Fermilab

Particle Physics Division
Mechanical Department Engineering Note

Number: MD-ENG-245 Date: 15 July 2010

Project Internal Reference: Project 425 Task 1.6.4.5

Project: NOvA

Title: APD/TEC Water Cooling for IPND and Far Detector Hydraulic Calculations

Author(s): Dave Pushka

Reviewer(s):

Key Words: Piping System, APD – TEC Cooling System

Abstract Summary:

Hydraulic and Thermal calculations were prepared for both the IPND (integration prototype near detector) and the Far Detector. System curves were prepared for both systems for the water flow range of 2 to 8 ml per second through each of the TEC housings. Heat gain from ambient is also calculated.

Applicable Codes: Piping shall conform to ASME B31.3, Group D Service

FESHM 5031.1 Engineering note form is included below.

FESHM 5031.1 PIPING ENGINEERING NOTE FORM

Prepared by: Dave Pushka Preparation Date: 5-27-2010

Piping System Title: NOVA APD / TEC Cooling System

Lab Location: NOVA Near Detector Service Building Lab Location code: NDSB

Purpose of system / System description: Water Cooling system

Piping System ID Number: none assigned

Appropriate governing piping code: ASME B31.1 Category D

Fluid Service Category (if B31.3): Category-D / Normal / Category-M / High Pressure (circle one)

Fluid Contents: Water

Design Pressure: 50 psig Design Temperature: 50 F

Piping Materials: PVC (ASTM D1785, type 1120)

Drawing Numbers (PID's, weldments, etc.): 3929.500-ME-466929

Designer/Manufacturer: Fermilab / Various

Test Pressure: 50 psig Test Fluid: Water Test Date: TBD

Statements of Compliance

Piping system conforms to FESHM 5031.1, installation ***is not*** exceptional: Yes / No

Piping system conforms to FESHM 5031.1, installation ***is*** exceptional and has been designed, fabricated, inspected, and tested using sound engineering principles: Yes / No

Reviewed by: ______________________________

(Print Name)

Signature: ______________________________ Date: __________

D/S Head's Signature: ______________________________ Date: __________

The following signatures are required for exceptional piping systems:

ES&H Director's Signature: ______________________________ Date: __________

Director's Signature or Designee: ______________________________ Date: __________

Pipe Characteristics

Size: Refer to P&ID Length: Refer to Drawings Volume: less than 100 gallons

Relief Valve Information

Type: not applicable, system open to atmosphere Manufacturer: not applicable

Set Pressure: not applicable Relief Capacity: not applicable

Relief Design Code: not applicable

Is the system designed to meet the identified governing code? Yes / No

Fabrication Quality Verification:

System Documentation

Process and Instrumentation diagram appended? Yes / No

Process and Instrumentation component list appended? Yes / No

Is an operating procedure necessary for safe operation? Yes / No
If 'yes', procedure must be appended.

Exceptional Piping System

Is the piping system or any part of it in the above category? Yes / No
If "Yes", follow the requirements for an extended engineering note for Exceptional Piping Systems.

Quality Assurance

List vendor(s) for assemblies welded/brazed off site:
Not applicable: not brazed or welded.

List welder(s) for assemblies welded/brazed in-house:
Not Applicable

Append welder qualification records for in-house welded/brazed assemblies.
Not Applicable

Append all quality verification records required by the identified code (e.g. examiner's certification, inspector's certification, test records, etc.)

Results of Calculations:

Figure 1, System Curve for the IPND system:

