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Single-Phase Helium Recooling in a Tevatron Spool Piece

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INTRODUCTION

Plans call for upgrading existing Tevatron spool pieces by adding a single-phase to two-phase heat exchanger or recooler. This will enhance the single-phase to two-phase heat transfer and, along with other upgrades, allow for higher energy beam in the upcoming run.

The performance of the heat exchanger was predicted numerically using a multi-node finite difference model. One Tevatron spool piece was modified to incorporate the recooler. Performance tests were conducted on this modified spool at the Magnet Test Facility within Technical Division in March and April 1999.

The present paper reviews the design of the Tevatron spool recooler. The discussion includes: a technical description of a Tevatron spool; the heat exchanger mathematical model; design criteria and constraints; fabrication and assembly procedure; tests and performance analysis.

DISCUSSION

At the 1998 Tevatron Spool Piece Improvements workshop several alternative ideas to improve the cryogenic performance of the Tevatron spools to reach one TeV operations were discussed. One of the topics of discussion was to improve heat transfer between the single- and two-phase helium in the Tevatron strings.

Although there is heat exchange between single- and two-phase helium in all dipole and quadrapole magnets, there is an increase in the single-phase temperature from magnet to magnet. A gradient along the string from feed can to turn around box is in the range of 200 to 500 mK. This cumulative temperature increase can be explained with the fact that the heat transfer surface is fixed and the temperature difference between the single- and two-phase is too small to drive the heat transfer at the necessary rate. Upgrading existing Tevatron spool pieces by adding a single-phase to two-phase heat exchanger will add more heat transfer surface, thus enhancing the single-phase to two-phase heat transfer, and equalizing magnet temperatures across the strings.

Ultimately a recooler should be located on the single-phase outlet from the spool. This would lower single-phase inlet temperature to the next half-cell. However, the single-phase flow direction is coherent with proton beam direction only for the downstream string, which means that for the spool located in the upstream string a recooler should be mounted on the upstream (proton beam direction) side of the spool. The existing spool design is such that it's considerably more costly and difficult to install a recooler on the upstream (proton beam direction) end of a spool. Also, analysis has shown that the gain from installing of the recoolers in two different locations does not justify the effort.

Computer simulation of the Tevatron strings was carried out by J.Theilacker to identify the best location for the modified spool in the string. Calculations indicated that, if recoolers were added to only one spool in each of the 48 strings of dipoles, the most effective location is in the middle of the strings.

TEVATRON SPOOL

Tevatron spools are modular components which may contain correction magnets, safety leads and quench stoppers, single phase instrumentation, pressure reliefs, a “vacuum break”, beam vacuum sniffer, and several other devices. Like other components, all spool pieces contain single-phase, two-phase, and nitrogen circuits. A typical Tevatron spool schematic is shown in Figure1. The single-phase helium enters and exits the spool through standard Tevatron single-phase bellows assemblies. After entering the spool it splits into two streams, the main flow and bypass flow.

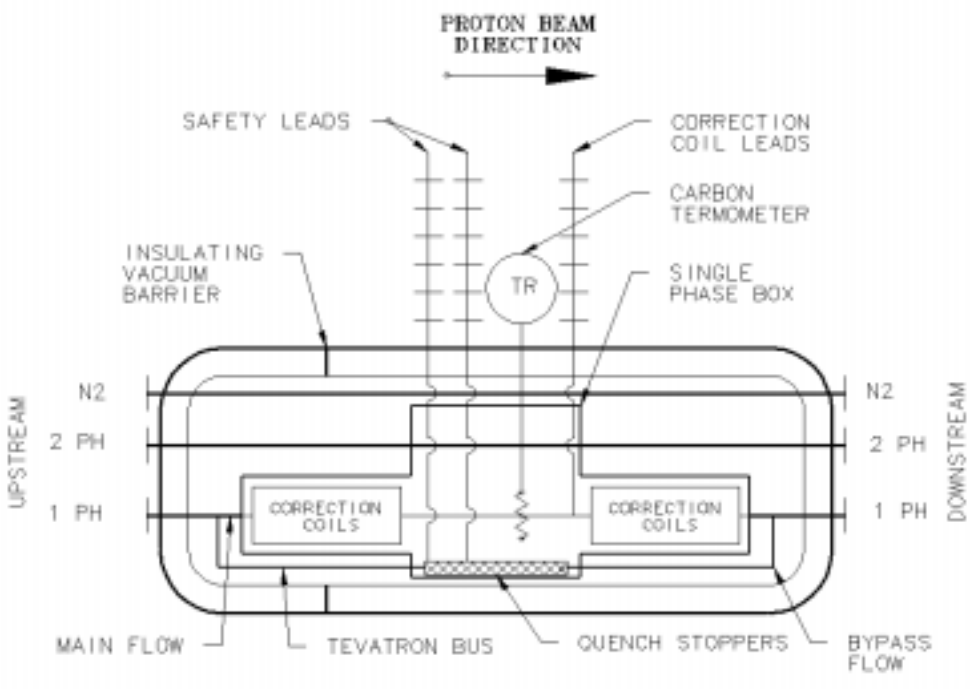


Figure 1. Tevatron Spool Piece Schematic Diagram

The main flow passes around and through the correction magnets and floods the single-phase box. The smaller bypass flow cools the Tevatron through-bus only. The bypass and main flows are parallel beginning from the single-phase box to the downstream (proton direction) single-phase bellows assembly.

