T962 TPC Liquid Argon Cryostat Relief Device Sizing Calculations

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(1.0) Introduction

This document presents calculations to size the relief device of the T962 TPC Liquid Argon Cryostat for the PPD1014 pressure vessel engineering note. This vessel will be located in the Minos Hall.

(2.0) General Information

(2.1) Fluid Properties

From ASME Boiler Pressure Vessel Code, Section VIII Div I, Appendix 11. Capacity Conversions For Safety Valves, Example #4, the density of dry air at 60F 14.7 psia is:

```
RhoStdAir  =  0.0766**(lb/ft^3)      (density of air at standard conditions)
```

Maximum allowable working pressure of the cryostat.

```
MAWP  =  30**psig      ( cryostat maximum allowable pressure)
```

The relief device is a 1 1/2 inch UD stamped burst disc, Fike SRL model.

Dimensions and Surface Area Of Cryostat

The surface area of the argon cryostat is needed to determine the Dimensions of argon cryostat inner vessel are:

```
InnerOD  =  30**in      (outside diameter of inner vessel)
Convert(ToFt)InnerOD
InnerOD  =  2.5**ft
```

From PHPK DRW # 07-2032-6501, SHEET 2 of :

```
InnerL  =  (799/16)**in      (overall length of inner vessel)
InnerL  =  49.9375**in
Convert(ToFt)InnerL
InnerL  =  4.1614583333**ft
```

The inner vessel neck is 18 in pipe.

```
NeckOD  =  18**in      (outside diameter of 18  pipe)
Convert(ToFt)NeckOD
NeckOD  =  1.5**ft
```

From PHPK DRW # 07-2032-6500, SHEET 4 of 5

```
NeckL  =  15.5**in      (length of vacuum insulated portion of neck)
Convert(ToFt)NeckL
NeckL  =  1.2916666666**ft
```

Thickness of MLI insulation layer:

```
InsT  =  0.5**in      (insulation thickness)
Convert(ToFt)InsT
InsT  =  0.4166666666e-1**ft
```

Inner most area of insulation.

```
CylArea  =  Pi*InnerOD*InnerL+2*Pi*InnerOD^2/4
CylArea  =  0.4250149436e2**(ft^2)
NeckArea  =  Pi*NeckOD*NeckL
NeckArea  =  6.0868357663**(ft^2)
InnerArea  =  CylArea+NeckArea
InnerArea  =  48.5883301294**(ft^2)
```

Outer most area of insulation.

```
CylAreaO  =  Pi*(InnerOD+InsT)*(InnerL+InsT)+2*Pi*(InnerOD+InsT)^2/4
CylAreaO  =  0.4370890768e2**(ft^2)
NeckAreaO  =  Pi*(NeckOD+InsT)*NeckL
NeckAreaO  =  6.2559145376**(ft^2)
OuterArea  =  CylAreaO+NeckAreaO
OuterArea  =  49.9648222229**(ft^2)
```

Arithmetical mean of the area of insulation:

```
InsArea  =  (InnerArea+OuterArea)/2
InsArea  =  0.4927657617e2**(ft^2)
```

(3.0)Relief Conditions

There are only three ways to add heat to the cryostat, causing liquid argon to boil or to raise the pressure, fire loss of vacuum and internal electric heater. The cryostat is designed so that there is no way flow warm argon gas or other fluids to heat up the liquid argon. The three cases are discussed below.