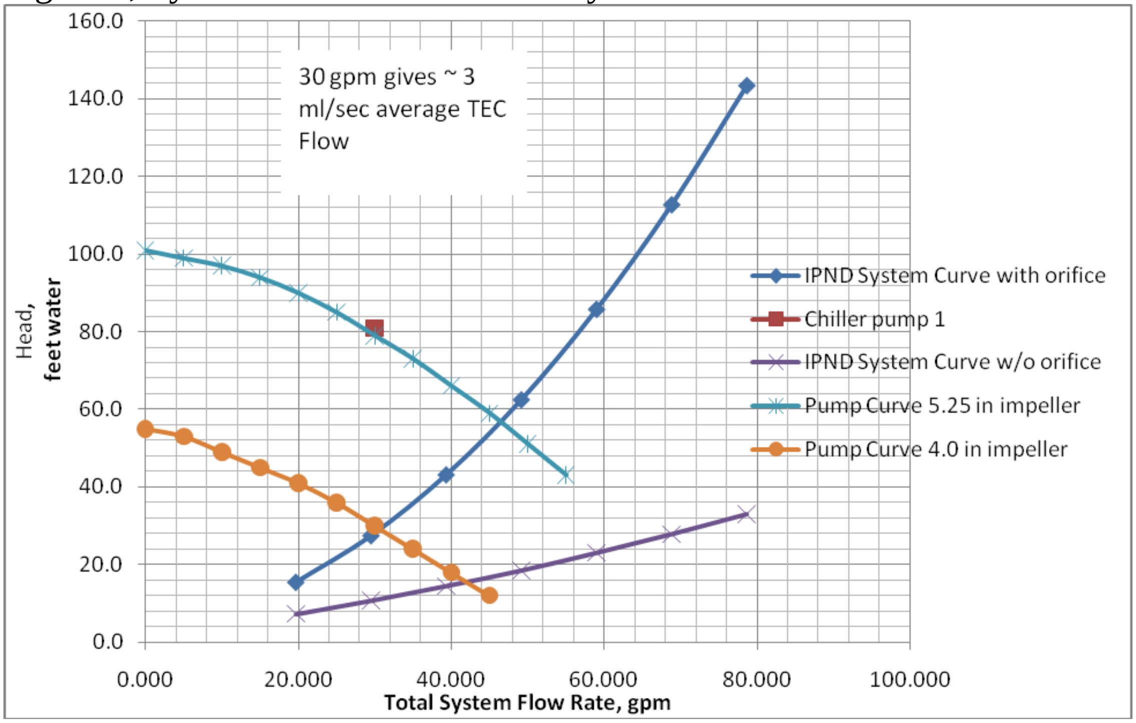
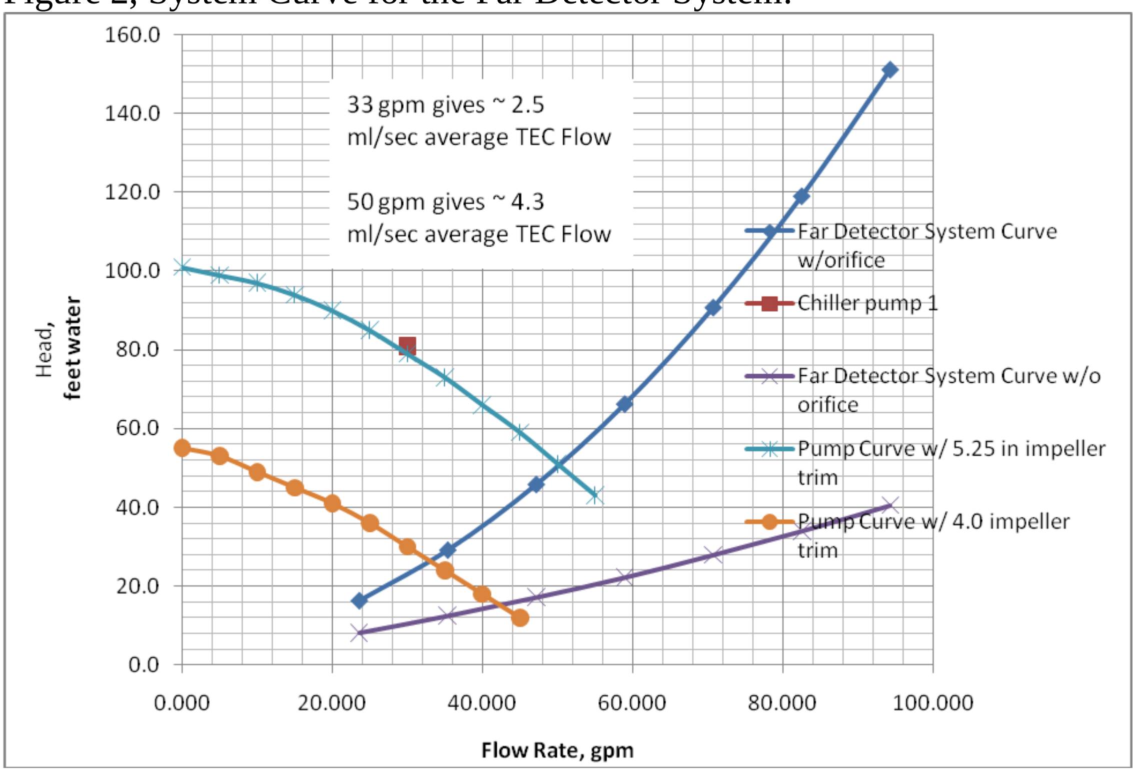
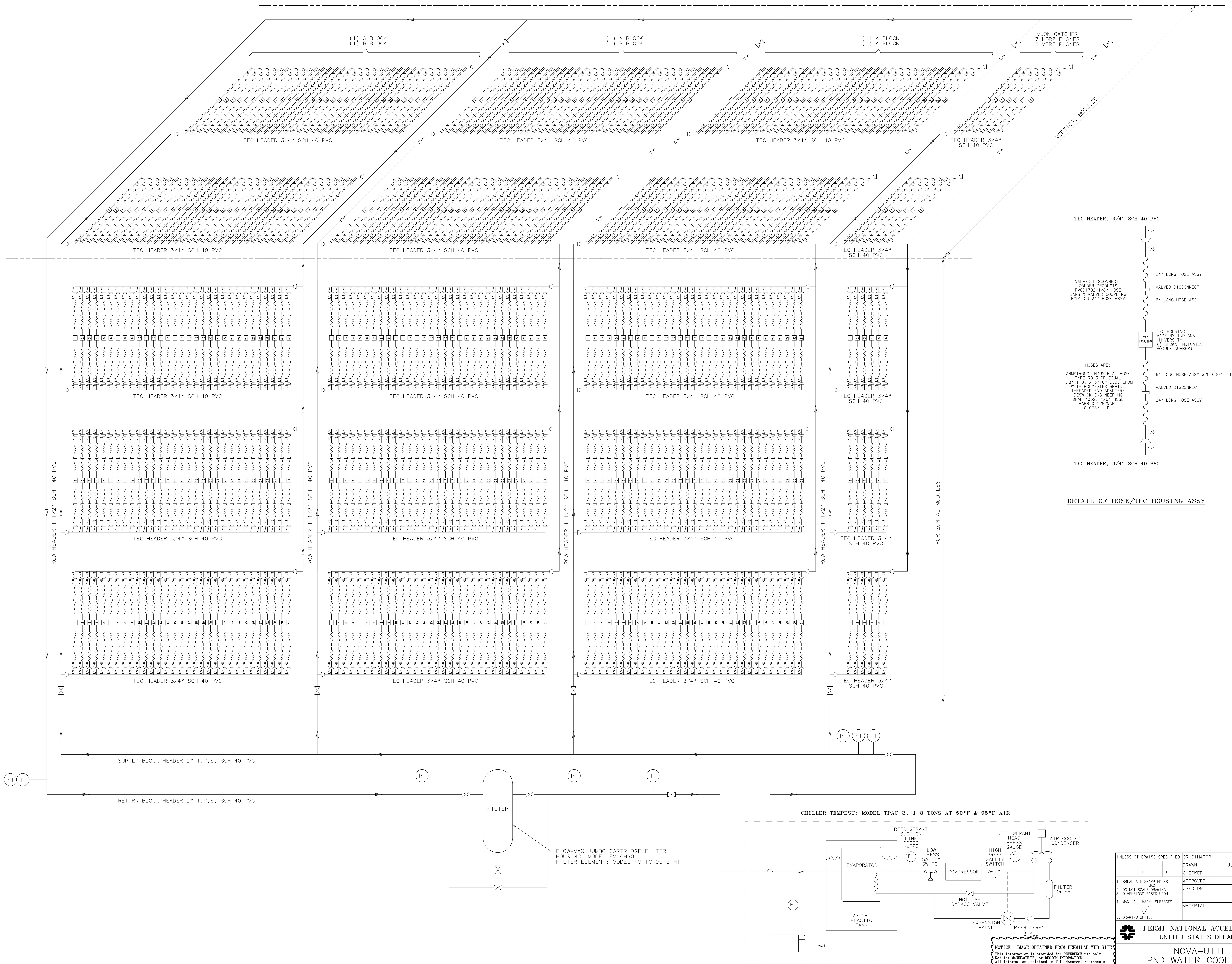