Because knowledge of the bypass flow is essential for meaningful design calculations, we have conducted warm pressure drop measurements. Test were made on spool TSF-124 at IB3 in October 1998. The spool had already been cut open, and the superconductor conduit was separated from the corrector package housing.

The objectives of the test were to determine the single-phase flow split between the corrector package (main flow) and the superconductor conduit (bypass flow). The test flow scheme is in Figure 2, similar to one used by J.Theilacker for Tevatron dipole single-phase flow split measurements. The measurements were made using a high pressure nitrogen gas bottle, pressure regulator, rotameter and ΔP cells. Flow rate and pressure drop were measured from the end of the spool that was still intact and the nitrogen was vented to atmosphere out the end of the tested circuit. Flow passages that didn't participate in the test were blocked with Apiezon Q sealing compound. Each phase of the test consisted of preliminary and final tests. Preliminary tests were used to determine the flow meter size and ΔP cell required. During the final tests, flow rates were measured while increasing and decreasing the inlet pressure to ensure steady state and to test for hysteresis. The results of the tests are presented below:

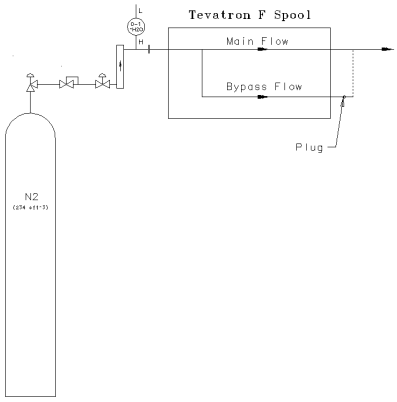


Figure 2. Flow Test Setup

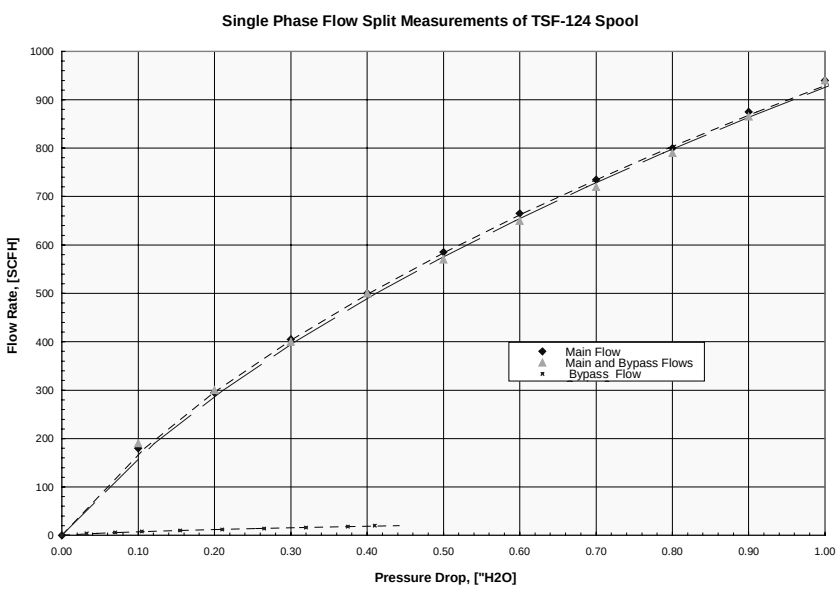


Figure 3. Single Phase Flow Split Measurements

A total of 29 test runs were made. The results showed that 4% of the single-phase flow bypasses the correction magnet, which is dictated by the as built ratio between the pressure drop in the main and bypass flow circuits.

The introduction of the recooler changes the original ratio. In order to allow for the increased pressure drop through the recooler a corresponding flow restrictor was required in the bypass flow circuit. This was accomplished by partially blocking the entry into the bypass flow tube at the downstream (proton direction) end. The through-bus passes the square opening in the flow restrictor. Subsequent tests were carried out to ensure that adequate cooling flow remained to cool the through-bus.

