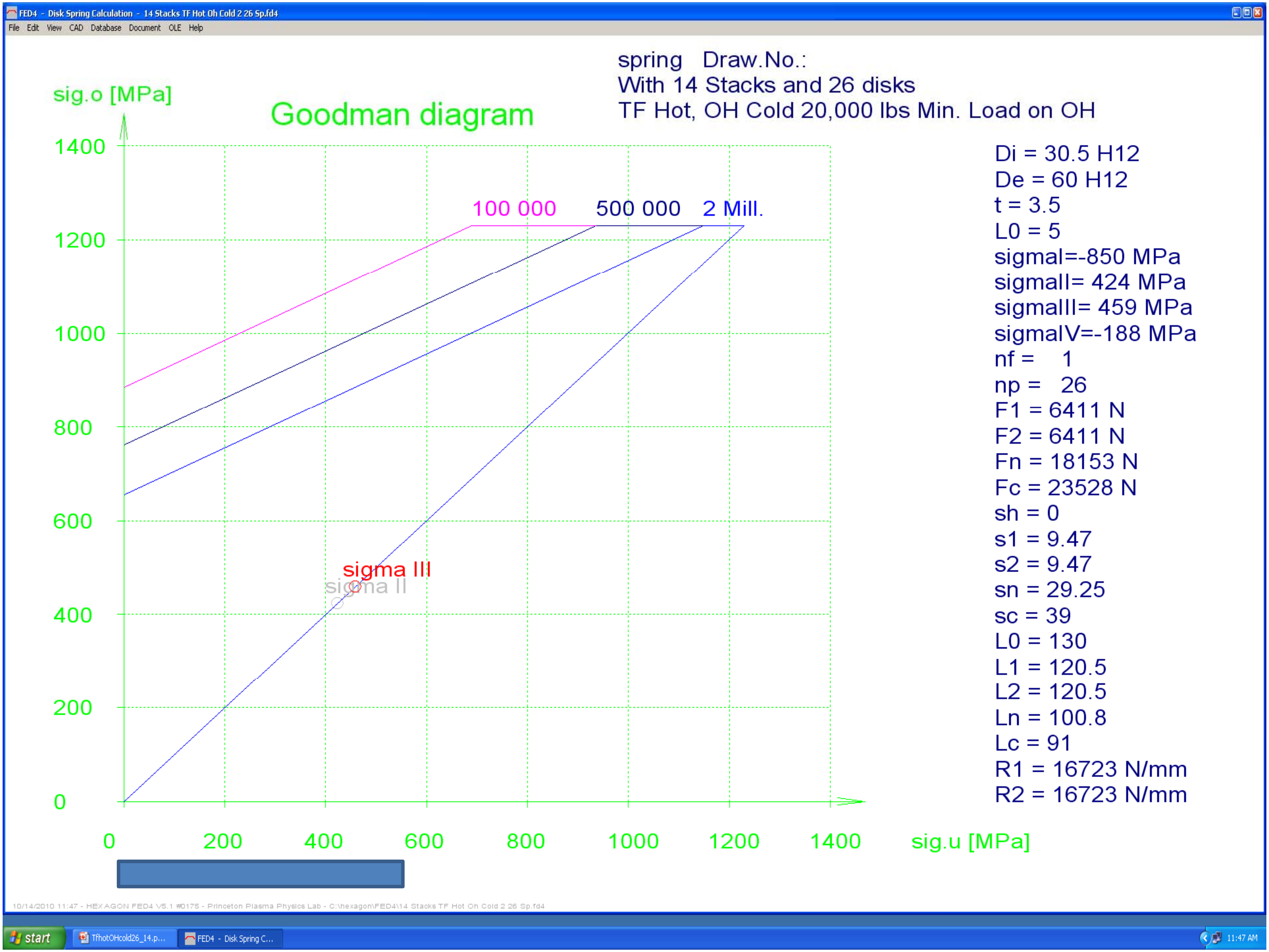
Princeton Plasma Physics Lab

C:\hexagon\FED4\14 Stacks TF Hot Oh Cold 2 26 Sp.fd4 10/14/2010 11:38

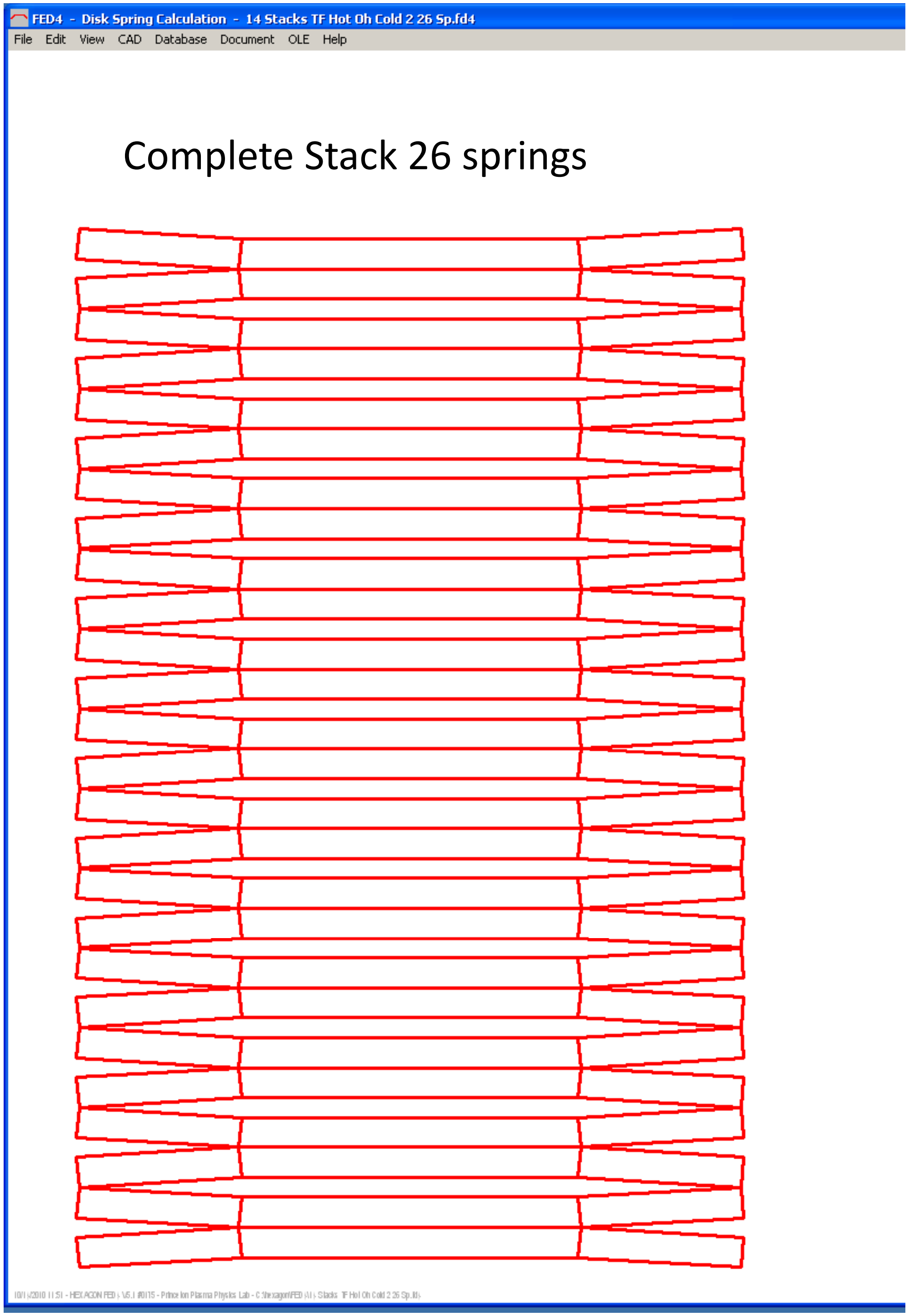

FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Cold 20,000 lbs Min. Load on OH
Force Path Diagram
F [N]
25E3
20E3
15E3
10E3
5000
0
Fc
Fn
F2
0
5
10
15
20
25
30
35
40
s [mm]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-850 MPa
sigmaII= 424 MPa
sigmaIII= 459 MPa
sigmaIV=-188 MPa
nf = 1
np = 26
F1 = 6411 N
F2 = 6411 N
Fn = 18153 N
Fc = 23528 N
sh = 0
s1 = 9.47
s2 = 9.47
sn = 29.25
sc = 39
L0 = 130
L1 = 120.5
L2 = 120.5
Ln = 100.8
Lc = 91
R1 = 16723 N/mm
R2 = 16723 N/mm
10/14/2010 11:42 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
start
11:42 AM


FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Cold 20,000 lbs Min. Load on OH
R [N/mm]
spring rate
20E3
15E3
10E3
5000
0
R2
Rc
0
5
10
15
20
25
30
35
40
s [mm]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-850 MPa
sigmaII= 424 MPa
sigmaIII= 459 MPa
sigmaIV=-188 MPa
nf = 1
np = 26
F1 = 6411 N
F2 = 6411 N
Fn = 18153 N
Fc = 23528 N
sh = 0
s1 = 9.47
s2 = 9.47
sn = 29.25
sc = 39
L0 = 130
L1 = 120.5
L2 = 120.5
Ln = 100.8
Lc = 91
R1 = 16723 N/mm
R2 = 16723 N/mm
10/14/2010 11:44 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
start
TfhotOHcold26_14.p...
FED4 - Disk Spring C...
11:44 AM


FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Cold 20,000 lbs Min. Load on OH
Spring energy
W [Nmm]
500E3
450E3
400E3
350E3
300E3
250E3
200E3
150E3
100E3
50E3
0
Wc
W2
0
5
10
15
20
25
30
35
40
s [mm]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-850 MPa
sigmaII= 424 MPa
sigmaIII= 459 MPa
sigmaIV=-188 MPa
nf = 1
np = 26
F1 = 6411 N
F2 = 6411 N
Fn = 18153 N
Fc = 23528 N
sh = 0
s1 = 9.47
s2 = 9.47
sn = 29.25
sc = 39
L0 = 130
L1 = 120.5
L2 = 120.5
Ln = 100.8
Lc = 91
R1 = 16723 N/mm
R2 = 16723 N/mm
