National Spherical Torus eXperiment Upgrade

Inner-PF Coil Interfaces to Coil Support Designs and Cooling Systems

NSTX-U-RQMT-RD-012-00

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Revision	Date	Description of Change
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References

[1] NSTX-U-RQMT-GRD-001, NSTX-U General Requirements Document

[2] NSTX-U-RQMT-SRD-002, *Magnet System System Requirements Document*

[3] NSTX-U-RQMT-SRD-004, *Vacuum Vessel and Internal Hardware System Requirements Document*

[4] NSTX-U-RQMT-SRD-005, *Auxiliary Systems System Requirements Document*

[5] Design Point Spreadsheet - https://sites.google.com/pppl.gov/systemengineering/home

[6] NSTXU CALC 131-08-00 - *Loads and Error Fields Due to Coil Winding Patterns and Alignment Tolerances*

[7] NSTX-U-RQMT-RD-011, *NSTX-U Dimensional Control Requirements*

[8] NSTX-U-RQMT-RD-005, *Air Side CS Diagnostics Requirements Document*

[9] MAG-180306-YZ-01, *Material Properties for Inner PF Coil FDR*, Yuhu Zhai

1. Scope

a. The scope of this document is to provide boundary conditions for NSTX-U coil support designs.

b. This document provides additional information beyond that provided in Refs. [2] - [4].

c. Interfaces are listed as per the NSTX-U GRD [1].

d. As per the NSTX-U Interface Database, the interfaces in Tables 1-1 through 1-3 are relevant for the inner-PF coils.

***Table 1-1**: Interfaces for PF-1a coils*

WBS #1	WBS #2	System #1	System #2	Type of Interface	Interface Boundary	Interface Description
1.1.3.3.3	1.3.2.1.2	PF-1a Coils	High-Pressure NTC Cooling Water Distribution	Fluid	connection between i) hose w/ fitting and ii) and fitting on the coil	Hose connections at coil leads; cold water cools outer layers first
1.1.3.3.3	1.7.3.4.2	PF-1a Coils	Center Stack Coil Thermocouples	Diagnostic	Surface of ground insulation	thermocouples applied to surface of coil
1.1.3.3.3	1.1.3.4	PF-1a Coils	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal
1.1.3.3.3	1.1.3.4	PF-1a Coils	Bus Bar Systems and Bus Tower	Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminals, supporting part of bus bar run
1.1.3.3.3	1.1.3.3.6	PF-1a Coils	Center Stack Casing	thermal	At surface of coil	microtherm blanket provides thermal isolation between coils and casing
1.1.3.3.3	1.1.3.3.11	PF-1a Coils	PF-1a Support Structure	Structural	At surface of coil support structures	Coil leads are supported as they extend from the winding pack
1.1.3.3.11	1.1.3.3.3	PF-1a Support Structure	PF-1a Coils	Structural	Surface of ground wall insulation	Inner-PF coils are supported against all loads by the CS assembly. Pre-load is applied to the coils by the coil supports.
1.4.1.2.2	1.1.3.3.3	Mirnov and Flux Loop System	PF-1a Coils	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils
1.1.3.3.10	1.1.3.3.3	Vertical Target Cooling System	PF-1a Coils	spatial	at the surface of the heat transfer tubes	heat transfer tubes need to allow the PF-1a coil to fit through with sufficient clearance for alignment.

***Table 1-2**: Interfaces for PF-1b coils*

WBS #1	WBS #2	System #1	System #2	Type of Interface	Interface Boundary	Interface Description
1.1.3.3.4	1.3.2.1.2	PF-1b Coils	High-Pressure NTC Cooling Water Distribution	Fluid	connection between i) hose w/ fitting and ii) and fitting on the coil	Hose connections at coil leads; cold water cools outer layers first
1.1.3.3.4	1.7.3.4.2	PF-1b Coils	Center Stack Coil Thermocouples	Diagnostic	Surface of ground insulation	thermocouples applied to surface of coil
1.1.3.3.4	1.1.3.4	PF-1b Coils	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal
1.1.3.3.4	1.1.3.4	PF-1b Coils	Bus Bar Systems and Bus Tower	Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminals, supporting part of bus bar run
1.1.3.3.4	1.1.3.3.6	PF-1b Coils	Center Stack Casing	thermal	At surface of coil	microtherm blanket provides thermal isolation between coils and casing
1.1.3.3.4	1.1.3.3.12	PF-1b Coils	PF-1b Support Structure	Structural	At surface of coil support structures	Coil leads are supported as they extend from the winding pack
1.1.3.3.12	1.1.3.3.4	PF-1b Support Structure	PF-1b Coils	Structural	Surface of ground wall insulation	Inner-PF coils are supported against all loads by the CS assembly. Pre-load is applied to the coils by the coil supports.
1.4.1.2.2	1.1.3.3.4	Mirnov and Flux Loop System	PF-1b Coils	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils

Table 1-3*: Interfaces for PF-1c coils*

WBS #1	WBS #2	System #1	System #2	Type of Interface	Interface Boundary	Interface Description
1.1.3.3.5	1.3.2.1.2	PF-1c Coils	High-Pressure NTC Cooling Water Distribution	Fluid	connection between i) hose w/ fitting and ii) and fitting on the coil	Hose connections at coil leads; cold water cools outer layers first
1.1.3.3.5	1.7.3.4.2	PF-1c Coils	Center Stack Coil Thermocouples	Diagnostic	Surface of ground insulation	thermocouples applied to surface of coil
1.1.3.3.5	1.1.3.4	PF-1c Coils	Bus Bar Systems and Bus Tower	Electrical Power	Flat surface of the coil flags.	Solid bus bars connect to the coil terminal
1.1.3.3.5	1.1.3.4	PF-1c Coils	Bus Bar Systems and Bus Tower	Structural	Flat surface of the coil flags.	Solid bus bars connect to the coil terminals, supporting part of bus bar run
1.1.3.3.5	1.1.3.3.8	PF-1c Coils	Ceramic Break Assembly & PF-1c Support	Structural	At surface of coil support structures	Coil leads are supported as they extend from the winding pack
1.1.3.3.8	1.1.3.3.5	Ceramic Break Assembly & PF-1c Support	PF-1c Coils	Structural	Surface of ground wall insulation	Inner-PF coils are supported against all loads by the CS assembly
1.4.1.2.2	1.1.3.3.5	Mirnov and Flux Loop System	PF-1c Coils	Diagnostic	Inner Poloidal Field Coil Ground Insulation Surface	Poloidal Flux Loops mounted on Inner Poloidal Field Coils

2. Structural Interfaces

2.1. EM Vertical Loads

a. The following EM load cases shall be considered:
- Static equilibrium PF current distributions with 10% headroom
- Static equilibrium PF current distributions with 10% headroom and no plasma current
- Post-disruption PF current distributions following the simple flux conservation model

b. The post-disruption current increments are Table 2.1-1.

***Table 2.1-1**: Post-disruption current increments*

	dI, circular plasma	dI, shaped plasma
	kA	kA
OH	2.25	2.02
PF1aU	-1.93	-0.85
PF1aL	-1.93	-0.85
PF1bU	-0.59	-0.55
PF1bL	-0.59	-0.55
PF1cU	0.15	0.65
PF1cL	0.15	0.65
PF2U	0.60	1.39
PF2L	0.60	1.39
PF3U	1.85	2.57
PF3L	1.85	2.57
PF4	5.17	4.98
PF5	5.69	4.57

c. Relevant load cases are as in Table 2.1-2 for single coils, and Table 2.1-3 & 2.1-4, for combinations of coil loads [5].

Table 2.1-2: *Vertical loads on inner-PF coils*

F_z (klbf)	PF1aU	PF1bU	PF1cU	PF1cL	PF1bL	PF1aL
Min w/o Plasma	-80.2	-34.7	-18.5	-58.9	-84.2	-42.6
Min w/Plasma	-71.7	-49.1	-32.6	-50.4	-78.6	-31.3
Min Post-Disrupt	-96.1	-32.9	-22.0	-59.7	-82.8	-35.2
Min	**-96.1**	**-49.1**	**-32.6**	**-59.7**	**-84.2**	**-42.6**
Max w/o Plasma	53.5	84.2	58.9	20.6	34.7	80.2
Max w/Plasma	37.0	78.6	50.4	32.6	49.1	71.7
Max Post-Disrupt	46.4	82.8	59.7	22.0	32.9	96.1
Max	**53.5**	**84.2**	**59.7**	**32.6**	**49.1**	**96.1**