A flow schematic of the modified Tevatron spool is shown in Figure 4. The recooler is in series with the downstream correction magnet and parallel to the bypass bus flow. The modified spool has two additional Cernox thermometers that are to be used during heat leak and duty measurements. The flow restrictor reduces bypass flow and limits the thermal short.

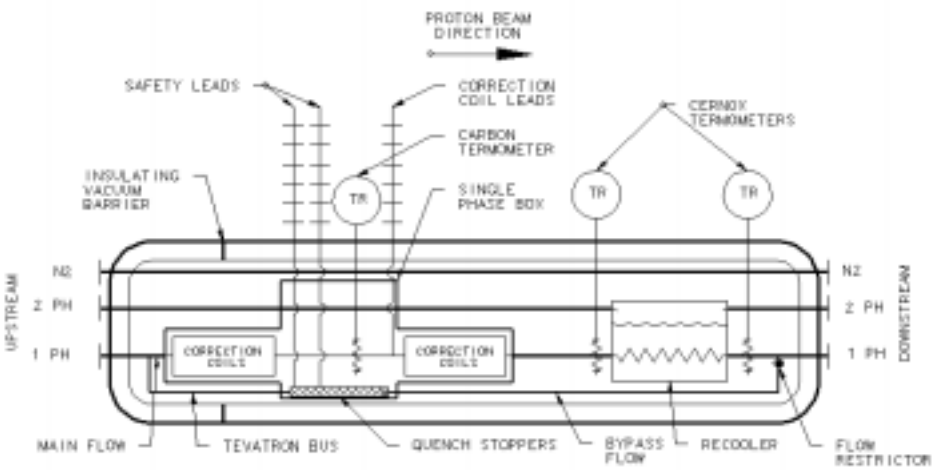


Figure 4. Modified Tevatron Spool Piece with Recooler

MATHEMATICAL MODEL

A multi node finite difference model was constructed to calculate the required heat transfer surface and geometry, along with the pressure drop for each circuit. Thermophysical properties of helium are calculated from Cryodata, Inc fundamental state equation using HePak computer code. The model is written in Engineering Equation Solver version 4.734 by F-Chart Software Inc. for Windows NT operating system.

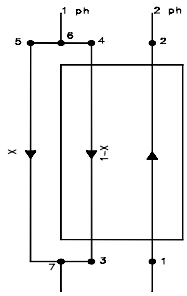


Figure 5. Recooler Flow Schematic

The flow circuit used for analysis is schematically shown in Figure 5. The single-phase helium enters the tube side of the heat exchanger (point 6) and splits into so called main flow (point 4) and bypass flow (point 5). Two-phase counterflows in the shell side (points 1 and 2). The main

helium single-phase flow cools off due to the heat exchange with two-phase and mixes with the bypass flow (point 7). The input parameters for the model include: tube size and fin geometry; single-phase pressure and inlet temperature; percent of bypass flow (X); two phase pressure and liquid quality; cold end temperature difference (point 1 and point 7).

The Recooler duty is derived from the First Law for steady flow:

$$Q = (1 - X) * (H_4 - H_3) + q_3 = (H_2 - H_1);$$

The rate of heat transfer across a finite area of the heat exchanger:

$$dq_i = U_i * dA_i * \delta T_i;$$

Total heat transfer surface is:

$$A = \int_0^Q \frac{dq}{U * \delta T};$$

If the number of finite elements is large enough, then it is safe to assume that $\frac{\partial C_p}{\partial P}$, $\frac{\partial C_p}{\partial T}$, $\frac{\partial E_i}{\partial P}$ and $\frac{\partial Ei}{\partial T}$ are equal to zero for a single node. This assumption allows use of the log mean temperature difference method (LMTD) to calculate δT_i at each node.

For the selected recooler geometry, ignoring axial conduction, a system of three simultaneous algebraic equations can be written:

$$\begin{cases} dq_i = \alpha_{boil} * \eta_{fin} * A_{1_i} * (T_{w2i} - T_{2\Theta_i}); \\ dq_i = \frac{\lambda_{Cu}}{\delta_w} * A_{c_i} * (T_{w1_i} - T_{w2_i}); \\ dq_i = \alpha_{conv} * A_{2_i} * (T_{1\Theta} - T_{w1_i}); \end{cases}$$

The first equation in the system describes heat transfer from boiling two-phase to the copper tube. The S.S.Kutateladze correlation is used to determine the boiling heat transfer coefficient:

$$\alpha_{boil} = 0.487e-10 * \frac{\lambda_{l*}\rho_l^{1.282} * P_l^{1.75} * (C_p)_l^{1.5}}{(r * \rho_v)^{1.5} * \sigma^{0.906} * \mu_l^{0.626}} * (T_{w2} - T_{2\Theta})^{1.5};$$