(3.1) Fire Condition

The mean thermal conductivity of air and argon between 1200F and Saturation temperature from CGA S-1.3 p32, Table 3 are:

```
khotair  =  0.024573**(BTU/(hr*ft*F))
khotar  =  0.015812**(BTU/(hr*ft*F))
```

Determine the overall heat transfer coefficient using the higher thermal conductivity of air.

```
U  =  khotair/InsT
U  =  0.589752**(BTU/(hr*ft^2*F))
```

Calculate the required relief valve capacity as per CGA S-1.3, section 5.3.3. To be consistent with the CGA method of calculations, make A non-dimensional variable equaling the number of square feet of surface.

```
A  =  InsArea/1**ft^2
A  =  0.4927657617e2
Ff  =  1.0      (correction factor)
```

From CGA S-1.3, Table 1, for argon:

```
Gi  =  10.2**((ft^5*hr*F)/(BTU*min))
```

The so called required flow capaity is:

```
Qa  =  Ff*Gi*U*A^0.82
Qa  =  0.1469720745e3**(ft^3/min)
```

As per CGA 5.3 (c), reduce the required flow capacity Qa to 30% of its value because of the fire protection sprinkler system in the cavern. Qa is the stamped capacity on a relief device in standard cubic feet of air.

```
Qa  =  0.3*Qa
Qa  =  0.4409162236e2**(ft^3/min)
```

(3.2) Fire Condition Required Mass Flow Rate

The required stamped capacity is applicable to the case when the relief device inlet is close to the cryostat and the relief device discharges directly to atmosphere. The T962 cryostat will have a very long exhaust vent pipe carrying the vapor to the outdoor atmosphere on the surface. The required mass flow rate will be found following procedures from ASME Boiler Pressure Vessel Code, Section VIII Div I, Appendix 11. Capacity Conversions For Safety Valves.

Determine required value of KvAb (Kv * Ab) of a relief device that has stamped capacity Qa.

```
Wa  =  Qa*RhoStdAir      (mass flow rate of air)
Wa  =  0.0337741827e2**(lb/min)
Convert(ToHr)Wa
Wa  =  0.2026450963e3**(lb/hr)
Mair  =  28.97      (molecular weight)
Ta  =  520**R      (temperature)
P  =  14.7**psia+1.1*MAWP      (inlet abso;ute pressure, 10% over MAWP)
P  =  0.477e2**psia
C  =  356
C  =  356**((R^0.5*lb)/(hr*in^2*psia))
```

Find KvAb (flow coefficient Kv times flow area Ab).

```
KvAb  =  Wa/(C*P)*(Ta/Mair)^0.5
KvAb  =  0.5055861242e-1**(in^2)
```

Next determine mass flow rate of argon vapor through the same valve at an inlet pressure of 121% of the MAWP

```
Pf  =  1.21*MAWP+14.7**psia
Pf  =  0.51e2**psia
```

At that pressure, the saturation temperature is

```
Tf  =  101.05**K
Tf  =  Tf*(9/5)**(R/K)
Tf  =  0.18189e3**R
Mar  =  39.944      (molecular weight of argon)
```

for argon ,

```
C  =  378**((R^0.5*lb)/(hr*in^2*psia))
```

The mass flow rate for the fire condition is:

```
Wf  =  KvAb*C*Pf*(Mar/Tf)^0.5
Wf  =  0.4567499276e3**(lb/hr)
```

The relief system must be designed to handle the mass flow rate of argon Wf.

ASME Boiler Pressure Vessel Code Section VIII, DIVISION 1, UG127 (a)(2)(b) requires the calculated relieving capacity be multiplied by 0.9 to account for uncertainty in flow resistance methods of calculation. The approach taken here is to assume a flow rate and calculate the pressure drop in the vent piping. So, to be consistent with the ASME UG127 requirement, the assumed flow rate will be the required flow rate divided by 0.9.

```
Wf  =  Wf/0.9
Wf  =  507.4999196497**(lb/hr)
```

(3.3) Loss Of Vacuum Condition

```
Pv  =  14.7**psia+1.1*MAWP      (inlet absolute pressure, 10% over MAWP)
Pv  =  0.477e2**psia
```

At that pressure, the saturation temperature is

```
Tv  =  100.99**K
Tv  =  Tv*(9/5)**(R/K)
Tv  =  0.181782e3**R
```

The thermal conductivity of air and argon at 100 F, from NIST are:

```
kair  =  0.015486**(BTU/(hr*ft*F))
kar  =  0.010624**(BTU/(hr*ft*F))
```