Table 2.1-3: *Vertical loads on combinations of inner-PF coils including -1aU/L and -1bU/L*

Combined Fz (klbf)	PF1aU+ PF1bU	PF1aU- PF1bU	PF1aL+ PF1bL	PF1aL- PF1bL	(PF1aU+ PF1bU)+ (PF1aL+ PF1bL)	(PF1aU+ PF1bU)- (PF1aL+ PF1bL)	(PF1AU+ PF1BU+ PF1BL+ PF1AL+OH)
Min_w/o_pls	-29.9	-164.4	-56.0	-46.7	-30.6	-56.0	-39.6
Min_w/pl	-67.9	-150.3	-48.3	-57.8	-44.4	-91.5	-53.4
Min_post-dis	-34.9	-178.9	-43.7	-37.4	-31.3	-66.8	-41.8
Min	**-67.9**	**-178.9**	**-56.0**	**-57.8**	**-44.4**	**-91.5**	**-53.4**
Max_w/o_pls	56.0	53.5	28.0	164.4	25.2	112.0	20.4
Max_w/pls	48.3	57.8	40.3	150.3	15.5	96.7	10.7
Max_post-dis	46.4	46.4	33.4	178.9	24.0	87.4	19.7
Max	**56.0**	**57.8**	**40.3**	**178.9**	**25.2**	**112.0**	**20.4**

Table 2.1-4: *Vertical loads on combinations of inner-PF coils including -1cU/L*

Combined Fz (klbf)	PF1cU+PF2U	PF1cU-PF2U	PF1cL+PF2L	PF1cL-PF2L	(PF1cU+PF2U) +(PF1cL+PF2L)	(PF1cU+PF2U) -(PF1cL+PF2L)
Min_w/o_pls	-40.9	-63.1	-47.0	-70.8	-50.4	-63.4
Min_w/pl	-50.1	-48.2	-41.7	-59.1	-34.8	-100.1
Min_post-dis	-33.8	-59.9	-57.4	-64.9	-44.7	-67.6
Min	**-50.1**	**-63.1**	**-57.4**	**-70.8**	**-50.4**	**-100.1**
Max_w/o_pls	47.0	70.8	31.7	63.1	33.2	94.0
Max_w/pls	41.7	59.1	55.9	48.2	73.5	83.4
Max_post-dis	57.4	64.9	37.9	59.9	47.3	114.8
Max	**57.4**	**70.8**	**55.9**	**63.1**	**73.5**	**114.8**

Note that these loads may be updated for additional loads from vertically displaced plasmas in the future.

2.2. Side Loads from 3D effects

a. Moments on inner-PF coils are provided in Table 2.2-1, for a displacement of 5 mm [6]. Actual displacements may be less, and actual side moments may be computed from given displacements using data in the far-right column.

b. Side loads on inner-PF coils are provided in Table 2.2-2, for coil tilts of 0.57 degree [6]. Actual tilts may be less, and actual side loads may be computed from given displacements using data in the far-right column.

Table 2.2-1: *Moments for a with respect to the TF field centerline, and scaling factor*

Coil	Mx for 5 mm shift [N-m]	Mx/ δ [N-m/m]
OH	2.354E+05	4.708E+07
PF1a	2.004E+04	4.007E+06
PF1b	6.290E+03	1.258E+06
PF1c	5.031E+03	1.006E+06

Table 2.2-2: Forces for a .57 deg rotation, and scaling factor

Coil	Fx for 0.57 degree tilt [N]	Fx/ θ [N/degree]
OH	4.6835E+05	8.2166E+05
PF1a	3.9893E+04	6.9988E+04
PF1b	1.2507E+04	2.1942E+04
PF1c	1.0013E+04	1.7566E+04

2.3. Required Pre Loads

a. Preload requirements are given in Table 2.3-1. Note that PF-1c does not require any mechanical preload.