The thermal performance of the fins needs to be corrected by fin efficiency, η_{fin}. The convective heat transfer coefficient for single phase flow inside a helically wound tube as given by modified Dittus-Boelter equation:

$$\alpha_{conv} = \frac{\lambda}{D_{tube}} * C * Re^{m} * Pr^{n} * \left[1 + 3.5 * (\frac{D_{tube}}{D_{helix}})\right];$$

The single-phase pressure drop for each node was determined as a function of geometry (elbow, coiled tube, etc.) and a flow regime. Modified version of Darcy-Weisbach equation was used:

$$\delta P_{H/E} = \sum_{i=1}^{n} \left\langle \frac{\zeta_i}{D_{tube}} * \left\{ L_{helix} * \left[1 + 3.5 * (\frac{D_{tube}}{D_{helix}})\right] + L_{straigth} \right\} * \frac{\rho_i * V_i^2}{2} \right\rangle + \sum K_{elb} * \frac{\rho * V^2}{2};$$

During the numerical integration, the friction factor, ζ, is calculated from local values of the Reynolds number.

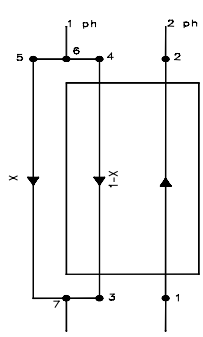
The following are input design parameters, flow schematic and calculation results which were used to design a recooler for the TSF-124 spool. Input design parameters were established based on a Tevatron string temperature profile analysis:

Input Design Parameters

- Single Phase Pressure — P=31.7 [psia]
- Two Phase Pressure — P=11 [psia]
- Single phase flow rate — G=20 [g/sec]
- Cold End Temperature Difference — dT_c=100 [mK]
- Heat Exchanger Type — Helix Coiled Tube
- Heat Load — Q=30 [W]

Flow Schematic

Bypass flow **X=0.12 [kg/kg]**
Heat Load $Q_{H/E} = (H_2 - H_1) * G_1 = 30$ **[W]**



#	P [psia]	T [K]	H [J/kg]	G [kg/sec]
1	11	3.928	-	0.0200
2	11	3.928	-	0.0200
3	17	3.975	9284	0.0176
4	17	4.375	10988	0.0176
5	17	4.375	10988	0.0020
6	17	4.375	10988	0.0200
7	17	4.028	9488	0.0200

Heat Exchanger Parameters

1. Outer Coil Diameter	- 4.50 [inch]
2. Tube	- Bare/ Finned Copper
3. Tube OD	- 0.625 [inch]
4. Tube ID	- 0.43 [inch]
5. Fin OD	- 1.000 [inch]
6. Fin Thickness	- 0.015 [inch]
7. Fin Density	- 8 [fins/inch]

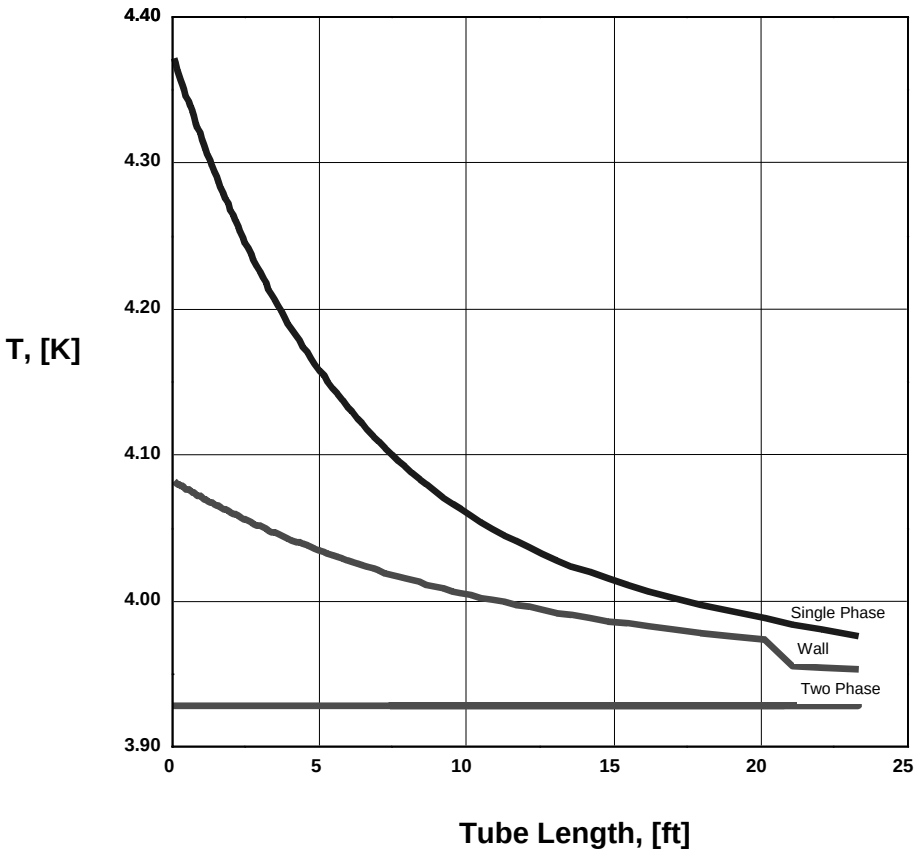


Figure 6. Temperature Distribution across the Heat Exchanger

Note that the sudden change in the wall temperature at the transition from bare to finned tube is due to the fact that axial conduction is ignored.

