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ANALYSIS OF HIGH VACUUM SYSTEMS USING SINDA'85

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SUMMARY

This paper contains the theory, algorithms, and test data correlation analysis of a math model developed to predict performance of the Space Station Freedom Vacuum Exhaust System. The theory used to predict the flow characteristics of viscous, transition and molecular flow is presented in detail. Development of user subroutines which predict the flow characteristics in conjunction with the SINDA'85/FLUINT analysis software are discussed. The resistance-capacitance network approach with application to vacuum system analysis, is demonstrated and results from the model are correlated with test data.

The model was developed to predict the performance of the Space Station Freedom Vacuum Exhaust System. However, the unique use of the user subroutines developed in this model and written into the SINDA'85/FLUINT thermal analysis model, provides a powerful tool that can be used to predict the transient performance of vacuum systems and gas flow in tubes of virtually any geometry. This can be accomplished using a resistance-capacitance (R-C) method very similar to the methods used to perform thermal analyses.

NOMENCLATURE

A	cross-sectional area of tube in square centimeters
D	diameter of tube (I.D.) in centimeters
G	conductance in liters per second
L	length of tube in centimeters
M	molecular weight in kilograms per mole
P_1	upstream pressure in torr
P2	downstream pressure in torr
P_∞	vacuum pressure in torr
Q	throughput in torr-liters per second
T	temperature in Kelvin
f	friction factor
g	acceleration due to gravity
r	radius of tube in centimeters
γ	specific heat ratio
ρ	density
η	viscosity in poises
r	radius of tube in cm

Subscripts:

mol	molecular regime
trans	transitional regime
visc	viscous regime

INTRODUCTION

The model presented in this text was developed to predict the characteristics of gases as they flow through tubes or other system components. The model is capable of predicting the pressure and throughput of gases in the viscous, transition, and molecular flow regimes. In addition, the model is capable of incorporating a characteristic pump curve as a boundary condition. The model was developed to predict the performance of the Space Station Freedom Vacuum Exhaust System. However, the unique use of the user subroutines developed in this model and written into the SINDA'85/FLUINT thermal analysis model, provide a powerful tool that can be used to predict the transient performance of vacuum systems and gas flow in tubes of virtually any geometry

THEORY

As a gas flows through a tube or system component a pressure drop is experienced. The flow regime that occurs in a tube depends on the size of the tube, temperature of the gas, pressure in the pipe, and the type of gas. From Reference 1, molecular flow prevails at low gas densities where the mean free path or the average distance a molecule travels between successive intermolecular collisions is large compared to the tube cross section. As the mean free path shortens for higher pressure conditions, intermolecular collisions will predominate rather than collisions with the walls of the tube. Such a high density gas flow is called viscous or continuum flow. In this flow regime the velocity profile is nearly parabolic. The mathematical relationships used to describe viscous flow depend on whether it is laminar, turbulent, incompressible, compressible, or critical. A complex transition region exists between the molecular and viscous regimes. Transition flow occurs when the molecular mean free path is about equal to the dimensions of the pipe. At this point, the flow is partially viscous and partially molecular in character.

In space related vacuum systems, a vessel, usually at or above atmospheric pressure, will be allowed to vent through a series of manifolds, pipes and non-propulsive vents to the vacuum of space. The flow will therefore start out in the viscous flow regime and progress through the transition regime to the molecular regime. In the test case discussed later in this paper, a pump was used to evacuate a chamber from 760 Torr down to 1×10^{-4} Torr. The following sections will discuss the theory and equations used to characterize the viscous, transition, and molecular flow regimes in this exercise. In addition, the R-C network approach used to model the flow will be discussed.