***Table 2.3-1**: Mechanical preload required for each inner-PF coil*

coil	units	value
PF-1a, preload	kbf	100
PF-1b, preload	kbf	60

3. Thermal Interfaces

a. There is no requirement for the transfer of heat from the inner-PF coils to their support structures.

b. Support structures shall allow and facilitate a layer of microtherm or similar insulation. This insulation shall allow sufficient time for emergency response in a coil Loss of Cooling (LoC) situation during bakeout. The required time is provided in the Vacuum Vessel and Internal Hardware SRD [3].

c. Structures shall accommodate the range of temperature variation in Table 3-1.[1]

***Table 3-1**: Predicted temperature variation of the coils under maximal operations*

Quantity	Units	PF-1a	PF-1b	PF-1c
Initial Temperature	C	12	12	12
Final Temperature	C	58	90	48

4. Spatial Interfaces

4.1. Coil Pack Outline

a. Coil dimensions for the PF-1a shall be as per Table 4-1 and Table 4-2.

***Table 4-1**: Parameters of the -1a coil*

Quantity	Units	Value
Nominal # of Conductors, Radial	---	4
Number of Turns	---	61
Conductor Width	m	.0122
Conductor Height	m	.0249
Cooling Hole Diameter	m	.00470
Conductor Corner Radius	m	0.001

[1] The calculations are based on adiabatic heating of the coil copper, and predict a higher temperature than would be found if the thermal properties of entrained water and the insulation were included.

Table 4-2: Dimensions of the -1a pack

Quantity	Units	Value
Minimum Coil Pack Width	m	.0653
Nominal Coil Pack Width	m	.0658
Maximum Coil Pack Width	m	.0663
Minimum Coil Pack Height	m	.4800
Nominal Coil Pack Height Including G11 for Mating to Structure	m	.4810
Maximum Coil Pack Height	m	.4820
Min ID	m	.5842
Max ID	m	.5858

b. Coil dimensions for the PF-1b shall be as per Table 4-3 and 4-4.

Table 4-3: Parameters of the -1b coil

Quantity	Units	Value
Nominal # of Conductors, Radial	---	2
Number of Turns	---	20
Conductor Width	m	.0137
Conductor Height	m	.0127
Cooling Hole Diameter	m	.00371
Conductor Corner Radius	m	0.001

***Table 4-4**: Dimensions of the -1b pack*

Quantity	Units	Value
Minimum Coil Pack Width	m	.0391
Nominal Coil Pack Width	m	.0396
Maximum Coil Pack Width	m	.0401
Minimum Coil Pack Height	m	.1915
Nominal Coil Pack Height Including G11 for Mating to Structure	m	.1925
Maximum Coil Pack Height	m	.1935
Min ID	m	.7440
Max ID	m	.7456

c. Coil dimensions for the PF-1c shall be as per Table 4-5 and 4-6.

***Table 4-5**: Parameters of the -1c coil*

Quantity	Units	Value
Nominal # of Conductors, Radial	---	2
Number of Turns	---	16
Conductor Width	m	.0198
Conductor Height	m	.0155
Cooling Hole Diameter	m	.00371
Conductor Corner Radius	m	0.001

***Table 4-6**: Dimensions of the -1c pack*

Quantity	Units	Value
Minimum Coil Pack Width	m	.0513
Nominal Coil Pack Width	m	.0518
Maximum Coil Pack Width	m	.0523
Minimum Coil Pack Height	m	.1928
Nominal Coil Pack Height Including G11 for Mating to Structure	m	.1938
Maximum Coil Pack Height	m	.1948
Min ID	m	1.0574
Max ID	m	1.0590

4.2. Tolerances

a. Tolerances of coil positions relative to tile components are defined in Ref. [7].

5. Electrical Power Interfaces

a. There is no direct electrical power interfaces between the coils and their support structures.

b. The amp-turn and ESW requirements are provided in the magnets SRD [2]

c. Coils and their support structures shall be designed for the voltage requirements in the Magnets SRD [2].

6. Electrical Signal Interfaces

None - no small electrical signals are used in the interfaces between the coils and their surroundings.

