nsls

IR UV X

BNL- 65831

Thermal Cycle Time Simulation Analysis of a Crotch Photon Absorber in an X-Ray Storage Ring

Jeffrey Morgan, Donald Lynch, and Martin Woodle
National Synchrotron Light Source
Brookhaven National Laboratory, P.O. Box 5000
Upton, NY 11973-5000

August 1998

NATIONAL SYNCHROTRON LIGHT SOURCE

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Under Contract No. DE-AC02-98CH10886 with the
UNITED STATES DEPARTMENT OF ENERGY

BNL-65831

Thermal Cycle Time Simulation Analysis of a Crotch Photon Absorber in an X-ray Storage Ring

National Synchrotron Light Source
Brookhaven National Laboratory
Upton, New York 11973-5000

8/24/98

Authors:
Jeffrey Morgan, Don Lynch, Marty Woodle

Abstract

The National Synchrotron Light Source is an electron accelerator facility at Brookhaven National Laboratory. To improve on the brightness of it's synchrotorn radiation it is important that this accelerator operates at its maximum design currents of excess of 500 mA at 2.5 GeV. Currently, it is running at 350 mA at the same energies of 2.5 GeV. With on-going developments and advancements in beam technology instrumentation, the National Synchrotron Light Source looks to maintain its position at the forefront of world class beam accelerators. But in order to accomplish this, this accelerator must run at higher currents. The aim of this study is to test the capability of certain components in the accelerator to operate under these increased currents using Finite Element Analysis and prototype experimentation.

Research efforts will be devoted to determine whether the component fails due to operating the beam at higher current levels. Full studies of the component's performance will be conducted along with any necessary improvements needed to operate at these levels.

It has been concluded that certain components in the accelerator might be subject to failure under these upgrades. Among these components is the exit chamber crotch component, which is the direct link between the actual accelerator storage ring and the beam ports. This component is cyclically subjected to a high temperature and its design life as this temperature is increased, is under question. Analyzing this component through finite element analysis as well as simulating a prototype beam on the actual part in experiment is essential in testing and verifying whether this component needs upgrading or is capable of handling the increased heat load.

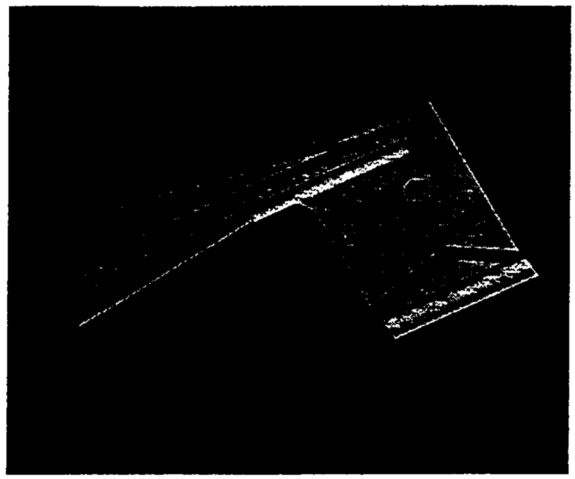


Figure 1: Crotch

Introduction:

At the National Synchrotron Light Source at Brookhaven National Laboratory, electrons are accelerated in a storage ring where photons are emitted tangent to the beam in to beam ports where they are used for many research experiments. The crotch assembly (see figure 1) is positioned at the entrance to these beam ports and collectively absorbs any runoff from the beam to protect uncooled sections of the beam chamber. As part of an experiment to test if this crotch can absorb (see figure 2) and withstand the radiation from a higher electron current within this storage ring without breakdown, the heating and cooling time for this crotch has to be calculated. This facility normally refills the electron beam an average of two times a day and has an estimated lifetime of 20 years. This experiment simulates the actual heating and cooling cycle time in the storage ring and the number of cycles to determine the projected lifetime of the part. It is desired to conduct this test in a short amount of time.