Figure 2, System Curve for the Far Detector System:



REV	DESCRIPTION	DRAWN	DATE
		APPROVED	DATE



UNLESS OTHERWISE SPECIFIED

± ± ±

1. BREAK ALL SHARP EDGES MAX.
2. DO NOT SCALE DRAWING.
3. DIMENSIONS BASED UPON
4. MAX. ALL MACH. SURFACES
5. DRAWING UNITS:

ORIGINATOR	D.PUSHKA	10-MAY-2010
DRAWN	J.CATALANELLO	11-MAY-2010
CHECKED	D.FRIEND	04-JUN-2010
APPROVED	D.PUSHKA	04-JUN-2010

USED ON

MATERIAL

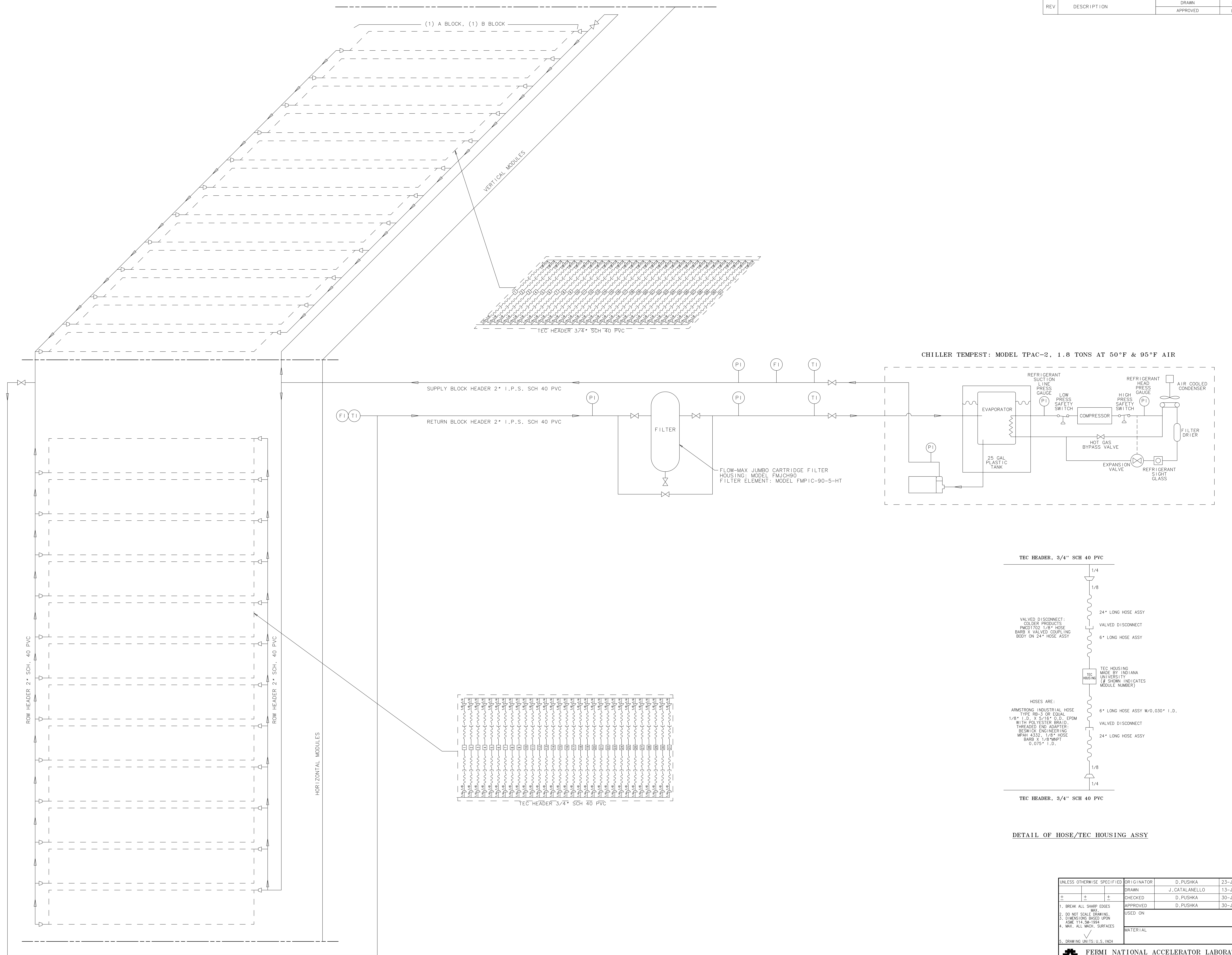
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

NOVA-UTILITIES
IPND WATER COOLING SYSTEM
SCHEMATIC DIAGRAM

SCALE	DRAWING NUMBER	SHEET	REV
NONE	3929.500-ME-466929	1 OF 1	

CREATED WITH : Ideas12NXSeries | GROUP: PPD/MECHANICAL DEPARTMENT

REV	DESCRIPTION	DRAWN	DATE
		APPROVED	DATE



UNLESS OTHERWISE SPECIFIED	ORIGINATOR	D.PUSHKA	23-JUN-2010
	DRAWN	J.CATALANELLO	13-JUL-2010
± ± ±	CHECKED	D.PUSHKA	30-JUL-2010
1. BREAK ALL SHARP EDGES MAX. 2. DO NOT SCALE DRAWING. 3. DIMENSIONS BASED UPON ASME Y14.5M-1994 4. MAX. ALL MACH. SURFACES √ 5. DRAWING UNITS: U.S. INCH	APPROVED	D.PUSHKA	30-JUL-2010
	USED ON		
	MATERIAL		

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

NOVA-UTILITIES COOLING SYSTEM P&ID FAR DETECTOR TEC (ONE ROW)

SCALE	DRAWING NUMBER	SHEET	REV
NONE	3929.500-ME-486095	1 OF 1	

CREATED WITH : Ideas12NXSeries | GROUP: PPD/MECHANICAL DEPARTMENT

Figure 3, IPND System P&ID (Piping and Instrumentation Diagram):

Drawing 3929.500-ME-46629

The IPND has six detector blocks and a small number of additional detector planes in the muon catcher portion of the detector. One chiller will service the entire IPND. Each block has either 74 or 76 TEC housings (depends if it is an “A” block or a “B” block. TEC housing counts for the IPND is 465 for the six blocks and 33 TEC housings for the muon catcher portion for a grand total of 498 TEC housings.