In the R-C network approach, the fluid flow is divided into discrete sections called nodes. As gas passes through the section of pipe connecting the node centers, a resistance to the flow exists, so that between the points a pressure difference is seen. In fact, no net flow will take place if this pressure difference does not exist. By an analogy with an electrical circuit, we define a *conductance* between the two points such that the flow rate through the system is the product of the conductance and the pressure difference, i.e.,

$$Q=(P_1-P_2)G \hspace{2cm} (2.1)$$

Where;

Q = Mass flowrate or throughput from node 1 to node 2 (Torr-liters/sec)
$P1$ = Pressure at the center of node 1 (Torr)
$P2$ = Pressure at the center of node 2 (Torr)
G = Conductance from the center of node 1 to the center of node 2 (liters/sec)

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Assuming no leaking or accumulation of gas in the system, Q will remain constant for any given time at node 1 and node 2 in the system. The R-C network analogy applied to fluid problems will allow use of the thermal analysis code SINDA'85/FLUINT to solve for transient pressures and throughputs at discrete points which represent the vacuum system. The FWDBK solution routine which applies the "Crank-Nicholson" implicit forward/backward differencing method to the R-C network will be used to perform the required calculations. For further details on the "Crank-Nicholson" method the reader is directed to References 3 & 4.

Since the method developed here applies to a specific type of vacuum system and many characteristics of the flow are known, a number of simplifying assumptions can be made.

1) The flow is isothermal. Past experience in the design and testing of vacuum systems has shown that in piping practice the isothermal assumption is a valid assumption.
2) The gas behaves as an ideal gas. The gas in this case is air which is assumed to be an ideal gas. However, any other ideal gas could be modeled using the methods presented in this paper.
3) Steady Flow. There is no accumulation of gas in the system.
4) The friction factor is constant along the pipe. The piping used in this case was stainless steel. In most vacuum systems, the piping material will be high grade to prevent outgassing. This usually translates into a uniform friction factor.
5) The flow is compressible in the viscous regime (Mach number of greater than 0.3).
6) The flow is fully developed. The velocity profile is the same at any position along the tube length.

The equations illustrated in this paper were developed using these assumptions.

The viscous flow regime is defined as the state in which the main form of energy and momentum transfer of the gas molecules is due to intermolecular collisions. This state occurs for high density gases where the mean free path of the gas molecules is small compared to the physical dimensions of the tube walls. When molecules of the gas collide with each other they do not lose momentum. Only when they collide with the wall of the tube do they reduce their momentum. Therefore, the throughput Q, is expected to be highest in the viscous flow regime. Since the Space Station Freedom Vacuum Exhaust system is designed so that choking will occur at the exit (i.e. the non-propulsive vent valve), the compressibility effects of the gas will dominate the flow equations (see assumption 5).

The maximum velocity of a compressible fluid in a pipe is limited by the velocity at which a pressure wave may be propagated through the fluid medium. This velocity is the speed of sound in the fluid. If the flow is choked, the mass throughput no longer depends own the downstream pressure. Choked areas in the vent system will be identified by a comparison of the downstream and upstream pressure ratio (P$_C$). From Reference 5, the equation used to determine P$_C$ is given by;

$$P_C = \frac{2}{(\gamma+1)}^{\frac{\gamma}{(\gamma-1)}}$$ (2.2)

Locations in the vent system where the ratio of the downstream node pressure and the upstream node pressure is greater than P$_C$ are considered unchoked. From Reference 5, compressible pipe flow equations used to determine conductance (G) and throughput (Q) for unchoked locations in the system are given by ;

$$G_{unchoked} = \left[\frac{\rho \, g \, A^2}{\frac{fL}{D} + 2\ln\left(\frac{P_1}{P_\infty}\right)} \right]^{\frac{1}{2}}$$ (2.3)

$$Q_{unchoked} = G_{unchoked}(P_1 - P_2) \qquad (2.4)$$

Locations in the vent system where the upstream and downstream node pressure are less than P_C are considered choked. Again from Reference 5, the conductance and throughput between two nodes in chocked flow is given by

$$G_{choked} = \frac{C_d A \sqrt{\gamma g \rho}}{\sqrt{P_1}} \left(\frac{P_1}{P_1 - P_\infty}\right) \qquad (2.5)$$

$$Q_{choked} = G_{choked}(P_1 - P_2) \qquad (2.6)$$

The Space Station Freedom Vacuum Exhaust System is designed to choke only at the non-propulsive vent (the exit) however, this method will allow the user to predict where choking may occur.