7. Fiber Optic Interfaces

None - no fiber optics used in this system

8. Software Interfaces

None - The coil itself has no software capability

9. Fluid Interfaces

a. Nominal cooling water system parameters for the inner-PF coils are as per Table 9-1, based on simple 0D calculations and a temperature of 12 degC; see Appendix 3. This calculation does not include the effects of bends in the flow path, and therefore provides only nominal values of flow

Table 9-1*: PF-1a Cooling Water System Parameters*

Quantity	Units	PF-1a	PF-1b	PF-1c
Coil Water Flow Velocity	m/s	2.5	3.5	3.3
Coil Water Volume Flow	GPM	0.68	0.60	0.56

b. The cooling water and supply and return must mate with 3/8" Tube Size, 37 Degree JIC Flare Fittings per SAE J514.

c. The cooling water configuration shall be such that the cold water supply enters the outer layer.

d. The supply hose and fittings (high pressure side) shall be provided with purple markings, and the return hose and fittings (low pressure side) shall be provided with black markings.

10. Gas Interfaces

None - no conveyance of gas associated with the coil and its interfaces..

11. Vacuum Interfaces

None - No vacuum seals or connections of vacuum volumes.

12. Plasma Interfaces

None - neither the coil nor the supports interface with the plasma.

13. Diagnostics Interfaces

a. The inner-PF coils shall have flux loops and thermocouples mounted to them.

b. The support structures and clearances shall allow three plasma current rogowskis to pass through. The rogowskis shall not link the -1a coils, but may link the -1b and -1c coils as appropriate.

c. Provision shall be made for the wires to exit vicinity of the coils, for connection to multi-conductor field cables.

c. Specific requirements for these can be found in the document [8].

Appendix 1: Coil Mechanical Properties

a. Coil copper conductor mechanical properties used for deriving the coil pack smeared mechanical properties for the coil support analysis are provided in Table A1-1

Table A1-1 *Conductor mechanical properties*

Quantity	**Units**	**Value**
Elastic modulus	GPa	120
Poisson Ratio		0.33
CTE	C^{-1}	16e-6

b. Coil insulation composite mechanical properties used for deriving the coil pack smeared mechanical properties for the coil support analysis are provided in Tables A1-2 through A1-3 [9]. *Note that these parameters may evolve as additional test data becomes available*.

Table A1-2*: Coil insulation composite coefficient of thermal expansion : X-conductor tangent; Y - thru thickness; and Z – conductor axis (toroidal)*

Quantity	**Units**	**Value**
CTE in normal direction, α_x	C^{-1}	25e-6
CTE in fill direction, α_y	C^{-1}	10e-6
CTE in wrap direction, α_z	C^{-1}	10e-6

***Table A1-3**: Coil insulation composite elastic modulus: X-conductor tangent; Y – thru thickness; and Z-conductor axis (toroidal direction)*

Quantity	**Units**	**Value**
Ex	GPa	8.01
Ey	GPa	4.49
Ez	GPa	14.71
Gxy	GPa	1.88
Gyz	GPa	1.88
Gxz	GPa	3.88
ν_{xy}		0.31
ν_{yz}		0.31
ν_{zx}		0.42

c. Smeared coil mechanical properties to be used for support analysis are provided in Tables A1-4 through A1-6. For implementing tables A1-4 through 6 refer to Figure A1-1 for the unit cell cylindrical coordinate system orientation. *Note that these parameters may evolve as additional test data becomes available*.

Fig A1-1: *Unit cell cylindrical coordinate system*

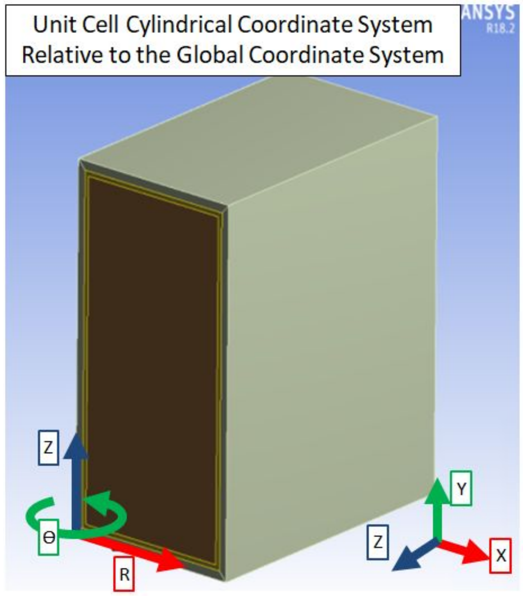

Table A1-4: *"Smeared" coil pack coefficient of thermal expansion*

Quantity	Units	Value
CTE in radial direction, max	C^{-1}	18.8e-06
CTE in radial direction, min	C^{-1}	18.8e-06
CTE in toroidal direction, max	C^{-1}	17.8-06
CTE in toroidal direction, min	C^{-1}	17.8-06
CTE in vertical direction, min	C^{-1}	18.3-06
CTE in vertical direction, max	C^{-1}	18.3e-06