Figure 4, Far Detector System P&ID (Piping and Instrumentation Diagram):

Drawing 3929.500-ME-486095

The Far detector has approximately 30 detector blocks. One chiller system will service 2 blocks, for a total of 744 TEC housings (362 TEC housing in one far detector block).

Drawing numbers 3929.500-ME-466929 and 3929.500-ME-486095 are available electronically as a PDF at:

http://www-admscad.fnal.gov/MSDMain/cgi-bin/TP_PPDifind-web.pl

Figure 5, IPND System Heat Load Summary:

Summary of Heat Loads:			
Heat Load per TEC	3	Watts	
Number of TECs	497		497
TEC Heat Load	1491	Watts	
Heat Load from Pump	1119	Watts	based on 1.5 HP Motor
Heat Transfer Rate, Q, from TEC Hoses, w/o insulation	2,112	Watts	
Heat Transfer Rate, Q, from TEC Headers, w/o insulation	877	Watts	
Heat Transfer Rate, Q, from ROW Headers, w/o insulation	831	Watts	
Heat Transfer Rate, Q, from BLOCK Headers, w/o insulation	973	Watts	
Total Heat Load, w/o insulation	7,403	Watts	
Total Heat Load w/o insulation	2.11	Tons	
Heat Transfer Rate, Q, from TEC Hoses, with insulation	1288	Watts	
Heat Transfer Rate, Q, from TEC Headers, with insulation	444	Watts	
Heat Transfer Rate, Q, from ROW Headers, with insulation	401	Watts	
Heat Transfer Rate, Q, from BLOCK Headers, with insulation	461	Watts	
Total Heat Load, with insulation	5203	Watts	6329
Total Heat Load with insulation	1.48	Tons	
System Total Flow Rate from Above Calculations	19.7	gpm	from Row 26
System Total Flow Rate from Above Calculations	1.24	liters/second	
System Total Flow Rate from Above Calculations	1.24	kg/second	mass flow rate, m dot
C sub P for water	4.1926	kJ/kg-K	Cp
Bulk Water Temperature Rise From Chiller out to Chiller Return	1.00	C	Formula : Q = m dot * Cp * Delta T, solve for T
Bulk Water Temperature Rise From Chiller out to Chiller Return	1.81	F	

Figure 6, IPND Heat Source Graph:

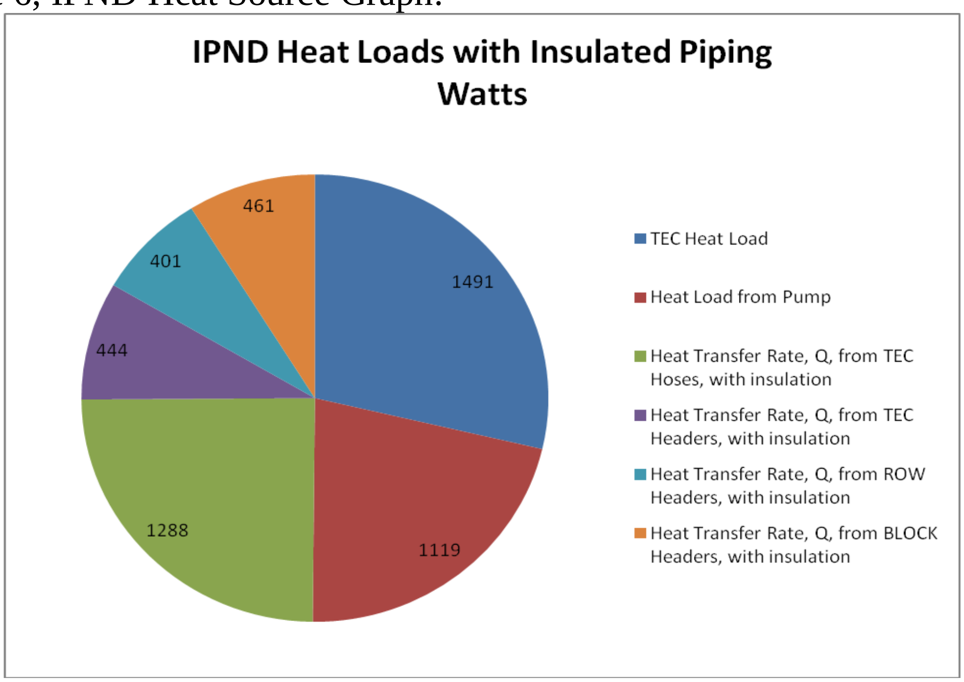
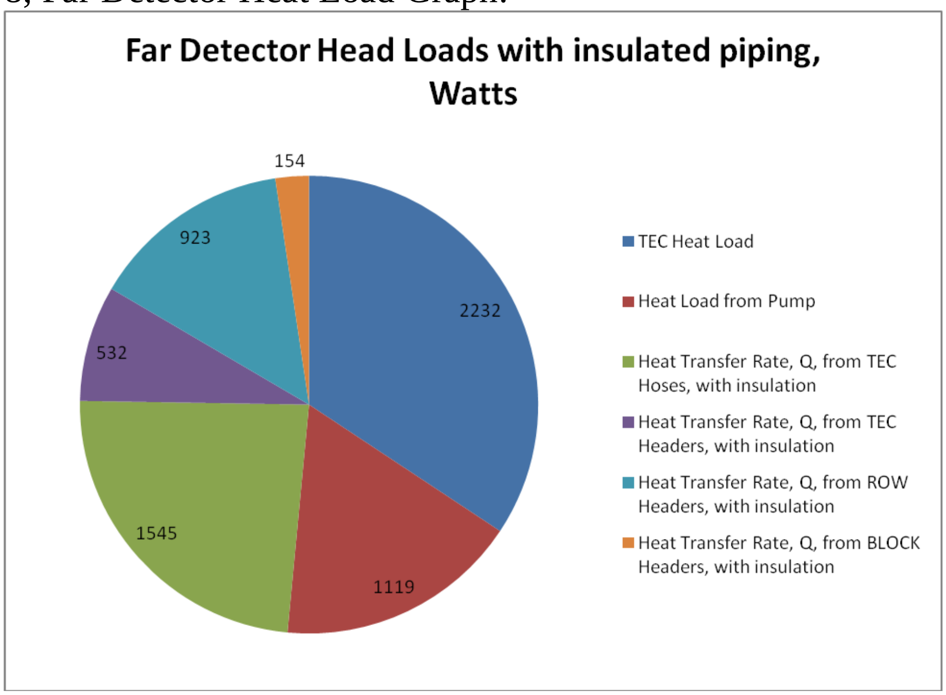