10/14/2010 11:46 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
start
11:46 AM


FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Cold 20,000 lbs Min. Load on OH
Goodman diagram
sig.o [MPa]
sig.u [MPa]
100 000
500 000
2 Mill.
sigma III
sigma II
0
200
400
600
800
1000
1200
1400
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-850 MPa
sigmaII= 424 MPa
sigmaIII= 459 MPa
sigmaIV=-188 MPa
nf = 1
np = 26
F1 = 6411 N
F2 = 6411 N
Fn = 18153 N
Fc = 23528 N
sh = 0
s1 = 9.47
s2 = 9.47
sn = 29.25
sc = 39
L0 = 130
L1 = 120.5
L2 = 120.5
Ln = 100.8
Lc = 91
R1 = 16723 N/mm
R2 = 16723 N/mm
10/14/2010 11:47 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF Hot Oh Cold 2 26 Sp.fd4
start
TfhotOHcold26_14.p...
FED4 - Disk Spring C...
11:47 AM

Complete Stack 26 springs



	A	B	C	D
1				
2		Calculations in (N and mm) units		
3				
4		Calcs Based on the SCHNORR data formulas.		
5				
6		Note: These calculations are for SCHNORR #15900 as basic shape		
7				
8				
9		De - Ouside diameter	60	mm
10		Di - Inside diameter	30.5	mm
11				
12		pi	3.14	
13		1/pi	0.3185	
14		3/pi	0.9554	
15		6/pi	1.9108	
16				
17		del=De/Di Schnorr Formula #2	1.9672	
18				
19		lndel=ln(De/Di)	0.6766	
20				
21		del-1	0.9672	
22		del+1	2.9672	
23				
24				
25				
26		(del-1/del)^2	0.2417	
27		(del+1)/(del-1)	3.0678	
28		(2/lndel)	2.9559	
29				
30				
31		K1 =1/pi(((del-1/del)^2))/((del+1)/((del-1)-(2/lndel))) Formula #3	0.6879	
32				
33		K2=6/pi(((del-1)/(lndel))-1)))/(lndel) Formula #4	1.2129	
34				
35		K3=3/pi(del-1/lndel) Formula #5	1.3657	
36				
37		K4=1 since thikness is less than 6 mm Formula #6 (see chapter	1	
38				
39				
40		FORCE and STRESS Calculations		
41				
42				
43				
44		lo= total height	5.004	mm
45		ho= lo-t	1.499	mm
46		t=average spring thickness	3.505	mm

Calculations based on SCHNORR catalogue equations for a single disk at constant compression
s = .364 mm

Stack compression in this case:
s = 9.47 mm.