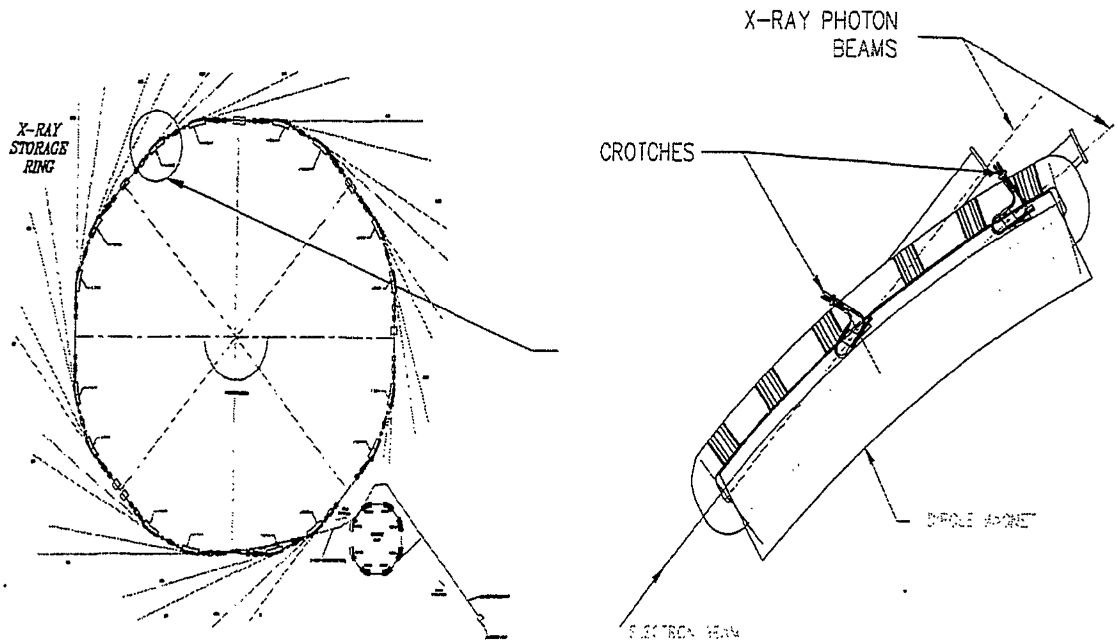


FIGURE 2: CROTCH LOCATION IN THE X-RAY RING

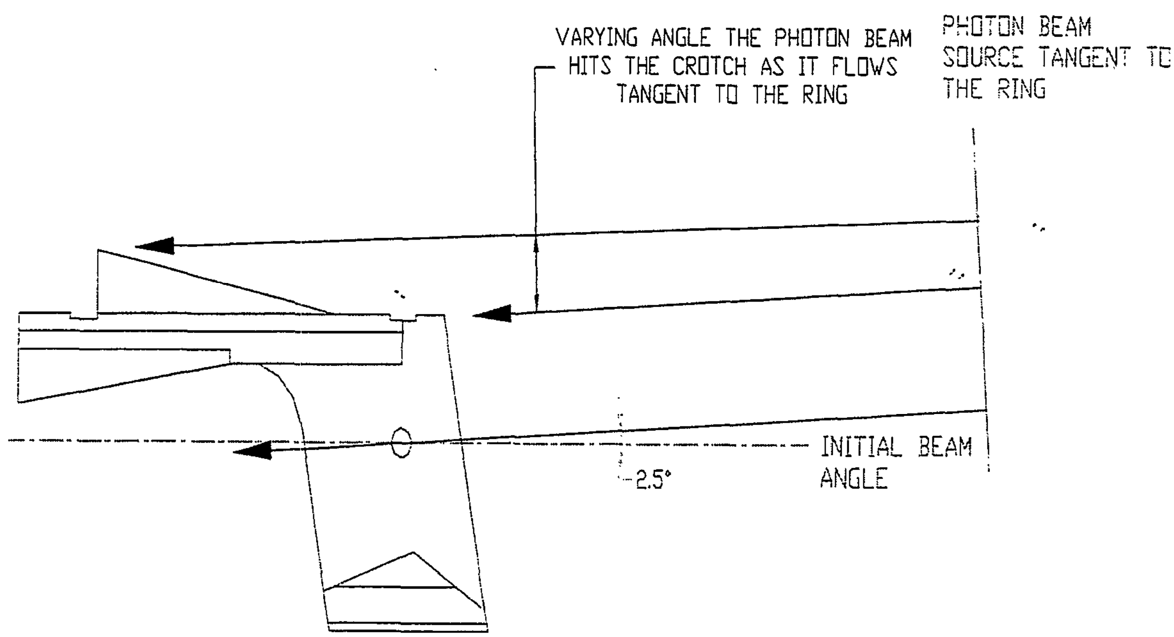


FIGURE 3: PHOTON BEAM PROFILE ON CROTCH

Problem:

Using a Finite element analysis software ALGOR™, the crotch was calculated to heat up to a steady temperature of 476 °F with cooling water running through as a heat sink at 80.4 °F. The primary focus of this section of the test is to calculate the amount of time needed for the crotch to cool from 476 °F to 82 °F. This will allow the establishment of a conservative yet accurate thermal cycling time can be obtained by doubling the cooling time.