Figure 7, Far Detector System Heat Load Summary:

Summary of Heat Loads (Far Detector, FD):			Notes or Comments:
Heat Load per TEC	3	Watts	
Number of TECs	744		
TEC Heat Load	2232	Watts	
Heat Load from Pump	1119	Watts	based on 1.5 HP Motor
Heat Transfer Rate, Q, from TEC Hoses, w/o insulation	2,535	Watts	
Heat Transfer Rate, Q, from TEC Headers, w/o insulation	1,052	Watts	
Heat Transfer Rate, Q, from ROW Headers, w/o insulation	1,946	Watts	
Heat Transfer Rate, Q, from BLOCK Headers, w/o insulation	324	Watts	
Total Heat Load, w/o insulation	9,208	Watts	
Total Heat Load w/o insulation	2.62	Tons	
Heat Transfer Rate, Q, from TEC Hoses, with insulation	1545	Watts	
Heat Transfer Rate, Q, from TEC Headers, with insulation	532	Watts	
Heat Transfer Rate, Q, from ROW Headers, with insulation	923	Watts	
Heat Transfer Rate, Q, from BLOCK Headers, with insulation	154	Watts	
Total Heat Load, with insulation	6505	Watts	
Total Heat Load with insulation	1.85	Tons	
System Total Flow Rate from Above Calculations	23.6	gpm	from Row 26
System Total Flow Rate from Above Calculations	1.49	liters/second	
System Total Flow Rate from Above Calculations	1.48	kg/second	mass flow rate, m dot
C sub P for water	4.1926	kJ/kg-K	Cp
Bulk Water Temperature Rise From Chiller out to Chiller Return	1.05	C	Formula : Q = m dot * Cp * Delta T, solve for T
Bulk Water Temperature Rise From Chiller out to Chiller Return	1.88	F	

Figure 8, Far Detector Heat Load Graph:



Discussion:

Work performed at Indiana University and the University of Minnesota has shown that the Thermo Electric Coolers (TECs) are sufficiently well cooled with 15 C water at a flow rate of 2 ml per second per TEC. So the system curves were generated for a flow range of 2 to 8 mL per second average flow rate. A minimum flow rate of 2 mL per second per housing is the design specification. Higher flow rates are acceptable, but use more pump energy.

The flow rate verses pressure drop for the TEC housing is based on measurements made by Bill Gilbert and Leon Mualem. Accuracy of these measurements has not been independently verified. Note that the TEC housings were intentionally fabricated with 0.030 inch diameter orifices on the hose fittings in order to place the bulk of the pressure drop across the TEC and result in very similar flows in each TEC. Even with a full flow filter and care in cleaning lines prior to assembly, the potential for plugging exists.

Chiller was specified and purchased by Bill Gilbert of the University of Minnesota. So these calculations are used to check the flow rate based on what was purchased, not to specify what to purchase. For the IPND System, the choice of pump for the chiller would better fit with a 4.0 inch impeller trim.

Sufficient net positive suction head is available and exceeds the value required based on the pump data sheet.

Temperature change across the loop is very small. For a system flow rate that results in an average TEC housing flow of 4 ml per second, the temperature change is only about one degree centigrade.

For both systems, the full pump energy is added to the heat load. This is conservative as the motors for these small pumps are typically not more than 82 to 84% efficient according to the NEMA MG1 Table 12-10. Pump is listed at 48% efficient near the operating point.

Chiller capacity is listed at 1.8 tons (6300 Watts) for cold water discharge at 10 C (50 F) and heat rejection at 35 C (95 F).

IPND System heat load with insulation on the piping is estimated at 1.48 tons (5200 Watts). IPND System heat load without insulation is estimated at 2.1 tons (9200 Watts). Doubling the insulation thickness from 1 centimeter to 2 centimeters reduces the heat load to 1.3 tons (4600 Watts).

Far Detector System heat load with insulation is estimated at 1.85 tons (6505 Watts). Far Detector System heat load without insulation is estimated at 2.6 tons (9208 Watts).

Line Sizes, IPND:

IPND Summaries:		
IPND Line Sizes:		
Hose, Pipe or Fitting I.d.	0.125	inch
Pipe Size for TEC header on block	0.75	nominal IP
Pipe Size for ROW header on block	1.5	nominal IP
Pipe Size for Block header on block	2	nominal IP

Line Sizes, Far Detector:

Far Detector Summaries:		
Far Detector Line Sizes:		
24 inch long hose (or Pipe) I.d.	0.125	inch
Pipe Size for TEC header on block	0.75	nominal IPS
Pipe Size for ROW header on block	2	nominal IPS
Pipe Size for Block header on block	2	nominal IPS

Line sizes for the IPND and the Far Detector are identical except for the ROW header. For the IPND, a 1.5 inch nominal pipe size is suitable while for the Far Detector, this line needs to be 2 inch nominal pipe size. This is only a difference of .48 inch diameter.