Determine the overall heat transfer coefficient using the higher thermal conductivity of air.

```
U  =  kair/InsT
U  =  0.371664**(BTU/(hr*ft^2*F))
Qa  =  (590**R-Tv)/(4*(1660**R-Tv))*Ff*Gi*U*A^0.82
Qa  =  6.3945438708**(ft^3/min)
```

(3.4) Loss of Vacuum Condition Required Mass Flow Rate

The same as for the fire condition determine required value of KvAb (Kv * Ab) of a relief device that has stamped capacity Qa.

```
Wa  =  Qa*RhoStdAir      (mass flow rate of air)
Wa  =  0.4898220605**(lb/min)
Convert(ToHr)Wa
Wa  =  0.2938932363e2**(lb/hr)
Mair  =  28.97      (molecular weight)
Ta  =  520**R      (temperature)
P  =  14.7**psia+1.1*MAWP      (inlet abso;ute pressure, 10% over MAWP)
P  =  0.477e2**psia
C  =  356**((R^0.5*lb)/(hr*in^2*psia))
```

Find KvAb (flow coefficient Kv times flow area Ab).

```
KvAb  =  Wa/(C*P)*(Ta/Mair)^0.5
KvAb  =  0.7332442035e-2**(in^2)
```

for argon ,

```
C  =  378**((R^0.5*lb)/(hr*in^2*psia))
```

The mass flow rate for the loss of vacuum condition is:

```
Wv  =  KvAb*C*Pv*(Mar/Tv)^0.5
Wv  =  0.6197394683e2**(lb/hr)
```

The required mass flow rate for the loss of vacuum is significantly smaller than for the fire case.

(3.5) Cryostat Heater Case

The only other method of adding heat to the cryostat is through its heater HTR-15-AR. The maximum heat output of the heater is:

```
Qhtr  =  350**W
```

At saturated conditions and 110% over the MAWP, the temperature and pressure for the heater case is:

```
Ph  =  14.7**psia+1.1*MAWP      (inlet absoute pressure, 10% over MAWP)
Ph  =  0.477e2**psia
Th  =  100.99**K
Th  =  Th*(9/5)**(R/K)
Th  =  0.181782e3**R
```

At these flow conditions the saturated liquid and vapor enthalpies are:

```
hf  =  (-0.102829e3)**(kJ/kg)      (liquid  enthalpy)
hg  =  47.4446**(kJ/kg)      (vapor  enthalpy)
```

The required vent rate is the boil-off:

```
Wh  =  Qhtr/(hg-hf)
Wh  =  2.3290850821**((W*kg)/kJ)
Convert({ToJ,ToJS,ToLb,ToHr})Wh
Wh  =  18.4851119545**(lb/hr)
```

The mass flow rate for the heater case is significantly smaller than for the loss of vacuum case.

(4.0) Vent System Pressure Drop

Only the calculations for the fire case will be presented. The fire case has the largest mass flow rate of the three failure cases. As well the argon temperature in the entire length of vent system is assumed to be 1200 F. This is perhaps not realistic, but it makes the calculations simpler.

For the calculations the vent system is divided into five sections, 1 1/2 inch pipe run off the exhaust of the cryostat, a 2 inch ID flexible hose, a long 4 inch horizontal pipe run in the MINOS Hall, 6" diameter vertical pipe that carrries the argon to the surface, and last a 3 inch carbon steel pipe run in the MINOS Assembly Hall. The calculations uses the following defined process points:

Point 1: The exhaust to the atmosphere from the 3 inch pipe on the surface

Point 2: Transition, on the surface, from the 3 inch pipe in the assembly hall to the 6 inch vertical pipe.

Point 3: transition from the bottom of the 6 inch pipe to the 4 inch pipe near the lower elevator foyer.

Point 4: transition from the 4 inch pipe to the 2" flexible hose near the MINOS detector.