Types of Analysis:

- The crotch is to be first analyzed through a very conservative unidirectional conduction analysis with only the triangular section of the crotch analyzed because of the beam concentration in this area (see figure 3). This would give a preliminary estimate of the duration of a single cycle.

- The second analysis will use ALGOR™ finite element analysis software to compare and simulate this cooling process using a more detail crotch structure with cooling at the appropriate locations. This is used as a check to verify on the accuracy of the conservative results in the first analysis.

ANALYSIS 1:

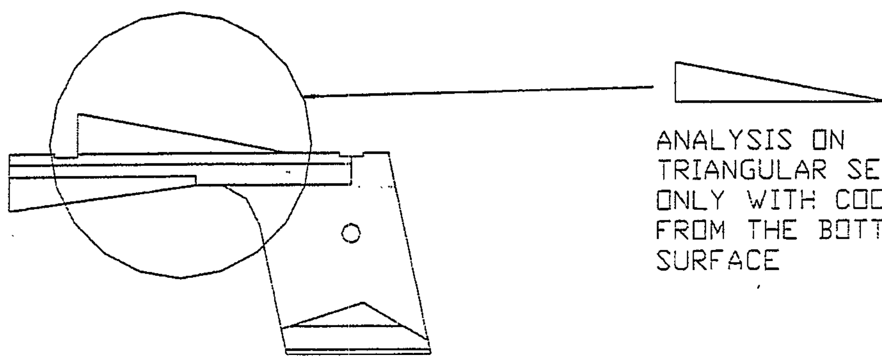


FIGURE 4: SECTION ANALYZED FOR COOLING

Assumptions:

- Temperature is uniformly distributed as 476 °F on the triangular surface.
- Unidirectional conduction.
- Triangular section is only used with the cooling placed on the bottom surface for this unidirectional analysis.
- Assume the distance from the heated surface to the cooling tubes to be 19mm.
- Assume constant temperature heat sink.
- Assume heat transfer coefficient is a constant h = .003125 $\frac{BTU}{\sec in^2 F}$

Properties:

		UNITS
Thermal Conductivity (k)	.005	$\frac{BTU}{(\sec) in^\circ F}$
Convective heat transfer coefficient (h)	.003125	$\frac{BTU}{(\sec) in^\circ F}$
Density (ρ)	.323	$\frac{lbm}{in^3}$
Length (L)	.748	in
Temperature (T): T_i =	476.492	°F
T_∞ =	80.4	
T_c =	82.0	
Specific heat (c_p)	.1	$\frac{BTU}{lbm^\circ F}$
Time (t)		Seconds

Formulas:

α	$\frac{k}{\rho c}$
Fourier number (F_o)	$\frac{\alpha t}{L^2}$
Biot number (Bi)	$\frac{hL}{k}$
Unidirectional conduction equation	$\frac{T_c - T_\infty}{T_i - T_\infty} = \frac{2\sin a_1}{a_1 + \sin a_1 \cos a_1} \exp(-a_1^2 F_0)$

$$\alpha = \frac{k}{\rho c} = \frac{.005}{(.323)(.1)} = .1548\ \frac{in^2}{s}$$

$$\mathbf{Bi} = \frac{hL}{k} = \frac{(.003125)(.748)}{.005} = .2338$$

(1) $$\frac{T_c - T_\infty}{T_i - T_\infty} = \frac{2\sin a_1}{a_1 + \sin a_1 \cos a_1} \exp(-a_1^2 F_0)$$;(Eq 4.62, A.Bejan)

From table 3.1 (*heat transfer,* A. Bejan) $a_1 = .3214$

$$\frac{T_c - T_\infty}{T_i - T_\infty} = \frac{82 - 80.4}{476.492 - 80.4} = .00404$$; (Left side of eq. 1)

$$\frac{2\sin a_1}{a_1 + \sin a_1 \cos a_1} e^{-a_1^2 F_0} = \frac{2(.3214)}{.3214 + (.3214)(1)} e^{-.1033 F_0} = e^{-.1033 F_0}$$; (Right side of eq. 1)

Substituting back into eq. (1)

$.00404 = e^{-.1033 F_o}$

Solving for F_o: $F_o = 53.35$

$$\mathbf{F_o} = \frac{\alpha t}{L^2}; \qquad t = \frac{F_0 L^2}{\alpha} = \frac{53.35(.748)^2}{.1548} = 192.8 \text{ seconds} \cong 3 \text{ minutes}$$

Therefore 1 cycle = 2t = 385.6 seconds = 6.5 minutes.