The transitional flow regime is characterized by both viscous and molecular flow properties. Transition flow occurs over a range of two or three decades of pressure where the molecule-to-wall collision pattern decreases and gives way to the intermolecular collision conditions which characterize viscous or continuum flow. Flow in the transition regime is not well understood but a great deal of experimental work has been done to investigate the region (see References 6, 7 & 8). An empirical expression given by Reference 1 describes the transition flow regime adequately as;

$$Q_{tran} = Q_{visc} + \left(\frac{1 + 0.828\left(\frac{r}{L}\right)^{\frac{1}{2}}}{1 + 1.11\left(\frac{r}{L}\right)^{\frac{1}{2}}}\right) \cdot Q_{mol} \qquad (2.7)$$

where Q_{visc} and Q_{mol} are defined as,

$$Q_{visc} = \frac{\pi r^4}{12 \eta L}\left(P_1^2 - P_2^2\right) \qquad (2.8)$$

$$Q_{mol} = \left(\frac{8 r}{3 L\left[1 + \frac{1}{\left(3 + \frac{3 L}{7 r}\right)}\right]}\right) \cdot 11.43 \ r^2 \left(\frac{T}{M}\right)^{\frac{1}{2}} (P_1 - P_2) \qquad (2.9)$$

and the conductance equation is as follows,

$$G_{tran} = \frac{Q_{tran}}{(P_1 - P_2)} \qquad (2.10)$$

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Transition pressure is the pressure at which the flow departs *significantly* from the parabolic velocity profile that characterizes viscous flow. From Reference 2 the transitional pressure (P_t) is calculated from;

$$P_t = 95.7(T/M)^{1/2}(\eta/D)$$

Where;

P_t = Transition pressure.(Torr)

η = Viscosity of the Gas (Poissions)
T = Temperature of the gas (°K)
D = Diameter of the pipe (cm)
M = Molecular Weight (Kg/Kmole)

From Reference 2 the lower limit of the transition range is given by;

$$P_l = 0.114 \, P_t \qquad (2.11)$$

Where;

P_l = Lower pressure limit of the transition regime (Torr)
P_t = Transition pressure (Torr).

This is the pressure where the flow goes from transition to molecular flow. The upper limit of the transition flow regime is given by;

$$P_u = 9.91 \, P_t \qquad (2.12)$$

Where;

P_u = Upper pressure limit of the transition regime (Torr)
P_t = Transition pressure (Torr).

This is the pressure where the flow changes from viscous to transition flow.
Using these equations, we can determine when the flow is in the viscous, transition, or molecular flow regimes based on the pressure. With this information, we can calculate conductance and throughput with the correct formulation.

Molecular gas flow is defined by the state at which the mean free path of the gas molecules is very large compared to the dimensional parameters of the tube. Gas molecules move in random straight lines impinging on the tube walls where at impact the molecule is stopped and randomly remitted. Any molecule that strikes the tube wall loses directional momentum because equal probability exists for it to proceed upstream or downstream after impact. The probability of the molecule traveling in any direction depends mainly on a solid angle defined by the length of the tube (l) and the tube radius (r). According to Reference 1, the probability of a molecule passing through the tube without striking the tube wall is a function of the ratio l/r which defines an attenuation factor applicable to the directional energy incident of the tube. Reference 6 has shown that the attenuation factor equals (8/3)x(r/l) for long tubes of circular cross section. From Reference 1, the throughput is given by;

$$Q_{mol} = \left(\frac{8 \, r}{3 \, L\left[1 + \frac{1}{\left(3 + \frac{3 \, L}{7 \, r}\right)}\right]}\right) \cdot 11.43 \; r^2 \left(\frac{T}{M}\right)^{\frac{1}{2}} (P_1 - P_2) \qquad (2.13)$$

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and the conductance equation is as follows;

$$G_{mol} = \frac{G_{mol}}{(P_1 - P_2)}$$

(2.14)

During a point in the transient depressurization process, the outgassing and leakage effects in the system will tend to dominate the throughput results in the molecular flow regime. This will cause the analytical results to trend toward a steady-state solution.

DETAILS OF THE SINDA'85/FLUINT MODEL

The SINDA'85/FLUINT model was developed to provide the analysts a tool to predict the performance of vacuum systems in an accurate and efficient manor. By applying the methods described in the theory section of this paper, the analysts can quickly evaluate proposed vacuum system designs and provide transient data to support any conclusions. The SINDA'85/FLUINT solver is a widely used code that was developed under government contract with the National Aeronautics and Space Administration (NASA) and is available through the Computer Software Management and Information Center (COSMIC) ,located at the University of Georgia, for a nominal fee. The model has the flexibility of predicting characteristics of flow through the viscous, transition, and molecular flow regimes. The model can simulate a blowdown to the space environment or a pumpdown using any pump for which an accurate pump curve exists. The flow block diagrams Shown in Figures one through four illustrate the logic used in the overall model and the major subroutines.