Point 5: transition from the 2 inch flexible hose to a short run of 1 1/2 inch pipe.

Point 6: The cryostat inner vessel.

The procedure of the calculations is to assume the maximum required mass flow rate of Wf and start at point 1 , atmospheric pressure. The flow conditions at point 1 are determined, and the presure drop in the next section of piping is calculated. The pressure at point 2 is found and the process repeated until the pressure of the cryostat at point 6 is found. This method of calculated is used because it involves no iteration.

(4.1) Minos Assembly Hall Pipe Run.

Start at point 1 on the surface. The mass flow rate is:

```
w[1]  =  Wf
w[1]  =  507.4999196497**(lb/hr)
```

To simplify the calculations, start the calculations at the exhaust of the pipe and assume the argon temperature to be 1200 F.

Fluid properties

```
T[1]  =  (460+1200)**R
T[1]  =  1660**R
```

The pressure is atmospheric. Atmospheric pressure at Fermilab is:

```
p[1]  =  14.3**psia
```

The density and viscosity of the argon is:

```
rho[1]  =  3.207e-2**(lb/ft^3)
mu[1]  =  3.54277e-5**(lb/(ft*s))
```

Piping Description

Pipe length

```
Le[1]  =  111**ft
```

Number of long radius 90 degree weld elbows:

```
nel90  =  11
```

Assume 5 45 degree weld elbows:

```
nel45  =  2
```

Pipe size

```
od[1]  =  3.500**in      (outside diameter 3 in pipe)
wall[1]  =  0.216**in      (wall thickness 3 in sch 40 pipe)
Convert(ToFt)od[1]
od[1]  =  0.2916666666**ft
Convert(ToFt)wall[1]
wall[1]  =  0.18e-1**ft
```

Internal diameter and flow area

```
id[1]  =  od[1]-2*wall[1]      (internal diameter)
id[1]  =  0.2556666666**ft
a[1]  =  Pi*id[1]^2/4      (flow area)
a[1]  =  0.5133790001e-1**(ft^2)
```

K factors

Determine velocity, Reynolds number and friction factor.

```
v[1]  =  w[1]/(a[1]*rho[1])      (velocity)
v[1]  =  0.3082470422e6**(ft/hr)
Convert(ToSec)v[1]
v[1]  =  85.6241784044**(ft/s)
Re[1]  =  id[1]*v[1]*rho[1]/mu[1]      (Reynolds number)
Re[1]  =  0.1981648067e5
epsilon  =  0.00015**ft      (commercial steel pipe roughness)
f[1]  =  FrictionFactor3(Re[1],epsilon,id[1])      (friction factor)
f[1]  =  0.2723287878e-1
```

K Factors

The K factor due to straight pipe length:

```
Kle  =  f[1]*Le[1]/id[1]
Kle  =  11.8234010897
```

From Crane Tech Paper 410, page A-29, rhe K factor for each 90 degree elbow is:

```
kel  =  15.4*f[1]
kel  =  0.4193863333
```

Assume the K factor for 45 degree elbow is half that of 90 degree elbow:

```
kel45  =  7.9*f[1]
kel45  =  0.2151397424
```

Assume a sharp edged entrance and exit pressure drops in this section of the pipe system.

```
Kin  =  0.5
Kout  =  1.0
```

The total K factor is:

```
Kt  =  Kin+Kout+Kle+nel90*kel+nel45*kel45
Kt  =  18.3669302409
```

Pressure Drop

Find the pressure drop.

```
dp[1]  =  Kt*rho[1]*v[1]^2/(2*gc)      (pressure drop)
dp[1]  =  0.6711093938e2**(lbf/ft^2)
Convert({ToIn,{lbf<-psi*in^2}})dp[1]
dp[1]  =  0.4660481901**psi
```