HEAT EXCHANGER DESIGN

A challenging aspect to the recooler design is to combine high performance, simplicity of fabrication, ease of installation and low cost in one package. The biggest limitations are dimensional restrictions. The existing spool design limits height, width, and length of the heat exchanger. Design constraints also include cold end temperature difference, required heat exchanger duty, hydraulic impedance, handling thermal contraction and vibration.

The project schedule, and resource availability limited our choice of heat exchangers to the shell-and-tube type. Although it is recognized that a matrix or compact heat exchanger would have superior pressure drop characteristics for the same ratio of surface area per unit volume, the selected type will satisfy the design requirements at lower cost. Further, its performance can be reliably predicted.

The spool recooler is a boiler heat exchanger, thus the flow direction does not affect the amount of heat transfer surface required. The effective temperature difference driving the heat transfer is the same for any flow pattern. In order to minimize changes to the existing spool's single-phase piping, the mixed counter and parallel flow pattern was selected.

An analysis of the heat transfer coefficient for different pressure, temperature and flow conditions was made. The calculations indicated that the recooler operation is very sensitive to the amount of bypass flow. If the flow diverted to the superconductor is allowed to rise above 12%, the performance of the heat exchanger degrades. The analysis also showed that closer to the cold end of the heat exchanger the boiling two-phase has a lower heat transfer coefficient than the single phase flowing in the tube. An increase in the outer tube surface in this region will balance heat transfer resistance and maximize use of the inner surface.

Cross sections of the recooler design are shown in the Figure 7. The assembly consists of the outer shell, two end plates, the single-phase coil and internal coil supports. The 20" long 6" OD 304L stainless steel outer shell contains the two-phase, while the single-phase flows through a coil of a 25-foot length of 5/8"OD copper tubing. Most of the tubing is bare with the exception of a fourteen inch straight run. The coil is elliptical in cross section to avoid a lower efficiency heat transfer region at the top of the cylinder where gas collects. The coil is supported with two copper bars along its length. The bottom support serve as the axial anchor. Using two supports produces a rigid structure which is necessary to

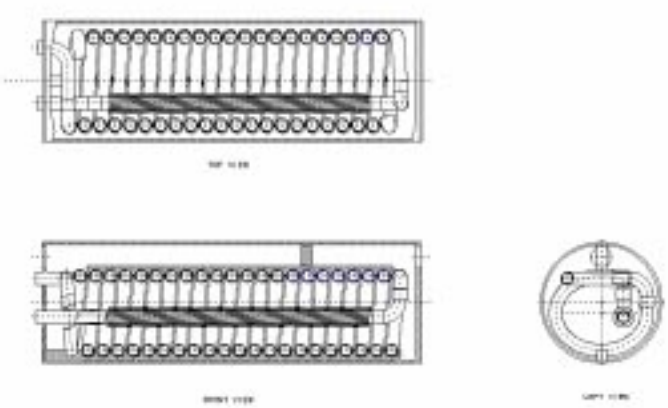


Figure 7. Recooler Assembly

withstand flow induced vibration. The two-phase entrance/exit ports are located at the top of each end plate.

The recooler is attached to the internal supports of the downstream corrector single-phase can. A nitrogen cooled copper shield and a multi-layer superinsulation are used to minimize heat leak from infrared radiation. The exchanger resides inside a truncated cylinder attached to the outside of the existing downstream vacuum can.

MODIFIED SPOOL TEST AT MTF

The test setup is shown schematically in Figure 8. It consists of a 1500 Watt refrigerator, 10,000liter LHe dewar, subcooler, distribution box, two phase return dewar, cold compressor, feed can, spool string, and turnaround box. The setup was instrumented with single-phase and two-phase inlet and outlet thermometers, single-phase and two-phase inlet and outlet pressure transducers, differential pressure transmitters, and flow indicators.