Or (.364 x 26) =
9.47 mm.
Force =6,428. N
("HEXAGON" F=6,411 N)

See slide #2

s= deflection of the single spring (from 75% of ho))	0.364	mm
E= modulus for steel	206000	N/mm^2
mu= Poisson's ratio	0.3	
1-mu^2	0.91	
4E/(1-mu^2)	905494.505	
t^4/(K1*de^2)	0.06094519	
s/t	0.10385164	
ho/t	0.42767475	
s/2t	0.05192582	
Formula #8a	6428.45	N
Formula #9 Stresses at the center of rotation (point OM)	-445.71	N/mm^2
(should be less then -1600N/mm^2)		
t^2/(K1*de^2)	0.00496093	
formula #10 Stress at point (I)	-849.75	N/mm^2
formula #11 Stress at point (II)	424.527204	N/mm^2
formula #12 Stress at point (III)	459.19	N/mm^2
1/del	0.50833333	
(K2-2K3)	-1.5185995	
(ho/t-s/2t)	0.37574893	
Formula #13 Stress at point (IV)	-188.56	N/mm^2
t^3/(K1*de^2)	0.01738807	
Formula #14 Spring Rate (dF/ds)	16781.43	N/mm
Formula #15 Spring Work (Integral from 0 to s, of F*ds)	1190.33	N-mm
2E/(1-mu^2)	452747.253	
t^5/(K1*de^2)	0.2136129	
Basic requirements for a good Disk spring design		
For the above basic equations to work		
This Spring is linear because ho/t=.428 (since for ho/t<0.4 are lii	slightly non-LINEAR	
del=De/Di=2.3923 and it should be between 1.75 and 2.5	O.K.	
Outside diameter De, Inside diameter Di		

ho/t=(lo-t)/t=.428 and it should be between 0.4 to 1.3 O.K.

ho=lo-t cone height, t=disk thickness

De/t=17.12 and it should be between 16. and 40. O.K.

Conclusion: This spring under the constant load of 3790.0 N is O.K.

Basic machine operation requirements:

1) TF coil inner leg maximum thermal expansion was calculated at 8.4mm

2) OH coil requires a preload of 20,000.0 lbs total or 7,413.3 N (12 St) per stack. Must calculate the required deflection (s) for the preload force?

3) OH coil thermal expansion was calculated at 6.0mm

So, the total each spring stack travel is = 8.4+6.0+calculated from minimum preload

For Fatigue predictions, using fatigue life diagrams for disk springs, one requires the Pre and Maximum loads stresses at points II or III (depending on del and ho/t).

OH Coil Pre Load System
TF hot OH hot

Calculations for the most probable system scenario.
From Pre load of 17.87 mm
(when TF and OH cool down pre load is restored)
TF coil thermal expansion = 8.4 mm
Reduces the stack compression to = 9.47 mm
Then, OH coil thermal expansion = 6.0 mm
Restores stack compression to = 15.47 mm

For a single spring s = .69 mm
For the stack = .69 x26 = 15.47 mm
Maximum obtained force on the OH coil
with 14 stacks = 10,162. x14 = 142,268. N
(31,970. lbs.)

Life based on “Sigma II” is over 2 million cycles

FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Hot 2 26 Sp.fd4

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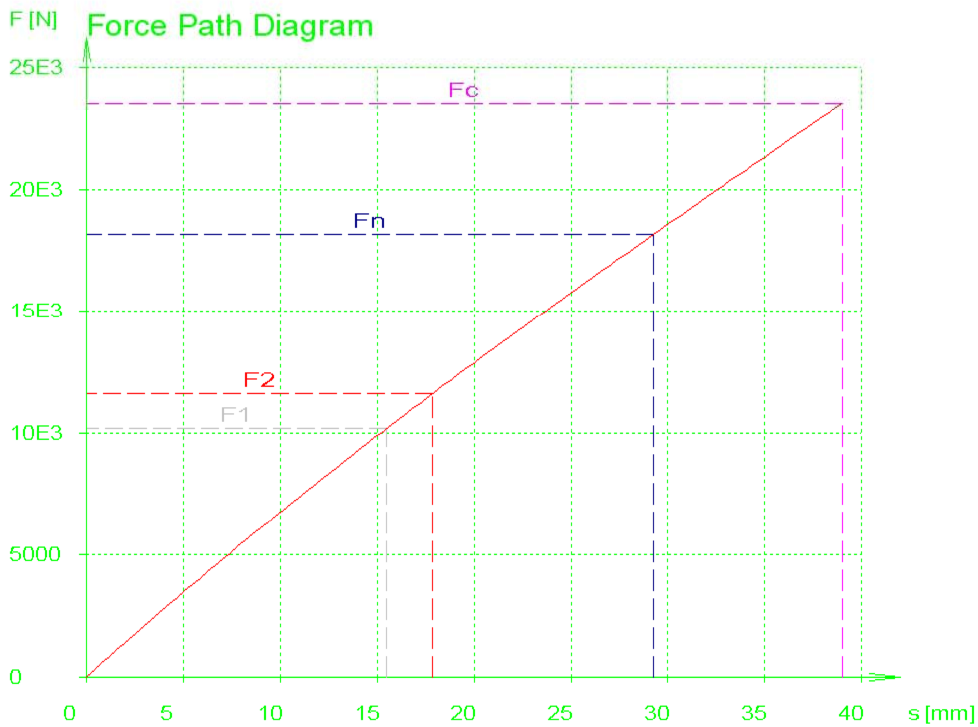