(4.2) Pressure Drop in vertical pipe, Section 2

pressure at point 2

```
p[2]  =  p[1]+dp[1]
p[2]  =  0.1476604819e2**psia
```

Mass flow rate.

```
w[2]  =  Wf
w[2]  =  507.4999196497**(lb/hr)
T[2]  =  (460+1200)**R
T[2]  =  1660**R
```

The density and viscosity of the argon is:

```
rho[2]  =  3.337e-2**(lb/ft^3)
mu[2]  =  3.54231e-5**(lb/(ft*s))
```

Piping Description

Pipe length

```
Le[2]  =  350**ft
```

Number of long radius 90 degree weld elbows:

```
nel90  =  0
```

Number of long radius 45 degree weld elbows:

```
nel45  =  0
```

Pipe size

```
od[2]  =  6.625**in      (outside diameter 6 in pipe)
wall[2]  =  0.280**in      (wall thickness 6 in sch 40 pipe)
Convert(ToFt)od[2]
od[2]  =  0.5520833333**ft
Convert(ToFt)wall[2]
wall[2]  =  0.2333333333e-1**ft
```

Internal diameter and flow area

```
id[2]  =  od[2]-2*wall[2]      (internal diameter)
id[2]  =  0.5054166666**ft
a[2]  =  Pi*id[2]^2/4      (flow area)
a[2]  =  0.2006268247**(ft^2)
```

K factors

Determine velocity, Reynolds number and friction factor.

```
v[2]  =  w[2]/(a[2]*rho[2])      (velocity)
v[2]  =  0.7580376411e5**(ft/hr)
Convert(ToSec)v[2]
v[2]  =  21.0566011421**(ft/s)
Re[2]  =  id[2]*v[2]*rho[2]/mu[2]      (Reynolds number)
Re[2]  =  0.1002553301e5
epsilon  =  0.00015**ft      (commercial steel pipe roughness)
f[2]  =  FrictionFactor3(Re[2],epsilon,id[2])      (friction factor)
f[2]  =  0.3132426243e-1
```

K Factors

The K factor due to straight pipe length:

```
Kle  =  f[2]*Le[2]/id[2]
Kle  =  21.6919871745
```

Assume a sharp edged exit for the exit pressure drops in this section of the pipe system. The entrance pressure drop was accounted for in the previous section.

```
Kout  =  1.0
```

The total K factor is:

```
Kt  =  Kout+Kle
Kt  =  22.6919871745
```

Pressure Drop

Find the pressure drop.

```
dp[2]  =  Kt*rho[2]*v[2]^2/(2*gc)      (pressure drop)
dp[2]  =  5.2175933074**(lbf/ft^2)
Convert({ToIn,{lbf<-psi*in^2}})dp[2]
dp[2]  =  0.3623328685e-1**psi
```

dp[2] is just the frictional pressure drop and does not include the pressure change due to the change in elevation.

(4.3) MINOS Hall 4 inch Pipe Pressure Drop, Section 3

The pressure at the entrance of setion 3 is

```
p[3]  =  p[2]+dp[2]+Le[2]*rho[2]*g/gc
p[3]  =  14.802281477**psia+0.116795e2**(lbf/ft^2)
Convert({ToIn,{lbf<-psi*in^2}})p[3]
p[3]  =  14.8833891159**psia
```

Mass flow rate.

```
w[3]  =  Wf
w[3]  =  507.4999196497**(lb/hr)
```

To simplify the calculations, assume the argon temperature to be 1200 F.