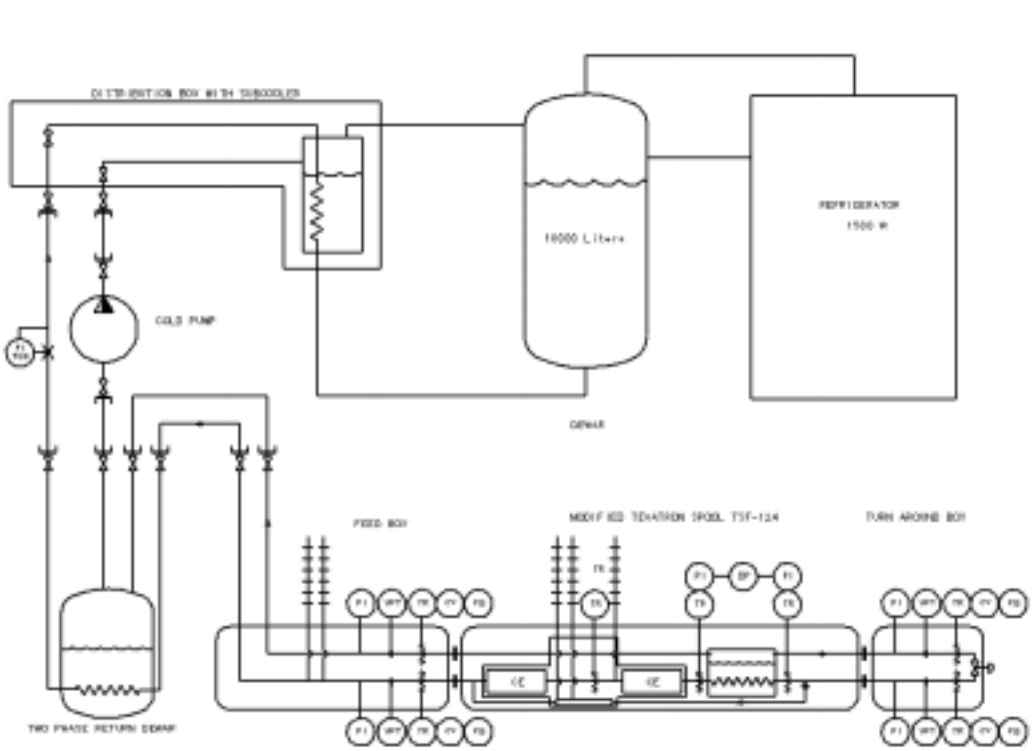


Figure 8. Test Flow Schematic

The objectives of the test were to measure the single-phase temperature reduction and pressure drop across the heat exchanger and verify the Tevatron's bus cooling conditions.

Table 1 summarizes the test data obtained at seventeen different steady state conditions regarding the helium flow through the TSF-124 spool.

Table 1. Heat Exchanger Test Results

Steady State	Single Phase		Two Phase		Heat Exchanger			
Point	Flow	Pressure	Pressure	Temperature	δTinlet	δToutlet	δP	Duty
[#]	[g/sec]	[psia]	[psia]	[K]	[mK]	[mK]	[inch H2O]	[W]
1	24.4	31.92	16.90	4.374	321	36	5.4	38.2
2	23.4	31.97	16.90	4.374	360	37	5.3	42.4
3	23.1	31.97	16.83	4.369	451	41	5.4	55.7
4	24.1	31.84	16.98	4.379	509	47	6.0	69.2
5	25.6	32.20	5.92	3.385	837	57	5.5	71.8
6	26.0	31.92	5.51	3.329	694	51	5.4	56.4
7	26.4	31.83	5.21	3.286	572	46	5.4	44.5
8	-	31.65	5.29	3.297	521	46	5.0	-
9	-	31.76	13.03	4.097	357	35	5.4	-
10	24.8	31.81	13.20	4.110	402	37	5.4	42.2
11	24.4	31.94	13.40	4.125	487	41	5.5	53.0
12	23.9	32.05	13.13	4.104	617	45	5.5	69.3
13	35.0	31.79	16.99	4.380	220	39	6.3	33.4
14	36.7	31.27	12.64	4.065	290	42	6.3	40.2
15	36.6	32.65	8.90	3.730	336	49	6.3	39.1
16	31.8	33.14	8.85	3.725	380	44	6.3	39.9
17	26.1	32.42	8.95	3.735	439	38	5.3	40.1

Measured single-phase temperature reduction is shown in the Figure 9.