Instrument List (typical for IPND and FD):

IPND Valve and Instrument List:							
	Tag	Range or Size	Units	Output	Make	Model	Description
Valves:							
	V-1	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve Filter Inlet
	V-2	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve Filter Outlet
	V-3	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve Filter By-Pass
	V-4	3/4	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve Filter Drain
	V-5	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve ROW Header One Supply
	V-6	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve ROW Header One Return
	V-7	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve ROW Header Two Supply
	V-8	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve ROW Header Two Return
	V-9	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve ROW Header Three Supply
	V-10	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve ROW Header Three Return
	V-11	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve ROW Header Four Supply
	V-12	2	Inch IPS	n/a	NIBCO	4660-S (Schedule 40 PVC)	Manual Isolation Valve ROW Header Four Return
Pressure Instruments							
	PI-1	0-60	psi	n/a	Ashcroft	Part # 25-1009AWL02L 0 - 60 psi	Filter Inlet Pressure
	PI-2	0-60	psi	n/a	Ashcroft	Part # 25-1009AWL02L 0 - 60 psi	Filter Outlet Pressure
	PI-3	0-60	psi	n/a	Ashcroft	Part # 25-1009AWL02L 0 - 60 psi	Block Header Supply Pressure
Temperature Instruments							
	TI-1	-20 to 120	F	n/a	Ashcroft	Part # 50EL60E040 -20/120	Supply (Chiller outlet) Temperature
	TI-2	-20 to 120	F	n/a	Ashcroft	Part # 50EL60E040 -20/120	Return (Chiller inlet) Temperature
Flow Instruments							
	FI-1	6 to 60	gpm	n/a	King Instrument	7200 Series, Order Number 0231	2 inch FNPT connections, Block Header (total system) Flow
	FI-2	3 to 21	gpm	n/a	King Instrument	7200 Series, Order Number 0181	1 inch FNPT connections, Row Header (di-block) Flow
	FI-3	3 to 21	gpm	n/a	King Instrument	7200 Series, Order Number 0181	1 inch FNPT connections, Row Header (di-block) Flow
	FI-4	3 to 21	gpm	n/a	King Instrument	7200 Series, Order Number 0181	1 inch FNPT connections, Row Header (di-block) Flow
	FI-5	3 to 21	gpm	n/a	King Instrument	7200 Series, Order Number 0181	1 inch FNPT connections, Row Header (di-block) Flow

Piping Temperature:

ASME B31.3 lists an operating temperature of PVC pipe at 100 F. This pipe will be used at approximately 50 F. To verify the adequacy of this material at the operating temperature, the manufacture was contacted and a reference with a graph of impact strength of this PVC piping material as a function of temperature are added to the end of this engineering note. The graph shows that at the operating point, the impact strength has fallen, but is still above the knee of the curve. Since this closed loop system is not apt to impart shock loads to the piping, and since the code required minimum material thickness is substantially thinner than the commercial pipe wall thickness, this material is acceptable for use at 50 F.

B31.3 Piping Code Calculations:

Hydraulic Data for Pipe:

Nominal Size	Schedule	i.d.	o.d	Absolute Roughness	Relative Roughness	Friction Factor For Full Turb
1/10	n/a	0.075	0.312	0.000015	0.00240000	0.038
1/9	n/a	0.125	0.312	0.000015	0.00144000	0.034
1/8	40	0.269	0.405	0.000015	0.00066914	0.034
1/4	40	0.364	0.54	0.000015	0.00049451	0.029
3/8	40	0.493	0.675	0.000015	0.00036511	0.028
1/2	40	0.622	0.84	0.000015	0.00028939	0.027
3/4	40	0.824	1.05	0.000015	0.00021845	0.025
1	40	1.049	1.315	0.000015	0.00017159	0.023
1 1/4	40	1.38	1.66	0.000015	0.00013043	0.022
1 1/2	40	1.61	1.9	0.000015	0.00011180	0.021
2	40	2.067	2.375	0.000015	0.00008708	0.019
2 1/2	40	2.469	2.875	0.000015	0.00007290	0.018
3	40	3.068	3.5	0.000015	0.00005867	0.0175

Maximum Anticipated System Pressure:

Pump shut in pressure	101	feet	based on a 5.25 inch diameter impeller on the chiller pump
Pump shut in pressure	43.7	psi	conversion to psi
Open Reservior Pressure	0	psi	this system does not have a pressurized expansion tank
Maximum Anticipated System Pressure :	43.7		
Maximum Material Temperature	100	F	based on chiller off during a 100 degree F summer day.
Minimum Material Temperature	32	F	based on chiller controls malfunction
Normal Material Temperature	50	F	

Pipe Material Selection:

Standard PVC pressure pipe spec:	ASTM D-1785 Class 1120		
Recommended Minimum Temperature	73	F	per table B-1 in ASME B31.3- 2008 edition
Maximum Material Temperature	140	F	per manufacture's data sheet.
Maximum Allowable Working Pressure	140	psi	per both Manufacture's data sheet and ASME B31. Table B-1 at 73 F.

ASME CODE CALCULATIONS FOR PIPING:

Internal Gage Pressure	P	50	psi	set by system pressure
Design Stress Limit for PVC	S	2000	psi	For D1785 Type 1120 PVC Material per ASME B31.3 Table B-1

Pressure-Thickness Calculations per ASME B31.3, Chapter VII:

Nominal Size	Schedule	i.d.	o.d	Min. Thickness Required, eqn 26a	Is t > t required?
1/8	40	0.269	0.405	0.005	OK
1/4	40	0.364	0.54	0.007	OK
3/8	40	0.493	0.675	0.008	OK
1/2	40	0.622	0.84	0.010	OK
3/4	40	0.824	1.05	0.013	OK
1	40	1.049	1.315	0.016	OK
1 1/4	40	1.38	1.66	0.020	OK
1 1/2	40	1.61	1.9	0.023	OK
2	40	2.067	2.375	0.029	OK
2 1/2	40	2.469	2.875	0.035	OK
3	40	3.068	3.5	0.043	OK

Conclusion: For all sized considered, the wall thickness of schedule 40 pipe is sufficient for the design pressure.