Di = 30.5 mm
De = 60 mm
t = 3.5 mm
L0 = 5 mm

nf = 1
np = 26
Lc = 91 mm
L0 = 130 mm

Stainless Steel Required

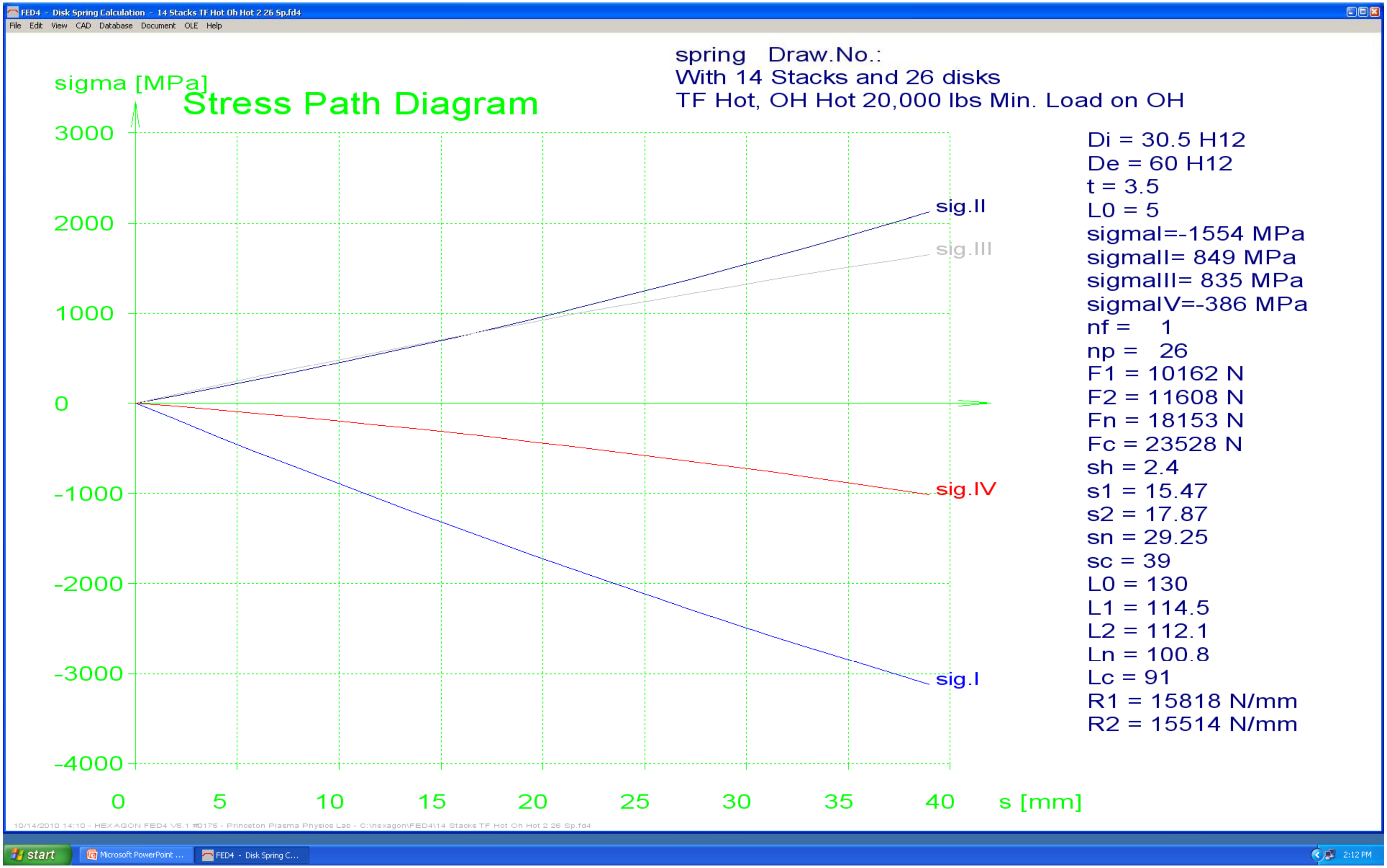
E = 206000 MPa
mue = 0.3
rho= 7.85 kg/dm^3
sigma perm = 1230 MPa
(DIN 2092)

	0	1	2	n	c	
s	0.00	15.47	17.87	29.25	39.00	mm
L	130.00	114.53	112.13	100.75	91.00	mm
F	0	10162	11608	18153	23528	N
R	18566	15818	15514	14515	14245	N/mm
sigma I	0	-1357	-1554	-2434	-3121	MPa
sigma III	0	731	835	1297	1650	MPa
si	0.00	0.60	0.69	1.13	1.50	mm
Li	5.00	4.41	4.31	5.00	0.00	mm
Fi	0	10162	11608	18153	23528	N

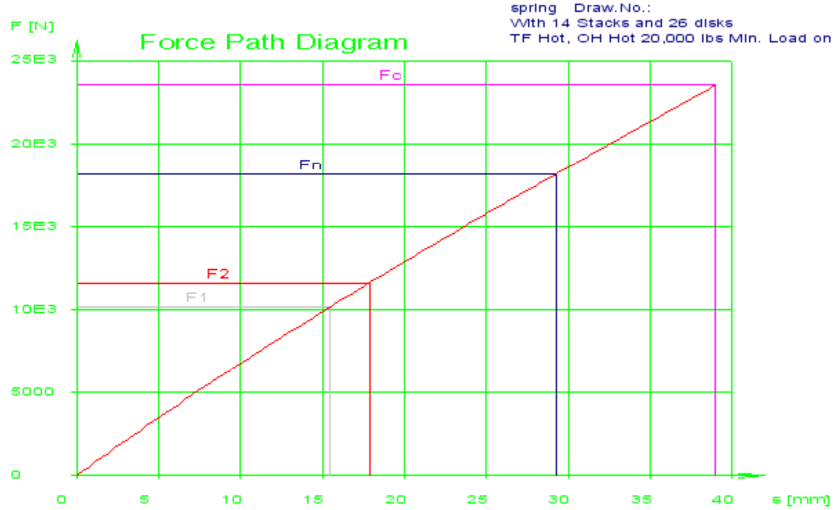
messages

\- none -

Total compression = 15.47 mm
Return to Pre Load = 17.87 mm
Total Force/Stack = 10,162 N
(2,284. lbs)
Total force on OH coil =
(2,284. x 14 = 31,970 lbs.)


FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Hot 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Hot 20,000 lbs Min. Load on OH
Stress Path Diagram
sigma [MPa]
3000
2000
1000
0
-1000
-2000
-3000
-4000
0
5
10
15
20
25
30
35
40
s [mm]
sig.II
sig.III
sig.IV
sig.I
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-1554 MPa
sigmaII= 849 MPa
sigmaIII= 835 MPa
sigmaIV=-386 MPa
nf = 1
np = 26
F1 = 10162 N
F2 = 11608 N
Fn = 18153 N
Fc = 23528 N
sh = 2.4
s1 = 15.47
s2 = 17.87
sn = 29.25
sc = 39
L0 = 130
L1 = 114.5
L2 = 112.1
Ln = 100.8
Lc = 91
R1 = 15818 N/mm
R2 = 15514 N/mm
10/14/2010 14:10 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF Hot Oh Hot 2 26 Sp.fd4
start
Microsoft PowerPoint ...
FED4 - Disk Spring C...
2:12 PM

spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Hot 20,000 lbs Min. Load on OH



Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-1554 MPa
sigmaII= 849 MPa
sigmaIII= 835 MPa
sigmaIV=-386 MPa
nf = 1
np = 26
F1 = 10162 N
F2 = 11608 N
Fn = 18153 N
Fc = 23528 N
sh = 2.4
s1 = 15.47
s2 = 17.87
sn = 29.25
sc = 39
L0 = 130
L1 = 114.5
L2 = 112.1
Ln = 100.8
Lc = 91
R1 = 15818 N/mm
R2 = 15514 N/mm

spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Hot 20,000 lbs Min. Load on OH

SINGLE DISK SPRING			
inside diameter	Di	mm	30.5 H12
outside diameter	De	mm	60 H12
thickness	t	mm	3.5
length	L0	mm	5
weight	m	g	57.61
usable spring travel sn=0.75*h0	sin	mm	1.125
max. spring travel h0=sc	sic	mm	1.5
spring force with sn=0.75*sc	Fin	N	18153
No. of springs per package	nf		1
No. of spring packages	np		26

Length mm	Sp.travel mm	Load N	Sigma MPa
L0 = 130.00			
L1 = 114.53	s1 = 15.47	F1 = 10161.96	sigma1 = 731
	sh = 2.40	Fh = 1445.82	sigmah = 104
L2 = 112.13	s2 = 17.87	F2 = 11607.78	sigma2 = 835
Ln = 100.75	sn = 29.25	Fn = 18152.58	sigman = 1297
Lc = 91.00	sc = 39.00	Fc = 23528.21	sigmac = 1650

	Date	Name
Compl.	08/25/2010	P. Rogoff
Check		
Stand.		

Disk Spring

Cond. | Modification | Date | Name

Princeton Plasma Physics Lab

Page

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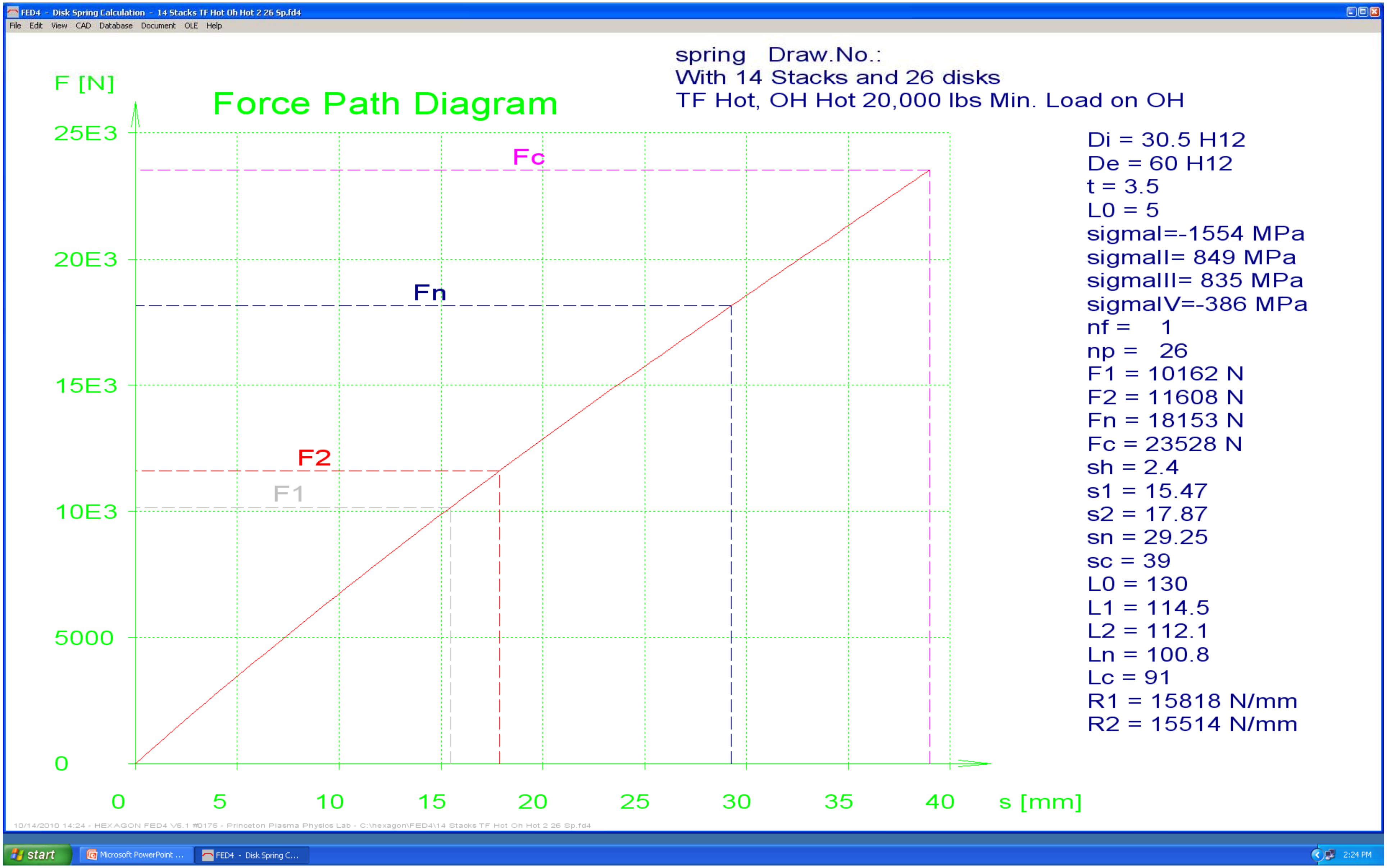
C:\hexagon\FED4\14 Stacks TF Hot Oh Hot 2 26 Sp.fd4 10/14/2010 14:20


FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Hot 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Hot 20,000 lbs Min. Load on OH
Force Path Diagram
F [N]
25E3
20E3
15E3
10E3
5000
0
Fc
Fn
F2
F1
0
5
10
15
20
25
30
35
40
s [mm]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-1554 MPa
sigmaII= 849 MPa
sigmaIII= 835 MPa
sigmaIV=-386 MPa
nf = 1
np = 26
F1 = 10162 N
F2 = 11608 N
Fn = 18153 N
Fc = 23528 N
sh = 2.4
s1 = 15.47
s2 = 17.87
sn = 29.25
sc = 39
L0 = 130
L1 = 114.5
L2 = 112.1
Ln = 100.8
Lc = 91
R1 = 15818 N/mm
R2 = 15514 N/mm
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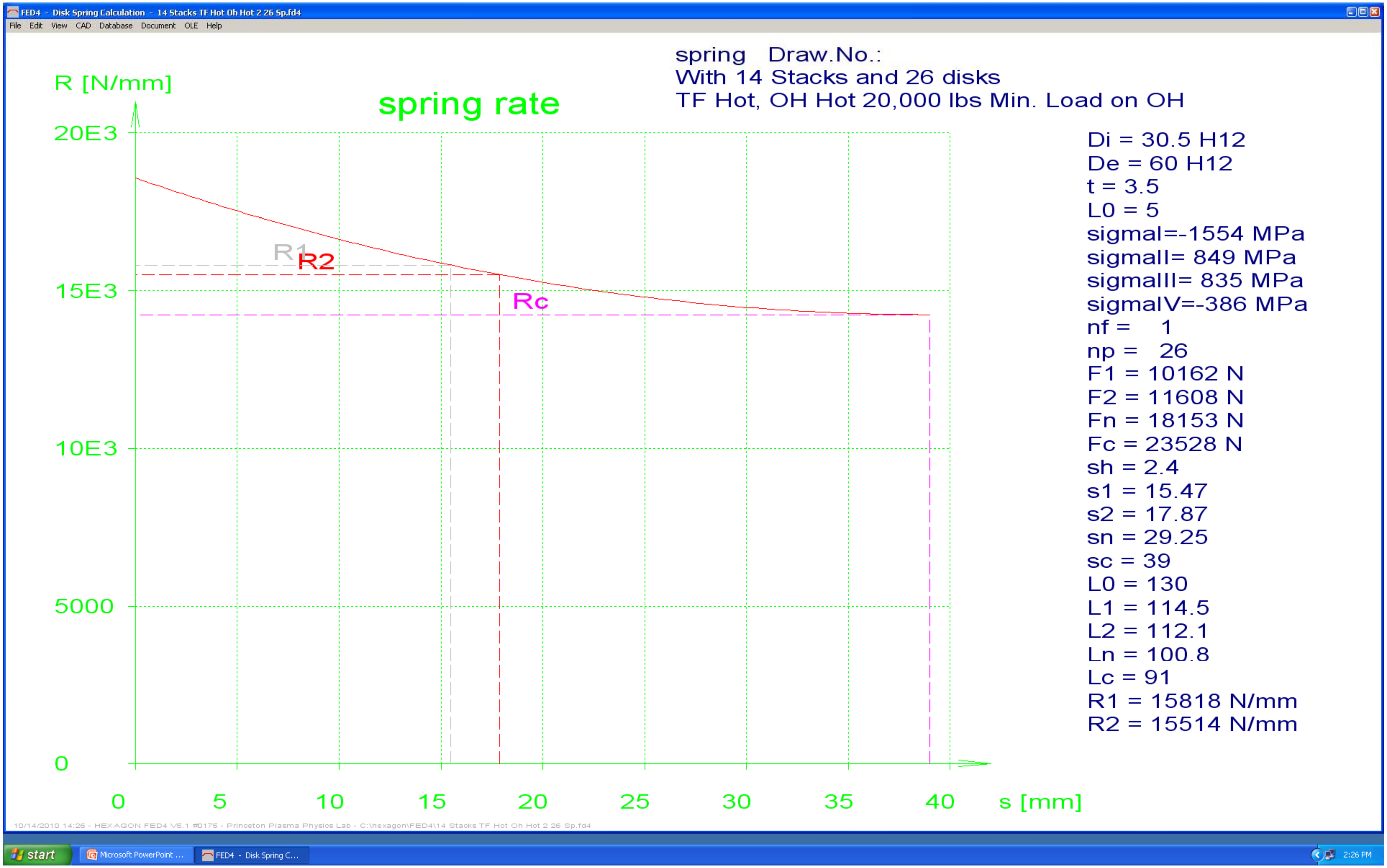
Microsoft PowerPoint ...
FED4 - Disk Spring C...
2:24 PM


FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Hot 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Hot 20,000 lbs Min. Load on OH
spring rate
R [N/mm]
20E3
15E3
10E3
5000
0
R1
R2
Rc
0
5
10
15
20
25
30
35
40
s [mm]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-1554 MPa
sigmaII= 849 MPa
sigmaIII= 835 MPa
sigmaV=-386 MPa
nf = 1
np = 26
F1 = 10162 N
F2 = 11608 N
Fn = 18153 N
Fc = 23528 N
sh = 2.4
s1 = 15.47
s2 = 17.87
sn = 29.25
sc = 39
L0 = 130
L1 = 114.5
L2 = 112.1
Ln = 100.8
Lc = 91
R1 = 15818 N/mm
R2 = 15514 N/mm
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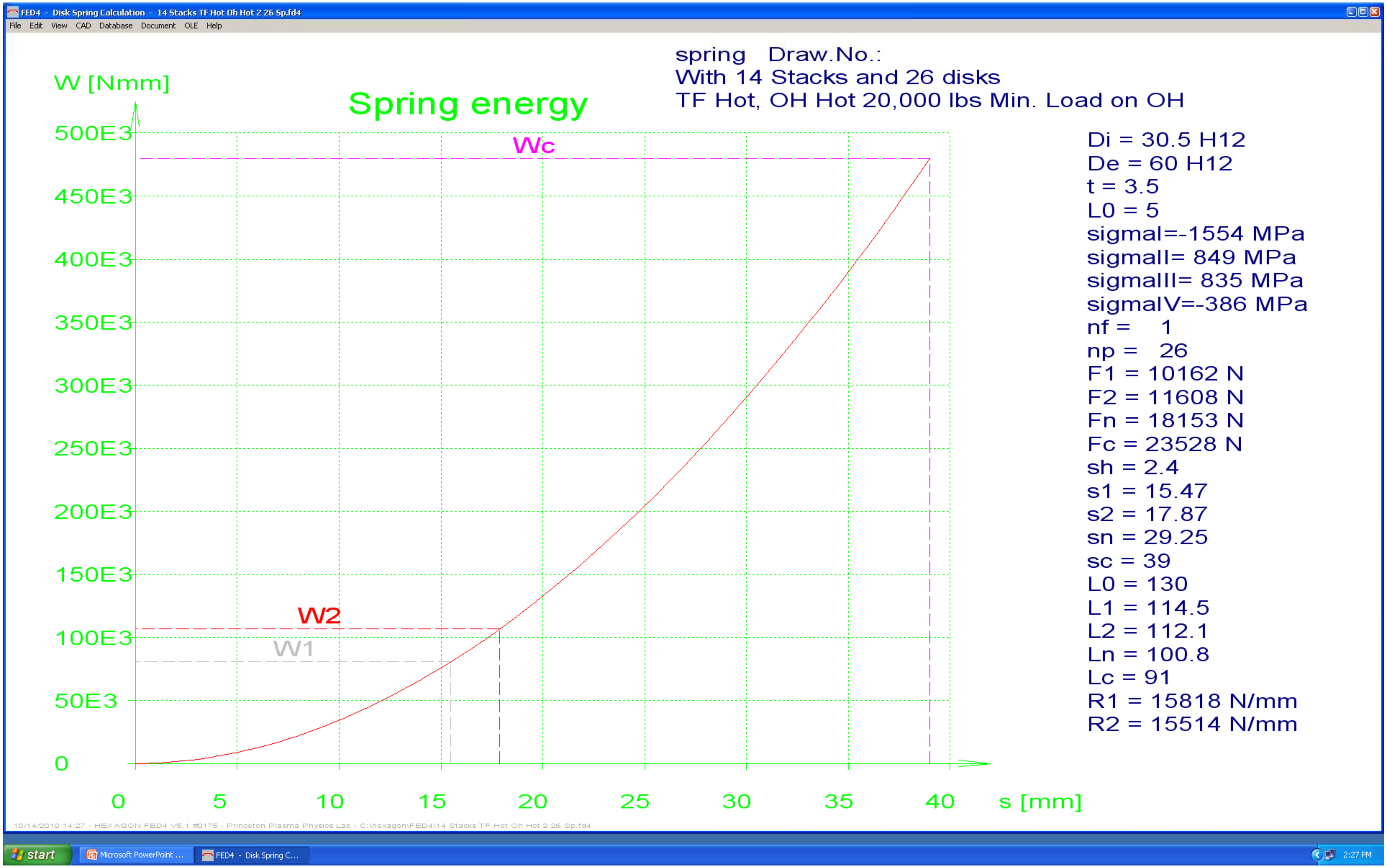
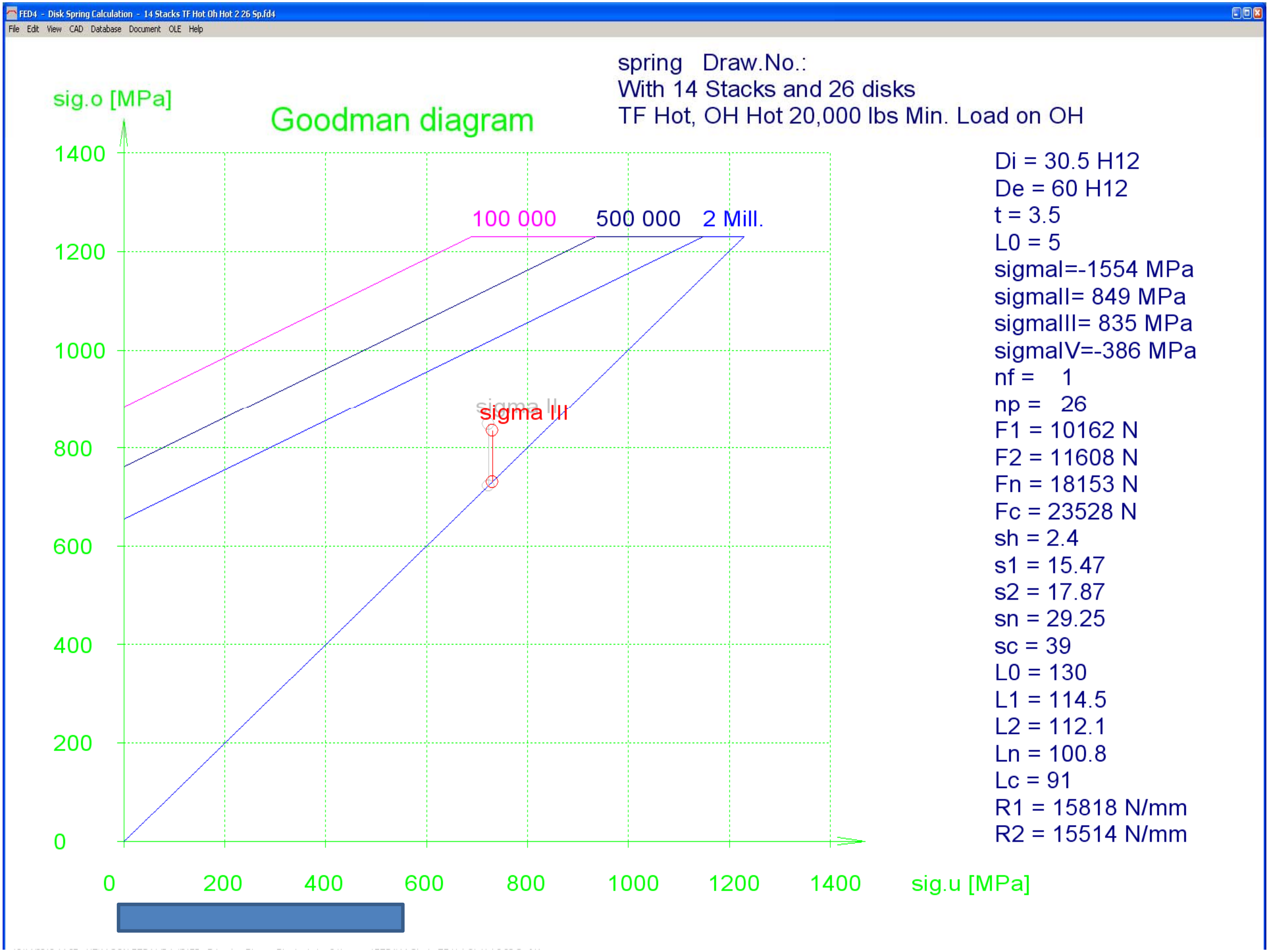
Microsoft PowerPoint ...
FED4 - Disk Spring C...
2:26 PM


FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Hot 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Hot 20,000 lbs Min. Load on OH
Spring energy
W [Nmm]
500E3
450E3
400E3
350E3
300E3
250E3
200E3
150E3
100E3
50E3
0
Wc
W2
W1
0
5
10
15
20
25
30
35
40
s [mm]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-1554 MPa
sigmaII= 849 MPa
sigmaIII= 835 MPa
sigmaIV=-386 MPa
nf = 1
np = 26
F1 = 10162 N
F2 = 11608 N
Fn = 18153 N
Fc = 23528 N
sh = 2.4
s1 = 15.47
s2 = 17.87
sn = 29.25
sc = 39
L0 = 130
L1 = 114.5
L2 = 112.1
Ln = 100.8
Lc = 91
R1 = 15818 N/mm
R2 = 15514 N/mm
10/14/2010 14:27 - HEXAGON FED4 V5.1 #0175 - Princeton Plasma Physics Lab - C:\hexagon\FED4\14 Stacks TF Hot Oh Hot 2 26 Sp.fd4
start
Microsoft PowerPoint ...
FED4 - Disk Spring C...
2:27 PM