***Table A1-5**: "Smeared" coil pack modulus values*

Quantity	Units	Value		
		PF-1A	**PF-1B**	**PF-1C**
Young's modulus in radial direction, E_R	GPa	28.0	30.4	37.7
Young's modulus in toroidal direction, E_Θ	GPa	90.2	84.9	90.0
Young's modulus in vertical direction, E_z	GPa	44.0	28.7	31.6
Shear modulus, G_{RZ}	GPa	8.3	7.0	8.4
Shear modulus, $G_{R\Theta}$	GPa	10.4	10.7	13.3
Shear modulus, $G_{Z\Theta}$	GPa	15.0	10.2	11.5

***Table A1-6**: Coil pack Poisson ratio values*

Quantity	Value		
	PF-1A	**PF-1B**	**PF-1C**
Poisson's ratio, ν_{RZ}	.384	.427	.415
Poisson's ratio, $\nu_{R\Theta}$	.341	.345	.345
Poisson's ratio, $\nu_{Z\Theta}$	.347	.344	.342

Appendix 2: Repetition Rate and Cycle Requirements

a. The coils and associated support structures shall be designed to operate with a 1200 second repetition rate.

b. The baseline case shall be to design the coils for 20,000 full power and current pulses.

c. If this qualification for 20,000 full power pulses cannot be achieved, then the spectrum implied by the GRD may be used. In this case, the PF-1a current can be scaled by the plasma current level.

Appendix 3: Derivation of coil flow requirements.

The steps for computing the flow rates are as follows.

The flow channel diameter d and length l are known from the geometry of the coil; here l is computed based on the assumption $l = 2\pi R N_{turns}$. The water flow velocity V_{flow} is used to compute the Reynold number of the flow as $R_m = V_{flow} d/\upsilon$, where $\upsilon = \mu/\rho$ is the kinematic viscosity. The dynamics viscosity μ and the density ρ are given by:

$$\mu = c_{v,0} + c_{v,1} T_{inlet} + c_{v,2} T_{inlet}^2 + c_{v,3} T_{inlet}^3 + c_{v,4} T_{inlet}^4 + c_{v,5} T_{inlet}^5 + c_{v,6} T_{inlet}^6$$
$$\rho = c_{\rho,0} + c_{\rho,1} T_{inlet} + c_{\rho,2} T_{inlet}^2$$

The parameters in these equations are given in Table A3-1, and the inlet temperature is taken to be 12 degC.

Table A3-1: Parameters to compute the dynamic viscosity and density

parameter	value
$c_{v,0}$	0.0017887
$c_{v,1}$	-0.000051271
$c_{v,2}$	7.91121E-07
$c_{v,3}$	-6.752E-09
$c_{v,4}$	3.1597E-11
$c_{v,5}$	-7.5437E-14
$c_{v,6}$	7.1718E-17
$c_{\varrho,0}$	1005.4
$c_{\varrho,1}$	-0.539
$c_{\varrho,2}$	-0.0026713

The friction factor is computed as $f_f = 0.3164/R_m^{0.5}$. The coil pressure drop is then $P_{coil} = 1000 f_f V_{flow}^2 l/2d$, in Pa.

The total pressure drop is then given by $P_{tot} = P_{coil} + P_{hose} + P_{return}$, where P_{return} and P_{hose} are given in Table A3-2. The value of V_{flow} is then selected so that P_{tot} is equal to 420 PSI.

Table A3-2*: Assumed coil parameters*

Quantity	Units	PF-1a	PF-1b	PF-1c
Channel Diameter	m	4.70E-03	3.71E-03	3.71E-03
Channel Length	m	123.9	49.3	55.8
Hose Drop (assumed)	psi	6	6	6
Return Pressure (assumed)	psi	15	15	15