Fluid properties

```
T[3]  =  (460+1200)**R
T[3]  =  1660**R
```

The density and viscosity of the argon is:

```
rho[3]  =  3.738e-2**(lb/ft^3)
rho[3]  =  3.738e-2**(lb/ft^3)
mu[3]  =  3.54232e-5**(lb/(ft*s))
mu[3]  =  3.54232e-5**(lb/(ft*s))
```

Piping Description

Pipe length

```
Le[3]  =  313**ft
```

Number of long radius 90 degree weld elbows:

```
nel90  =  6
```

Number of 45 degree long radius weld elbows:

```
nel45  =  2
```

Pipe size

```
od[3]  =  4.500**in      (outside diameter 4 in pipe)
wall[3]  =  0.120**in      (wall thickness 4 in sch 10 pipe)
Convert(ToFt)od[3]
od[3]  =  0.375**ft
Convert(ToFt)wall[3]
wall[3]  =  1.e-2**ft
```

Internal diameter and flow area

```
id[3]  =  od[3]-2*wall[3]      (internal diameter)
id[3]  =  0.355**ft
a[3]  =  Pi*id[3]^2/4      (flow area)
a[3]  =  0.9897980354e-1**(ft^2)
```

Flex Hoses

There are two 4 inch internal diameter with lengths:

```
dflex  =  4.0**in
Lflex1  =  3.5**ft
Lflex2  =  5.5**ft
```

Multiply the total length of the flex hoses to account for the increased pressure drop caused by the internal corrugated interior surface.

```
Lflex  =  3*(Lflex1+Lflex2)
Lflex  =  27.**ft
```

Flex hose flow area:

```
aflex  =  dflex^2*Pi/4
aflex  =  0.1256637061e2**(in^2)
```

K factors

Determine velocity, Reynolds number and friction factor.

```
v[3]  =  w[3]/(a[3]*rho[3])      (velocity)
v[3]  =  0.1371671431e6**(ft/hr)
Convert(ToSec)v[3]
v[3]  =  38.1019841949**(ft/s)
Re[3]  =  id[3]*v[3]*rho[3]/mu[3]      (Reynolds number)
Re[3]  =  0.1427340048e5
epsilon  =  0.000005**ft      (drawn tubing roughness)
f[3]  =  FrictionFactor3(Re[3],epsilon,id[3])      (friction factor)
f[3]  =  0.2818365075e-1
```

The K factor due to straight pipe length:

```
Kle  =  f[3]*Le[3]/id[3]
Kle  =  24.8492470031
```

From Crane Tech Paper 410, page A-29, the K factor for each 90 degree elbow is:

```
kel  =  20.0*f[3]
kel  =  0.563673015
```

Assume the K factor for 45 degree elbow is half that of 90 degree elbow:

```
kel45  =  10.0*f[3]
kel45  =  0.2818365075
```

The entrance and exit K factors are accounted for in adjacent sections

```
Kout  =  1.0
```

Flex Hose K factor

Determine velocity, Reynolds number and friction factor.

```
vflex  =  w[3]/(aflex*rho[3])      (velocity)
vflex  =  1080.4055755884**(ft^3/(hr*in^2))
Convert({ToSec,ToFt})vflex
vflex  =  43.2162230235**(ft/s)
Reflex  =  dflex*vflex*rho[3]/mu[3]      (Reynolds number)
Reflex  =  0.1824140582e6**(in/ft)
Convert(ToFt)Reflex
Reflex  =  0.1520117151e5
epsilon  =  0.00015**ft      (commercial steel pipe roughness)
fflex  =  FrictionFactor3(Reflex,epsilon,dflex)      (friction factor)
fflex  =  0.2859032853e-1
```

The flexible hose K factor:

```
Kflex  =  fflex*Lflex/dflex
Kflex  =  0.1929847176**(ft/in)
```

Use Crane Tech Paper 410, formula 3-24 to converted the K factor for 4 inch pipe.

```
Kflex  =  Kflex*(id[3]/dflex)^4
Kflex  =  0.1197281758e-4**(ft^5/in^5)
Convert(ToFt)Kflex
Kflex  =  2.979220145
```

Pressure Drop

The total K factor is:

```
Kt  =  Kle+nel90*kel+nel45*kel45+Kflex
Kt  =  31.7741782537
```

Find the pressure drop.

```
dp[3]  =  Kt*rho[3]*v[3]^2/(2*gc)      (pressure drop)
dp[3]  =  0.2679623368e2**(lbf/ft^2)
Convert({ToIn,{lbf<-psi*in^2}})dp[3]
dp[3]  =  0.1860849561**psi
```