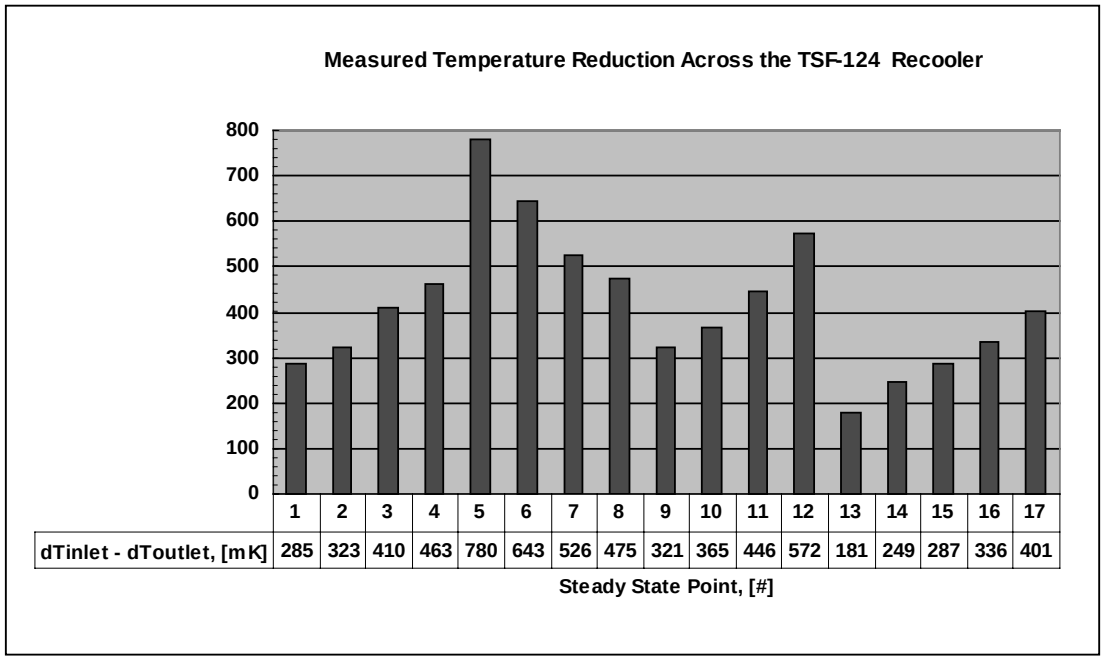


Figure 9. Temperature Reduction Across TSF-124 Recooler.

Test results were analyzed to determine actual percent of the bypass flow through the restrictor. The recooler's model was modified to have bypass flow as an output parameter for a given heat exchange surface. Calculations indicated that 1.5% of the single-phase flow bypasses the heat exchanger.

The pressure drop data are presented in Figure 10. The measurements agree well with calculations. Note that for runs 14 through 17 the differential pressure transducer was pegged at its maximum value.

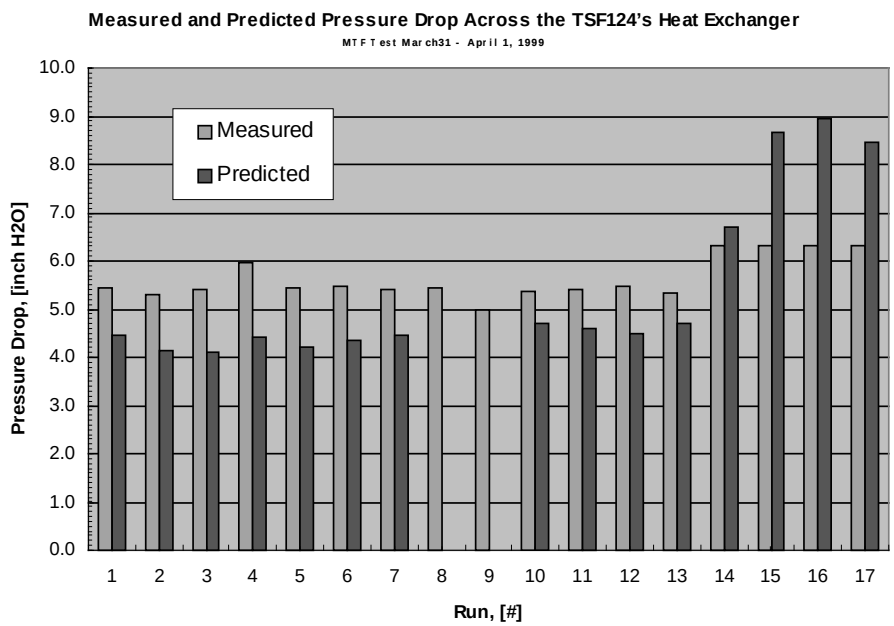


Figure 10. Pressure Drop Data

It was decided that an adequate power test of the prototype would be to demonstrate 1 TeV performance at 4.6 K, that is, the test plan did not attempt to find the maximum current that the bus would carry at 4.6 K, 25 g/s, and 32 psia. The risk is that the reduced bypass flow would be unable to carry away heat generated in the bus during current ramping. Self-heating in the bus varies approximately as the square of the current ramp rate. Traditionally Tevatron dipoles and quadrupoles have been tested in the test facility using a "fixed target" excitation wave form (known as "CYCLE") where the maximum ramp rate is 200 A/s and the flattop 20 s (In actual practice the Tevatron ramp rate never exceeds 125 A/s). For this spool test the flattop was shortened to 2 s. In principle, the current carrying capability of the superconducting cable depends on the magnetic field it sees, and the quench performance of a magnet reflects the large field the cable in the magnet sees. So in the low to zero field environment the Tevatron bus sees in the spool should result in a quench performance far superior to that of a dipole or quadrupole magnet.