1 year (400 cycles) can be simulated in approximately 2 days.

The entire expected lifetime of 20 years could be simulated in 2 months.

ANALYSIS 2:

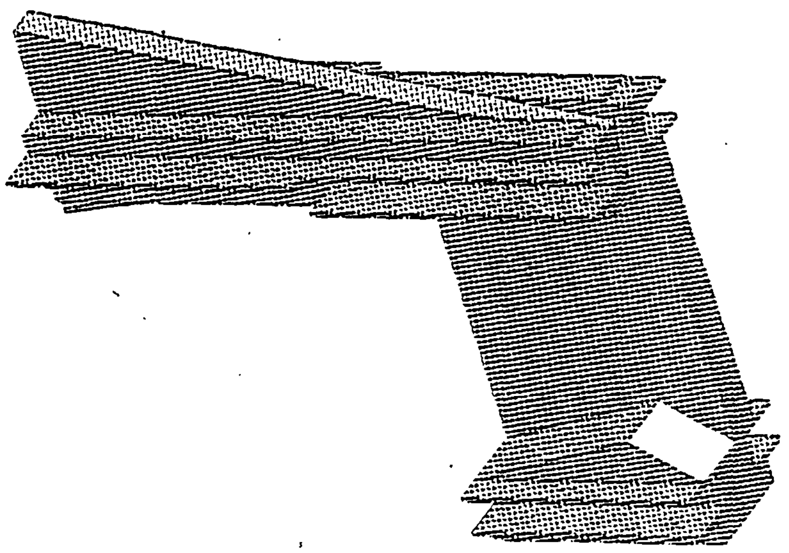


Figure 5: Three dimensional Finite Element Model of Crotch

Assumptions:

- Heat flux from the water pipe is held constant
- Water in pipes are at a constant temperature.
- Tubes are made into rectangular boxes with the same surface area as the actual circular shape to simplify the finite element analysis.
- Only the tubes are used to cool the crotch. (i.e. no radiation cooling)
- Assume heat transfer coefficient at the water is a constant h = .003125 $\frac{BTU}{\sec in^2 F}$

Set up:

Prior to this cooling cycle analysis, the steady state temperature distribution of the crotch due to a heat flux was calculated and simulated using ALGOR™. Therefore the cooling analysis would be to absorb the heat flux at the surface of the crotch followed by using transient thermal analysis, with accurate time steps where the cooling process can be simulated in coordination with the listed assumptions.

Calculations:

With the same nomenclature from the previous analysis and the temperature distribution of the crotch at steady state temperatures, transient analysis for the cooling can be observed. The only acting cooling surfaces in the crotch are the cooling tubes. The cooling tubes in this sample are rectangular shaped to simplify the meshing of the part and for better and more accurate results from the ALGOR™ software. The cooling analysis of the crotch was set at a delta t of .1 seconds and a time step of .25 seconds, for a total of 60 seconds used as the first iteration using ALGOR™ software for transient analysis. The second iteration was to run the same transient analysis at a longer time step and the third iteration was to run the transient analysis at a delta t of .01, set at 100 time steps for a total of 60 seconds.

Table 1: Temperature Profile of Crotch Cooling

Analysis	A	B	C
delta t (sec)	0.1	0.1	0.01
final time (sec)	60	60	60
time step (sec)	5	10	100

Analysis: time (sec)	A Temp. (F)	B Temp. (F)	C Temp. (F)
0	476.492	476.492	476.492
0.5	346.848		
1	294.653	300.408	290.711
1.5	259.486		
2	233.25	236.814	230.52
2.5	212.78		
3	196.247	198.778	194.317
3.5	182.513		
4	170.844	172.731	169.408
4.5	160.761		
5	151.943	153.443	150.789
5.5	144.167		
6	137.273	138.535	136.289
6.5	131.139		
7	125.67	126.767	124.807
7.5	120.788		
8	116.429	117.395	115.668
8.5	112.535		
9	109.057	109.907	108.383
9.5	105.952		
10	103.179	103.923	102.595
10.5	100.704		
11	98.4969	99.1438	97.9917
11.5	96.5274		
12	94.7711	95.3292	94.3372
12.5	93.2052		
13	91.8094	92.2877	91.4392
13.5	90.5654		
14	89.457	89.8643	89.143
14.5	88.4693		
15	87.5895	87.9346	87.3246
15.5	86.8057		