(4.4) MINOS Hall 2 inch Flex Hose Pressure Drop, Section 4

Section 4 is a 35 foot long 2" flex hose with a reducer on its inlet. The pressure at the entrance of section 4 is

```
p[4]  =  p[3]+dp[3]
p[4]  =  15.0694740721**psia
Convert({ToIn,{lbf<-psi*in^2}})p[4]
p[4]  =  15.0694740721**psia
```

Mass flow rate.

```
w[4]  =  Wf
w[4]  =  507.4999196497**(lb/hr)
```

To simplify the calculations, assume the argon temperature to be 1200 F.

Fluid properties

```
T[4]  =  (460+1200)**R
T[4]  =  1660**R
```

The density and viscosity of the argon is:

```
rho[4]  =  3.379e-2**(lb/ft^3)
mu[4]  =  3.54233e-5**(lb/(ft*s))
```

Flex Hose

There are two 4 inch internal diameter with lengths:

```
dflex  =  2.0**in
Lflex  =  35**ft
```

Multiply the length of the flex hose by 3 to account for the increased pressure drop caused by the internal corrugated interior surface.

```
Lflex  =  3*Lflex
Lflex  =  105**ft
```

Flex hose flow area:

```
aflex  =  dflex^2*Pi/4
aflex  =  3.1415926537**(in^2)
```

Flex Hose K factor

Determine velocity, Reynolds number and friction factor.

```
vflex  =  w[4]/(aflex*rho[4])      (velocity)
vflex  =  4780.7706913876**(ft^3/(hr*in^2))
Convert({ToSec,ToFt})vflex
vflex  =  191.2308276555**(ft/s)
Reflex  =  dflex*vflex*rho[4]/mu[4]      (Reynolds number)
Reflex  =  0.3648270865e6**(in/ft)
Convert(ToFt)Reflex
Reflex  =  0.304022572e5
epsilon  =  0.00015**ft      (commercial steel pipe roughness)
fflex  =  FrictionFactor3(Reflex,epsilon,dflex)      (friction factor)
fflex  =  0.2575627596e-1
```

The flexible hose K factor:

```
Kflex  =  fflex*Lflex/dflex
Kflex  =  1.3522044881**(ft/in)
Convert(ToFt)Kflex
Kflex  =  16.2264538579
```

Pressure Drop

The K factor for the reducer is:

```
Kred  =  0.15
```

The total K factor is:

```
Kt  =  Kred+Kflex
Kt  =  0.1637645385e2
```

Find the pressure drop.

```
dp[4]  =  Kt*rho[4]*vflex^2/(2*gc)      (pressure drop)
dp[4]  =  0.3144769464e3**(lbf/ft^2)
Convert({ToIn,{lbf<-psi*in^2}})dp[4]
dp[4]  =  2.1838676837**psi
```

(4.5) MINOS Hall 1 1/2 inch Pipe Pressure Drop, Section 5

The pressure at the entrance of setion 3 is

```
p[5]  =  p[4]+dp[4]
p[5]  =  17.2533417558**psia
Convert({ToIn,{lbf<-psi*in^2}})p[5]
p[5]  =  17.2533417558**psia
```

Mass flow rate.

```
w[5]  =  Wf
w[5]  =  507.4999196497**(lb/hr)
```

To simplify the calculations, assume the argon temperature to be 1200 F.