The power testing started with a 900 GeV equivalent flattop, and after 10 successful ramp cycles at a given flattop, the flattop current was raised by 50 A and another 10 ramp cycles run. After 10 ramp cycles were completed at 4500 A, the test was halted. In retrospect the goal

ought to have been set at 1030 GeV equivalent because that is the goal of the commissioning program for the machine as a whole. The above test was run with a fairly slow acceleration to the maximum ramp rate of 20 A/s/s; it was repeated with the snappier ramp rate of 75 A/s/s and continued through 10 cycles at 4550 A. So the self-heating during these tests substantially exceeds that expected in Tevatron operation, but there was no quench.

CONCLUSIONS

Some of the more important conclusions associated with the recooler are listed below:

- The developed heat exchanger has been experimentally shown to be effective in reducing the single-phase temperature on the outlet of the spool over a wide range of pressures, temperatures and flow rates.
- The recooler meets heat exchange efficiency and pressure drop parameters.
- The model predictions are in reasonable agreement with the test results.
- Adequate cooling flow remains to cool the Tevatron bus.

NOTATION

1PH	Single-phase circuit
2PH	Two-phase circuit
A	Area, [m^2]
α_{boil}	Two-phase boiling heat transfer coefficient, [W/(m^2*K)]
α_{conv}	Single-phase convective heat transfer coefficient, [W/(m^2*K)]
C	Coefficient based on the flow regime, dimensionless
CG	Cryogenic carbon glass thermometer
C_p	Specific heat, [J/(kg*K)]
CX	Cryogenic cernox thermometer
D_{helix}	Diameter of the helix, [m]
DP	Differential pressure indicator
$\delta P_{H/E}$	Pressure drop across the heat exchanger, [Pa]
δT_{inlet}	Temperature difference on the inlet to the heat exchanger, [mK]
δT_{outlet}	Temperature difference on the outlet of the heat exchanger, [mK]
D_{tube}	Inside diameter of tube, [m]
δ_w	Copper tube wall thickness, [m]
E	Internal energy, [J/kg]
FI	Flow indicator
H	Enthalpy, [J/(kg*K)]
η_{fin}	Fin efficiency, [W/W]
U	Overall coefficient of heat transfer, [W/(m^2*K)]
K_{elb}	Coefficient of friction resistance in elbow, dimensionless
λ	Thermal conductivity, [W/(m*K)]
L	Length of tube, [m]
μ	Viscosity, [Pa*sec]
m	Coefficient based on the flow regime, dimensionless
n	Coefficient based on the flow regime, dimensionless

N2	Nitrogen circuit
P	Pressure, [Pa]
PI	Pressure indicator
Pr	Prandtl number, dimensionless
Q	Recooler duty, [W]
q	Heat transfer rate, [W]
q_3	Static heat leak, [W]
ρ	Density, [kg/m^3]
r	Laten heat of vaporization at saturation, [J/kg]
Re	Reynolds number, dimensionless
σ	surface tension between the liquid and its own vapor, [N/m]
T	Temperature, [K]
TR	Cryogenic carbon resistance thermometer
V	Fluid velocity, [m/sec]
VPT	Vapor-pressure thermometer
X	Vapor quality, [kg/kg]
ζ	Friction factor, dimensionless

Subscripts

1Θ	Single phase
2Θ	Two-phase
Cu	copper
i	indicates node number
l	indicates that subscripted liquid property is to be evaluated at the saturation temperature of the boiling fluid
v	indicates that subscripted vapor property is to be evaluated at the saturation temperature of the boiling fluid
W1	Tube inner wall
W2	Tube outer wall

ACKNOWLEDGMENTS

Many people have participated in the upgrade of a Tevatron spool. I would like to thank those in the Technical Division who have worked on the incorporating recooler in the spool piece, and testing of the spool. I am also grateful to personnel in the Beams Division Cryogenics Department for assistance in design and construction of the recooler. In particular, I wish to acknowledge the contribution of the following people: John Carson, Wilson Cross, Tom Dombeck, Kerry Ewald, Mike McAshan, Tom Peterson, Dean Sorensen. I especially want to thank Jay Theilacker for his guidance and advice in conducting this work. The author is indebted to Tom Nicol and Ray Hanft for their help and useful discussions. The help of Alex Martinez in reviewing this paper is also gratefully appreciated.

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