FED4 - Disk Spring Calculation - 14 Stacks TF Hot Oh Hot 2 26 Sp.fd4
File Edit View CAD Database Document OLE Help
spring Draw.No.:
With 14 Stacks and 26 disks
TF Hot, OH Hot 20,000 lbs Min. Load on OH
sig.o [MPa]
Goodman diagram
1400
1200
1000
800
600
400
200
0
100 000
500 000
2 Mill.
sigma III
0
200
400
600
800
1000
1200
1400
sig.u [MPa]
Di = 30.5 H12
De = 60 H12
t = 3.5
L0 = 5
sigmaI=-1554 MPa
sigmaII= 849 MPa
sigmaIII= 835 MPa
sigmaIV=-386 MPa
nf = 1
np = 26
F1 = 10162 N
F2 = 11608 N
Fn = 18153 N
Fc = 23528 N
sh = 2.4
s1 = 15.47
s2 = 17.87
sn = 29.25
sc = 39
L0 = 130
L1 = 114.5
L2 = 112.1
Ln = 100.8
Lc = 91
R1 = 15818 N/mm
R2 = 15514 N/mm

	A	B	C	D
1				
2		Calculations in (N and mm) units		
3				
4		Calcs Based on the SCHNORR data formulas.		
5				
6		Note: These calculations are for SCHNORR #15900 as basic shape		
7				
8				
9		De - Ouside diameter	60	mm
10		Di - Inside diameter	30.5	mm
11				
12		pi	3.14	
13		1/pi	0.3185	
14		3/pi	0.9554	
15		6/pi	1.9108	
16				
17		del=De/Di Schnorr Formula #2	1.9672	
18				
19		Indel=ln(De/Di)	0.6766	
20				
21		del-1	0.9672	
22		del+1	2.9672	
23				
24				
25				
26		(del-1/del)^2	0.2417	
27		(del+1)/(del-1)	3.0678	
28		(2/Indel)	2.9559	
29				
30				
31		K1 =1/pi(((del-1/del)^2))/((del+1)/((del-1)-(2/Indel))) Formula #3	0.6879	
32				
33		K2=6/pi(((del-1)/(Indel))-1)))/(Indel) Formula #4	1.2129	
34				
35		K3=3/pi(del-1/Indel) Formula #5	1.3657	
36				
37		K4=1 since thikness is less than 6 mm Formula #6 (see chapter	1	
38				
39				
40		FORCE and STRESS Calculations		
41				
42				
43				
44		lo= total height	5.004	mm
45		ho= lo-t	1.499	mm
46		t=average spring thickness	3.505	mm

Calculations based on SCHNORR catalogue equations for a single disk at constant compression s = .595 mm

Stack compression in this case: s = 15.47 mm.

Or (.595 x 26) = 15.47 mm.

Force = 10,196. N

(“HEXAGON” F=10,162N)

See slide #2

s= deflection of the single spring (from 75% of ho))	0.595	mm
E= modulus for steel	206000	N/mm^2
mu= Poisson's ratio	0.3	
1-mu^2	0.91	
4E/(1-mu^2)	905494.505	
t^4/(K1*de^2)	0.06094519	
s/t	0.16975749	
ho/t	0.42767475	
s/2t	0.08487874	
Formula #8a	10196.43	N
Formula #9 Stresses at the center of rotation (point OM)	-728.57	N/mm^2
(should be less then -1600N/mm^2)		
t^2/(K1*de^2)	0.00496093	
formula #10 Stress at point (I)	-1358.53	N/mm^2
formula #11 Stress at point (II)	724.417318	N/mm^2
formula #12 Stress at point (III)	731.21	N/mm^2
1/del	0.50833333	
(K2-2K3)	-1.5185995	
(ho/t-s/2t)	0.34279601	
Formula #13 Stress at point (IV)	-327.62	N/mm^2
t^3/(K1*de^2)	0.01738807	
Formula #14 Spring Rate (dF/ds)	15875.94	N/mm
Formula #15 Spring Work (Integral from 0 to s, of F*ds)	3114.53	N-mm
2E/(1-mu^2)	452747.253	
t^5/(K1*de^2)	0.2136129	
Basic requirements for a good Disk spring design		
For the above basic equations to work		
This Spring is linear because ho/t=.428 (since for ho/t<0.4 are lii	slightly non-LINEAR	
del=De/Di=2.3923 and it should be between 1.75 and 2.5	O.K.	
Outside diameter De, Inside diameter Di		

ho/t=(lo-t)/t=.428 and it should be between 0.4 to 1.3 O.K.

ho=lo-t cone height, t=disk thickness

De/t=17.12 and it should be between 16. and 40. O.K.

Conclusion: This spring under the constant load of 3790.0 N is O.K.

Basic machine operation requirements:

1) TF coil inner leg maximum thermal expansion was calculated at 8.4mm
2) OH coil requires a preload of 20,000.0 lbs total or 7,413.3 N (12 St) per stack. Must calculate the required deflection (s) for the preload force?
3) OH coil thermal expansion was calculated at 6.0mm

So, the total each spring stack travel is = 8.4+6.0+calculated from minimum preload

For Fatigue predictions, using fatigue life diagrams for disk springs, one requires the Pre and Maximum loads stresses at points II or III (depending on del and ho/t).

Bellville Washer Stack
(Verification by Testing)

Bellville Washer Stack

Comparison of the Calculated to Test data for a single washer stack

Test data Spring Rate = 3,922. lb/in

Calculated from the required minimum load on the OH coil,
Total Load = 20,157.0 lbs. at 9.47 mm displacement or = .373 in.
There are 14 Stacks, with 26 Bellville spring each.

Therefore: 20,157/14 = 2,128.5 lbs/mm,
2,128.5 X 25.4 mm/in =54,064 lbs/in for 14 stacks,
Than K = 54,064/14 = 3,862. lb/in

Calculated K = 3,862 lb/in

Spring rate check, at .373 in disp. is: 3,862. X .373 = 1,440 lb per stack
therefore, total load for 14 stacks = 1,440. X 14 = 20160. lb