Analysis: time (sec)	A Temp. (F)	B Temp. (F)	C Temp. (F)
16	86.1076	86.3987	85.8351
16.5	85.4858		
17	85.0769	85.1765	84.9984
17.5	84.752		
18	84.4494	84.5404	84.3777
18.5	84.1675		
19	83.905	83.988	83.8398
19.5	83.6606		
20	83.433	83.3085	83.3738
20.5	83.2211		
21	83.0239	83.0923	82.9703
21.5	82.8403		
22	82.6694	82.7314	82.621
22.5	82.5104		
23	82.3625	82.4184	82.3188
23.5	82.2248		
24	82.0967	82.1471	82.0574
24.5	**81.9755**		
25	**81.8666**	**81.912**	**81.8313**
25.5	81.7635		
26	81.6676	81.7083	81.6359
26.5	81.5783		
27	81.4953	81.5319	81.467
27.5	81.4182		
28	81.3464	81.3791	81.321
28.5	81.2797		
29	81.2176	81.2469	81.1949
29.5	81.1599		
30	81.1062	81.1324	81.086
30.5	81.0564		
31	81.01	81.0333	80.992
31.5	80.9669		
32	80.9268	80.9476	80.9108

The time for the crotch to cool under these three analysis are:

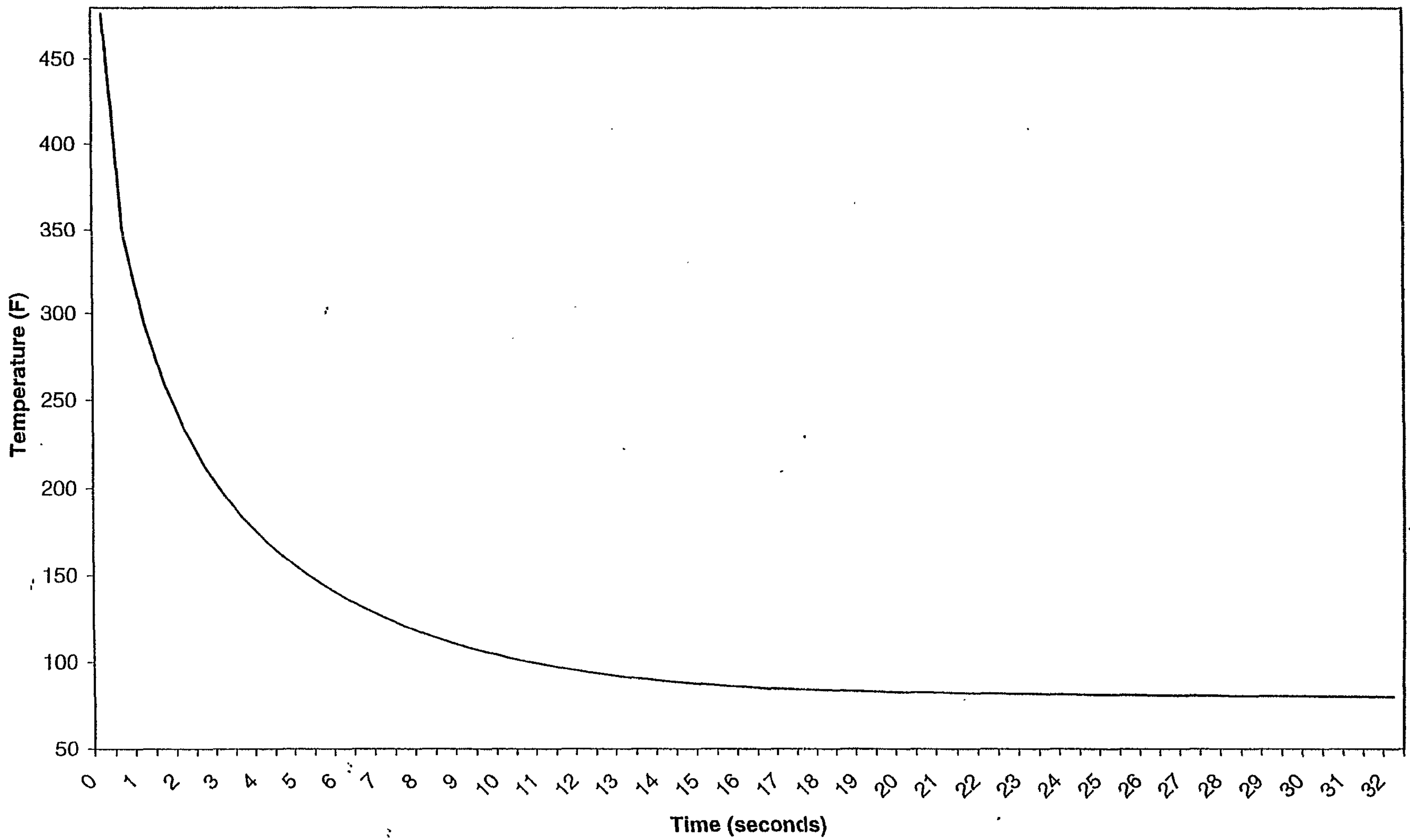
Analysis	A	B	C
Temp. (F)	81.9755	81.912	81.8313
Time (sec)	24.5	25	25