Fluid properties

```
T[5]  =  (460+1200)**R
T[5]  =  1660**R
```

The density and viscosity of the argon is:

```
rho[5]  =  3.803e-2**(lb/ft^3)
mu[5]  =  3.54232e-5**(lb/(ft*s))
```

Piping Description

Pipe length

```
Le[5]  =  6**ft
```

Number of long radius 90 degree weld elbows:

```
nel90  =  2
```

Pipe size

```
od[5]  =  1.900**in      (outside diameter 1 1/2 in pipe)
wall[5]  =  0.109**in      (wall thickness 1 1/2 in sch 10 pipe)
Convert(ToFt)od[5]
od[5]  =  0.1583333333**ft
Convert(ToFt)wall[5]
wall[5]  =  0.9083333333e-2**ft
```

Internal diameter and flow area

```
id[5]  =  od[5]-2*wall[5]      (internal diameter)
id[5]  =  0.1401666666**ft
a[5]  =  Pi*id[5]^2/4      (flow area)
a[5]  =  0.1543047773e-1**(ft^2)
```

K factors

Determine velocity, Reynolds number and friction factor. Some of the fittings in this section of piping have a larger diameter than 1 1/2 inch sch 10 pipe. It will be conservatively assumed that all fittings are 1 1/2 pipe.

```
v[5]  =  w[5]/(a[5]*rho[5])      (velocity)
v[5]  =  0.8648290716e6**(ft/hr)
Convert(ToSec)v[5]
v[5]  =  240.230297685**(ft/s)
Re[5]  =  id[5]*v[5]*rho[5]/mu[5]      (Reynolds number)
Re[5]  =  0.3615022952e5
epsilon  =  0.00015**ft      (commercial steel pipe roughness)
f[5]  =  FrictionFactor3(Re[5],epsilon,id[5])      (friction factor)
f[5]  =  0.2544279007e-1
```

The K factor due to straight pipe length:

```
Kle  =  f[5]*Le[5]/id[5]
Kle  =  1.0891087306
```

From Crane Tech Paper 410, page A-29, the K factor for each 90 degree elbow is:

```
kel  =  16.0*f[5]
kel  =  0.4070846411
```

The entrance K factor is for a sharp edged entrance into the pipe.

```
Kin  =  0.5
```

From Fike Technical Bulletin TB8104, the certified flow factor for a Fike 1 1/2 inch, ASME code stamped, SRL burst disc. The Kr factor is what is often called a flow coefficient or K factor.

```
Kr  =  0.38
```

Through tee K factor, Crane Tech Paper 410 p A29:

```
Kttee  =  20*f[5]
Kttee  =  0.5088558013
```

Branch tee K factor, Crane Tech Paper 410 p A29:

```
Kbtee  =  60*f[5]
Kbtee  =  1.5265674041
```

Pressure Drop

The total K factor is:

```
Kt  =  Kle+nel90*kel+Kr+Kttee+Kbtee+Kin
Kt  =  4.8187012184
```

Find the pressure drop.

```
dp[5]  =  Kt*rho[5]*v[5]^2/(2*gc)      (pressure drop)
dp[5]  =  0.164352695e3**(lbf/ft^2)
Convert({ToIn,{lbf<-psi*in^2}})dp[5]
dp[5]  =  1.1413381601**psi
```

(4.6) Cryostat Pressure

The cryostat pressure is:

```
p[6]  =  p[5]+dp[5]
p[6]  =  18.3946799161**psia
```

summarize the calculations

```
process point 1    pressure drop  = 0.4660481901**psi     pressure = 14.3**psia
process point 2    pressure drop  = 0.3623328685e-1**psi     pressure = 0.1476604819e2**psi
process point 3    pressure drop  = 0.1860849561**psi     pressure = 14.8833891159**psia
process point 4    pressure drop  = 2.1838676837**psi     pressure = 15.0694740721**psia
process point 5    pressure drop  = 1.1413381601**psi     pressure = 17.2533417558**psia
process point 6    pressure drop  = ---    pressure = 18.3946799161**psia
```

Determine the cryostat using atmospheric pressure (which is lower than in MINOS hall)

```
Pcryostat  =  p[6]-14.3**psia
Pcryostat  =  4.094679916**psi
```

The maximum cryostat pressure for the fire case is less than its MAWP. Therefore the vent system is properly sized for all three cases: fire, loss of vacuum and heater power.