IPND System Volume Calculations:

IPND Volume Summaries:		
24 inch hose volume		
Combined Length of Supply and Return hoses	4	feet
Number of TEC / Housings per TEC Header	31	
Internal area	0.0122718	square incl
24 inch hose volume	18.260507	in3
24 inch hose volume	0.0790498	gallons
TEC Header Volume		
Combined Length of supply and return TEC headers on block	15	feet
Number of TEC Headers per Row Header	5	
Internal area	0.5332665	square incl
TEC Header Volume	479.93985	in3
TEC Header Volume	2.0776617	gallons
ROW Header Volume		
Combined Length of supply and return ROW headers on block	40	feet
Number of Row Headers per Block Header	4	
Internal area	2.0358306	square incl
ROW Header Volume	3908.7947	in3
ROW Header Volume	16.921189	gallons
Block Header Volume		
Combined Length of Block supply and return headers on Detector	150	feet
Number of Block Headers	1	
Internal area	3.355605	square incl
Block Header Volume	6040.089	in3
Block Header Volume	26.147572	gallons
Total Piping Volume	45.225472	gallons

Far Detector System Volume Calculations:

Far Detector Volume Summaries:		
24 inch hose volume		
Length of hose	4	feet
Number of TEC / Housings per TEC Header	31	
Internal area	0.0122718	square inch
24 inch hose volume	18.260507	in3
24 inch hose volume	0.0790498	gallons
TEC Header Volume		
Length of header on block	14	feet
Number of TEC Headers per Row Header	24	
Internal area	0.5332665	square inch
TEC Header Volume	2150.1305	in3
TEC Header Volume	9.3079244	gallons
ROW Header Volume		
Length of Row header on block	20	feet
Number of Row Headers per Block Header	1	
Internal area	3.355605	square inch
ROW Header Volume	805.3452	in3
ROW Header Volume	3.4863429	gallons
Block Header Volume		
Length of Block header on Detector	50	feet
Number of Block Headers	1	
Internal area	3.355605	square inch
Block Header Volume	2013.363	in3
Block Header Volume	8.7158572	gallons
Total Piping Volume	21.589174	gallons

IPND Net Positive Suction Head Calculations:

PUMP Net Positive Suction Head Available, NPSHA:			
Barometric Pressure, minimum at sight,	28.7	in hg	estimated for 750 feet mean sea level
Barometric Pressure, minimum at sight,	14.09744	psi	unit conversion
Gauge Pressure of open reservior,	0	psi	open reservior = 0 by defination
Vapor Pressure of water at 60 F (start-up conditions)	0.26	psi	from Burkes Pump Engineering Date
Specific Gravity of water at 60 F	0.999		from Burkes Pump Engineering Date
Static Height of reservior surface above pump inlet centerline	2	feet	estimated
Head Loss in the pump Suction Piping	3	feet	estimated
PUMP Net Positive Suction Head Available, NPSHA:	31.0	feet	
Pump Net Positive Suction Head Required, NPSHR:	10	feet	from Scot Pump Data Sheet for 50 gpm
Does NPSHA > NPSHR?	Okay		

PVC Pipe Manufacture Email Confirming Material is Suitable for the 50 F service temperature:

Dave Pushka

From: "Mai Huynh" <MaiHuynh@JMEagle.com>
To: "Dave Pushka" <pushka@fnal.gov>
Cc: "Murat Uslu" <MuratUslu@JMEagle.com>
Sent: Friday, May 21, 2010 8:58 PM
Subject: RE: Use of ASTM D-1785, class 1120 PVC pipe at 50 F

Mr. Pushka,
Thank you for your interesting in using PVC piping material with chilled water project. The PVC 1120 material designation code for pressure rated pipe, and the pressure rating of pipe was calculated at 73 degree F so when a piping system operating above that temperature then that pipe pressure rating will be dropped a little bit it depends on how high the temperature above 73 degree F. However if the pipe line operates at 50 degree F there should be no effect to the pipe line operating pressure.

Mai P Huynh
Quality Assurance Manager
JM Eagle
5200 West Century Blvd
Los Angeles, CA 90045
Tel. (310) 693 8200 Ext. 7302
Fax (310) 693 8230

-----Original Message-----
From: Dave Pushka [mailto:pushka@fnal.gov]
Sent: Friday, May 21, 2010 9:07 AM
To: - JMPlumbing; - JMWebSupport1
Subject: Use of ASTM D-1785, class 1120 PVC pipe at 50 F

Hello,

I am investigating using your PVC piping material with chilled water at 50 F and 50 psi. Unfortunately, ASME B31.3 Table B-1 lists the recommended minimum operating temperature at 73 F. I've not found on-line literature which provides a minimum temperature recommendation. But there are many installations operating at temperatures below 73 F that appear to operate satisfactory.

Can you provide any documentation to indicate that your plumbing material meeting ASTM D-1785, class 1120 is suitable for operation at 50 F and 50 psi?

Thanks
Dave Pushka, PE
Fermilab
Batavia, IL 60510
630-840-8767

The Madison Group
505 S. Rosa Rd., Ste. 124
Madison, WI 53719
(608)231-1907; (608)231-2694 fx
info@madisongroup.com

Failure Analysis of a PVC Pipe

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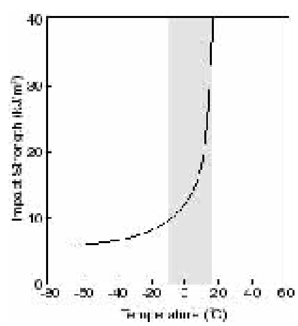
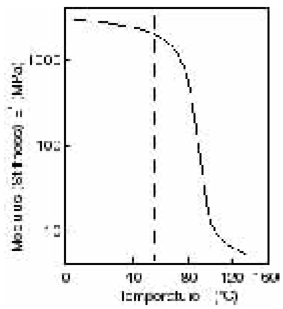
Plastic pipe, tubing and other profiles are an extremely popular alternative to copper, steel, aluminum and other materials. In fact, by 2003 it is predicted that 33% of all US pipe production will be made with plastic. Plastic pipes, tubing and profiles are used in a wide variety of industries including, building & construction, automotive, consumer goods, lawn & garden, windows & doors, furniture, plumbing and electrical. One of the most widely used materials for these products is polyvinylchloride or commonly known as PVC. This material is popular in these industries because of the wide range of properties that can be obtain depending on the additives that are mixed with it. PVC can be made to have high strength, rigidity and hardness; good electrical properties; high chemical resistance and be self extinguishing - all this at a relatively inexpensive price. However, depending if a plasticizer additive is used with the PVC, along with what kind and how much, the characteristics of the final part can be dramatically altered to have high impact strength with relatively low hardness and rigidity.