Averaging the three analysis together gives a final result of: Average Temperature = 81.90627

Average Time = 24.8333

Therefore 1 cycle = 2t = 49.6666 seconds = 0.8277767 minutes

Figure 6: Crotch Cooling Analysis



Results of Analyses:

Table 2: Results

	ANALYSIS 1	ANALYSIS 2
Cycle time (sec)	385.6	24.8333
Temperature (F)	82	81.9063

The cycle time found in the first analysis is very conservative and needs to be refined to to improve the cycle time estimate. Also due to the numerous conservative assumptions, this gives way to a higher time value. This analysis has given a ball park estimate of how long it would take for one full cycle.

For the second analysis, the model used was far more accurate and analyzed the part with the explicit temperatures present on the crotch at steady state. The time calculated to lower the temperature of the crotch is much less then in analysis 1 due to a non-conservative approach and was also significantly effected by a non-uniform temperature distribution assumed in this analysis.

These two analyses give reasonable estimates of thermal cycle time for the crotch but are not entirely accurate due to in real life situations. The convective heat transfer (h) varies with temperature change and also the fluid flowing in the tubes around the crotch would have to be analyzed more rigorously. The results obtained in these analyses are accurate enough to use for determining the experimental costs and for the preliminary experimental running time.

Cost Analysis:

The labor costs of actually running this experiment can now be estimated with the cycle time calculated. With the parameters shown below and the calculated cycle time, the cost of running this simulation on the crotch can be obtained. The crotch reliability experiment will be run using 14 hours shifts, five days a week.

Table 3: Labor Costs

Analysis:	1	2
initial setup time (hours)	40	40
time per cycle (minutes)	6.5	0.8278
time per day (minutes) 14hr shift	840	840
cycles per day	129	1014
# of days to simulate a year	3.1008	0.3945
# of days to simulate a lifetime	62.016	7.8895
total number of run hours	992.25	126.23
* lifetime plus 20% for added experimentation	1190.7	151.48
an additional 5% increase due to setup times	1250.2	159.05
total # of hours in the shop	1290.2	199.05
shop costs = 63.5/hr		
Total shop costs =	81930	12640

* The added time (20%) allows for additional cycles to add conservatism to the results.

Concluding Remarks:

The primary purpose of this analysis was to calculate the thermal cycle time for the crotch subjected to a heat flux and then allowed to cool. This would show how long it would take to simulate the effects on this crotch of a higher heat load. With the actual crotch currently cycling twice a day, 200 days year for an estimated lifetime of 20 years, the lifetime of this crotch must be simulated in a much shorter amount of time. With these calculations, the labor cost of this experiment was evaluated and shown in the table 3 shown above. The future work is to run the experiment with a simulated heat flux on the exposed surface of the crotch, for the total expected lifetime cycles to verify that this assembly will withstand the higher current upgrades.

Acknowledgements:

The author would like to thank Peter Stefan for his assistance in completing this analysis.

Reference:

- Bejan Adrian, *Heat Transfer,* (1993) John Wiley and Sons, Inc, PP 91-211
- Lynch D., *500 mA Taskforce,* (1995), unpublished Brookhaven National Laboratory material
- Montanez P., *500 mA Taskforce,* (1995), unpublished Brookhaven National Laboratory material