PPPL Calculation Form - No: 2137-CALC-004

Calculation # **NSTXU-CALC-53-07-00** Revision #**0** _ WP # **2137**

Purpose of Calculation: *See page 2*

Codes and Versions: *See page 2*

References: *See page 2*

Assumptions *See page 2*

Calculation: *See pages 3, 4, 5*

Conclusion: *See page 3*

Cognizant Individual (or designee) printed name, signature, and date

John Dellas _____ John Dellas Digitally signed by John Dellas DN: cn=John Dellas, o=Princeton Plasma Physics Laboratory, ou=NSTX-U Recovery Project - Power Systems, email=jdellas@pppl.gov, c=US Date: 2018.07.23 11:29:08 -04'00'

Preparer's printed name, signature and date

John Lacenere _____ Digitally signed by John Lacenere DN: cn=John Lacenere, o=PPPL, ou=PPPL Engineering/AC Power, email=lacenere@pppl.gov, c=US Date: 2018.07.23 10:13:30 -04'00'

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

Checker's printed name, signature, and date

Charles Neumeyer _____ Charles L. Neumeyer Digitally signed by Charles L. Neumeyer DN: cn=Charles L. Neumeyer, o=PPPL, ou, email=neumeyer@pppl.gov, c=US Date: 2018.07.23 11:32:16 -04'00'

National Spherical Torus eXperiment - Upgrade

NSTX-U

Calculation of Power Cable Heating due to DC Current Pulsing to PF1B Coil

PPPL Calculation Form 2137-CALC-004
NSTXU-CALC-53-07-00
WP #2137
Date: July 23, 2018

Digitally signed by John Lacenere
DN: cn=John Lacenere, o=PPPL, ou=PPPL Engineering/AC Power, email=lacenere@pppl.gov, c=US
Date: 2018.07.23 10:14:34 -04'00'

Prepared By
John Lacenere

Charles L. Neumeyer

Digitally signed by Charles L. Neumeyer
DN: cn=Charles L. Neumeyer, o=PPPL, ou, email=neumeyer@pppl.gov, c=US
Date: 2018.07.23 11:32:36 -04'00'

Reviewed By
Charles Neumeyer

John Dellas

Digitally signed by John Dellas
DN: cn=John Dellas, o=Princeton Plasma Physics Laboratory, ou=NSTX-U Recovery Project - Power Systems, email=jdellas@pppl.gov, c=US
Date: 2018.07.23 11:46:59 -04'00'

Approved By – Responsible Engineer
John Dellas

Table of Contents

Record of Changes 1
Purpose of Calculation: 2
Codes and Versions: 2
References: 2
Assumptions: 2
Calculations: 3
Conclusion: 3
Table 1: Calculated Cable Temperature Rise (ºC) for Parallel 750kcmil CU 4
Table 2: Calculated Cable Temperature Rise (ºC) for Single 1000kcmil CU 5

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	07/23/18	Initial Release	

NSTX-U Calculation Form

Purpose of Calculation:

The PF1B power circuitry from the Field Coil Power Conversion (FCPC) DC rectifiers to the NSTX-U Power Cable Transition Structure (PCTS) is mostly by 5kV class shielded CU cables. A portion of the power cable run will be via existing (qty 2) parallel 750kcmil CU cables, whereas, the remainder will be by new single 1000kcmil CU cable. The pulse power will emanate from existing FCPC SDS switches through existing OH rectifiers and repurposed spare ETF2 converters via a 3-wire system to the Power Cable Termination Structure (PCTS) located within the NSTX-U test cell.

Analysis of the PF1B power circuit requires these cables to be appropriately sized in cross-sectional area and capable of delivering a 1.0 second flat-top 21kA bi-polar (+/-) 2kV DC pulse power to the Poloidal Field PF1B upper and lower coils. Further, these cables must deliver pulse current every 1,200 seconds without exceeding 80°C and below the PPPL procedure's maximum temperature rating of T_{max} = 90°C.