An unplasticized PVC pipe, shown above, is quite rigid with high strength and good chemical resistance. These properties make it attractive for use in above or below ground plumbing applications. However, a very important change in property occurs as the temperature gets colder - the impact strength of PVC drastically changes for the worse. This means that at low temperatures the ability of PVC to dissipate the energy from a sudden blow is limited and may result in part failure. The best way to describe this phenomenon, apart from demonstrating the impact of several PVC pipes at different temperatures, is to graph the impact strength of PVC as a function of temperature, shown in the figure below.



The most interesting part of this graph, the area that can explain many plastic failures, is boxed out in gray. Here, you will see a dramatic decrease in impact strength as the temperature gets colder - the part is becoming increasingly more brittle. The impact strength is 4x less at -10ºC than at 20ºC - a temperature range that is easily experienced in many regions of the US. This phenomenon is one that is not seen with every day metals and is commonly overlooked when designing with plastics.

One can improve this situation by using additives, in this case a plasticizer, that ultimately moves the graph to the left and gives the part a high impact strength at a much lower temperature. However, the gain in one property usually means the loss of other properties, in this case, the loss of stiffness. The figure below shows the modulus (stiffness) of PVC as a function of temperature (solid line). The dashed line indicates the temperature at which the modulus will decrease dramatically, approximately 50ºC for this PVC. For many uses, 50ºC is a temperature that the product would never experience, however, if an additive is used to increase the impact strength (as described above) then this graph will also move to the left lowering the temperature that the stiffness is lost.



Thus, a comprise must be made for how much, if any, additive is to be used for the application and environment that the product will be used. In the case of PVC pipe, high mechanical strength, rigidity, hardness and high chemical resistance is required at the lowest cost. Plasticizing additives typically add to the cost of a product and are not use in pipe production. Other additives can reduce costs, such as, calcium carbonate. Unfortunately, these cost reducing additives typically make the product even more brittle causing the Impact Strength graph shown in the first graph to move to the right, making the product more brittle and more susceptible to failure.

An example of a failed PVC pipe is shown in the figure below.

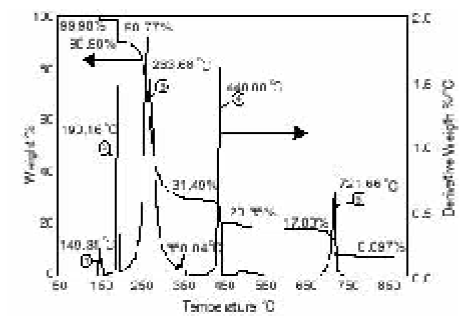
To determine the cause of failure a variety of techniques can be used

- Visual Inspection of the Failed Part
- Structural Finite Element Analysis

- Dynamic Finite Element Analysis
- Material Evaluation
- Process Evaluation

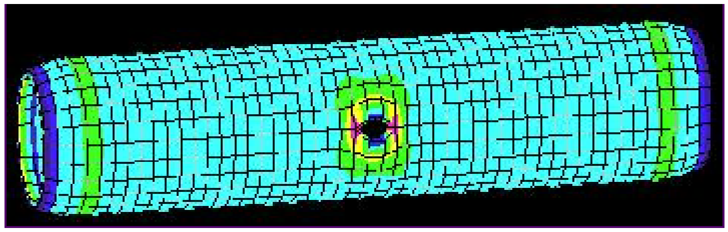
A visual inspection of the part indicates that this was a brittle failure as opposed to a ductile failure. Many brittle failures occur very quickly, whereas, ductile failures will typically occur over a longer period of time. It was revealed that the pipe was in a cold condition of approximately -5.0ºC. The pipe was in an enviornment where the temperature was low enough that it became very brittle. A force, which could be caused by an external blow or from internal pipe pressure, became to great and the part failed catastrophically. The cause of failure may not be because the engineer specified the wrong pipe for the job or enviornment, but because of the formulation of the material or the processing conditions at the production plant were wrong.

To determine if the pipe had the correct formulation a wide variety of material tests can be performed. One such test is the thermogravimetric analyzer (TGA). This device is often used to identify the components of a plastic part. It works by gradually heating a small sample of the plastic to a very high temperature. At different temperatures the compounds of the plastic will decompose. The TGA accurately records the change of weight with respect to the temperature. The figure below shows an example of a TGA test on PVC sample. Here, the decomposition of the different compounds can be seen along with the percent weight lose. Using data from an extensive library, the decomposition peaks are matched with known materials to decompose at the same exact temperature.

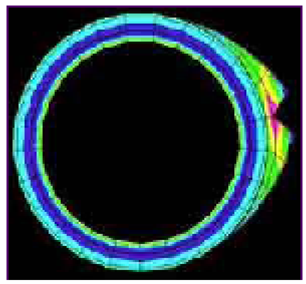


TGA Analysis of a PVC sample. (1) Volatiles: humidity, monomers, solvents (2) DOP plasticizer (3) HCl formation (4) carbon-chain scission (5) CO_2 formation

To establish the mode and forces of failure, along with providing confidence that a failure took place in the manner that was determined, a finite element analysis (FEA) can be made. This type of analysis allows the engineer to place the part in a realistic environment under normal to extreme conditions and observe what happens to the part - if failure occurs. The animation below shows the predict failure of a pipe caused by an extreme internal pressure using FEA.



(click on figure to view FEA failure of animation - 340kB)



(click on figure to view FEA failure animation - 510kB)