Codes and Versions:

- NFPA 70-2014 Ed. (NEC) Table 310.60(C)(69) Ampacities (RMS) of Insulated Single Copper Conductor in Air based on Conductor Temperature of 90ºC

References:

- PPPL Procedure OP-ECS-039 Rev 6, titled "NSTX Dummy Load Power Test", paragraph 5.2.2 DC Circuit Components.
- PPPL DC Pulse Heating Thermal Resistance Derivation. Basis for calculated cable heating: Cable T_{max} = 90ºC, Max Cable T_{rise} = 50ºC, Ambient Temp = 25ºC
- National Bureau of Standards Handbook 100 / Copper resistance tables
- Fink/Beaty Standard Handbook for Electrical Engineers, chapter Properties of Materials

Assumptions:

- 20ºC Electrical Resistance = 0.866 μΩ/in for single conductor 1000kcmil CU cable
- Thermal Resistance = 38.8ºC-in/Watt for single conductor 1000kcmil cable
- Thermal Capacitance = 44.2 Joules/ºC-in for single conductor 1000kcmil cable
- 20ºC Electrical Resistance = 0.578 μΩ/in for two parallel conductor 750kcmil CU cables
- Thermal Resistance = 20.8ºC-in/Watt for two parallel conductor 750kcmil cables
- Thermal Capacitance = 66.2 Joules/ºC-in two parallel conductor 750kcmil cables
- FCPC ambient temperature ≥ 25ºC
- Allowable cable temperature shall be ≤ 90ºC
- Total I^2dt = 4.39E+08 (includes the pulse RAMP + FLAT-TOP + DECAY)
- Cables are to be installed in open ladder-type cabletray and must maintain a minimum spacing between each cable to be NLT one full cable diameter. Therefore, per NEC Table 310.60(C)(69) the maximum continuous RMS current ampacity are maximized to the conductor's "in Air" rating.

Calculations:

The solution to the thermal differential equation is:

$$\Theta_{op} = \Theta_{amb} + \Delta\Theta_{max}\left(1 - e^{\frac{-t}{\tau}}\right)$$

The initial value is Θ_{amb}, the ambient temperature of the cable, and the steady state value is $\Theta_{amb} + \Delta\Theta$, where $\Delta\Theta$ is determined by the magnitude of I. The initial value, Θ_{amb}, is assumed to be that temperature on which the cable ratings are based. The steady state value is achieved when the

Conclusion:

Power cables are designed and are rated for maximum continuous (≥ 3 hours) electrical power conduction AC RMS, or DC equivalent, current such that the power cable's temperature will not exceed the manufacturer's cable insulation temperature rating. For this calculation, the PF1B power cable insulation maximum temperature rating is 90ºC.

However, the cable temperature rise calculations provided herein are based upon equivalent cable heating due to high short time pulse current (21kA) with long cool down time (1200 sec) between pulses.

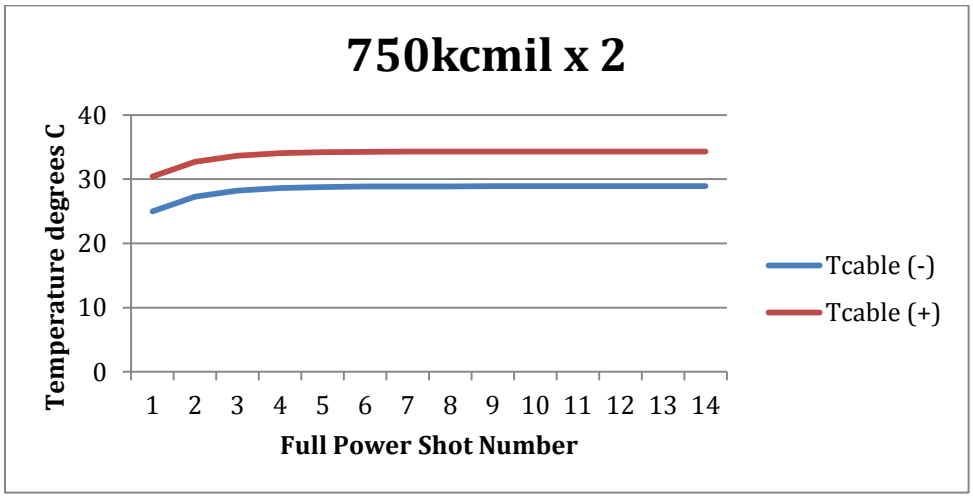
Therefore, based upon these findings:

1. The 1000kcmil cable's temperature should not exceed ~49ºC and is well under the cable's maximum allowable 90ºC rating.
2. The two parallel 750kcmil cables' temperature should each not exceed ~34ºC and is well under each individual cable's maximum allowable 90ºC rating.

Table 1: Calculated Cable Temperature Rise (ºC) for Parallel 750kcmil CU

For parallel 750 Kcmil cables: For 1.0 second 21kA with 1200 second cool down time between pulses.

	Before Pulse	After Pulse
Pulse #	Tcable (-)	Tcable (+)
1	25	30
2	27	33
3	28	34
4	29	34
5	29	34
6	29	34
7	29	34
8	29	34
9	29	34
10	29	34
11	29	34
12	29	34
13	29	34
14	29	34

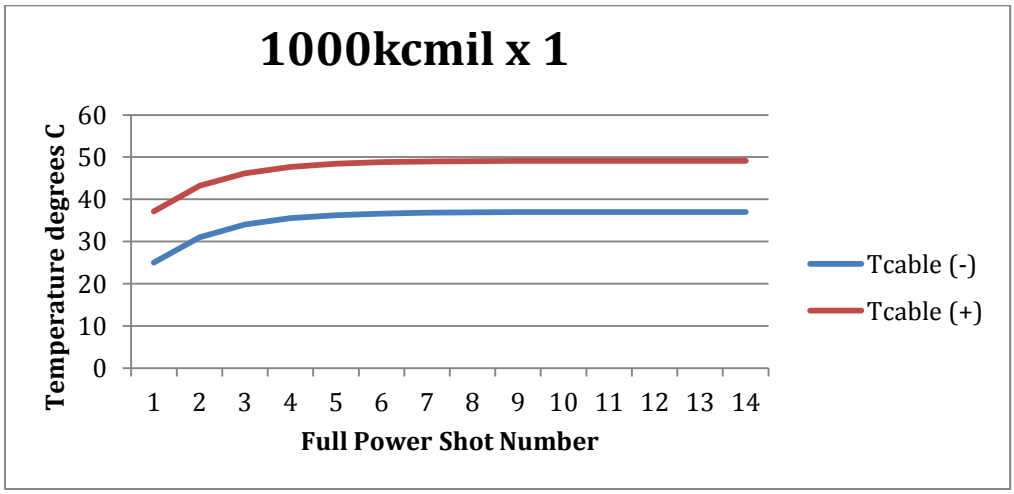


Note: The calculated cable temperature rise for each pulse is approximately 5ºC. After the 7th pulse, the max cable temperature does not exceed approximately 34ºC. This max cable temperature is well below the max cable temperature limit of 90ºC.

Table 2: Calculated Cable Temperature Rise (ºC) for Single 1000kcmil CU

For Single 1000 Kcmil cable: For 1.0 second 21kA with 1200 second cool down time between pulses.

	Before Pulse	After Pulse
Pulse #	Tcable (-)	Tcable (+)
1	25	37
2	31	43
3	34	46
4	36	48
5	36	48
6	37	49
7	37	49
8	37	49
9	37	49
10	37	49
11	37	49
12	37	49
13	37	49
14	37	49



Note: The calculated cable temperature rise for each pulse is approximately 12ºC. After the 7th pulse, the max cable temperature does not exceed approximately 49ºC. This max cable temperature is well below the max cable temperature limit of 90ºC.