The model requires input from the analysts in several sections. The following paragraphs will identify specific parts of the SINDA'85/FLUINT model that require user input along with specific examples from the test model. The explanations will assume that the reader has some prior knowledge of the SINDA'85/FLUINT solver.

The first step to building any model is to divide the system to be modeled into discreet nodal segments connected by conductors. Figure 5 illustrates how the test setup was nodalized. The size of the nodes is dependent on the geometry and the locations where pressure and throughput data is required. For example, if a test set is to be analyzed, the analysts will want a node center at each location where pressure readings are to be made. In addition, points where diameter changes exists are candidates for node divisions. It should be noted, that runtime on the computer is proportional to the number of nodes present. In our test case, with smooth stainless steal piping, it was found that a course nodalization produced the same results as a fine nodalization.

As with all SINDA'85/FLUINT models, this is the section where the nodalization is defined. The following is the Header Node Data section from the test case model;

```
C *****************************************************************
HEADER NODE DATA,   VAC
C *****************************************************************
C
        1,              760.0,   250000.0     $ Tank
     GEN 2,   5,   1,   750.0,       -1.0     $ Line
     -9999,              760.0,       -1.0     $ Space
```

Of course, the normal SINDA'85/FLUINT designations for boundary nodes and arithmetic nodes is used. However, instead of an initial temperature in the second field, insert the initial pressure guess in Torr (example 760.0 Torr). In field 3, in place of the normal mass entry, insert the volume of the node segment in milliliters (example 250000.0 ml). In the test case all the volume
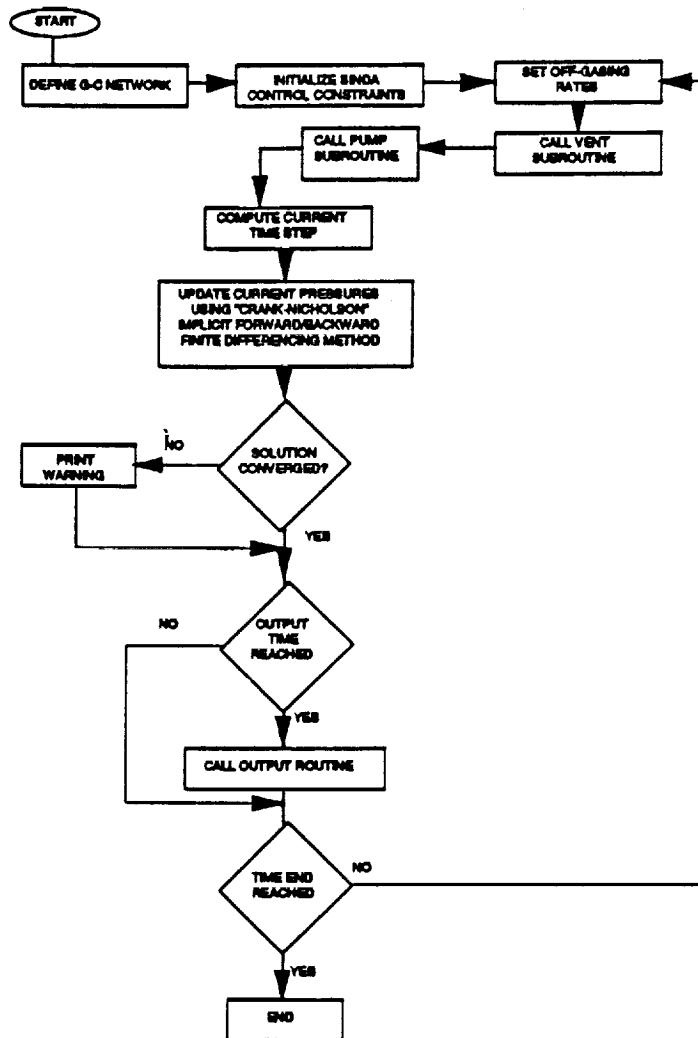
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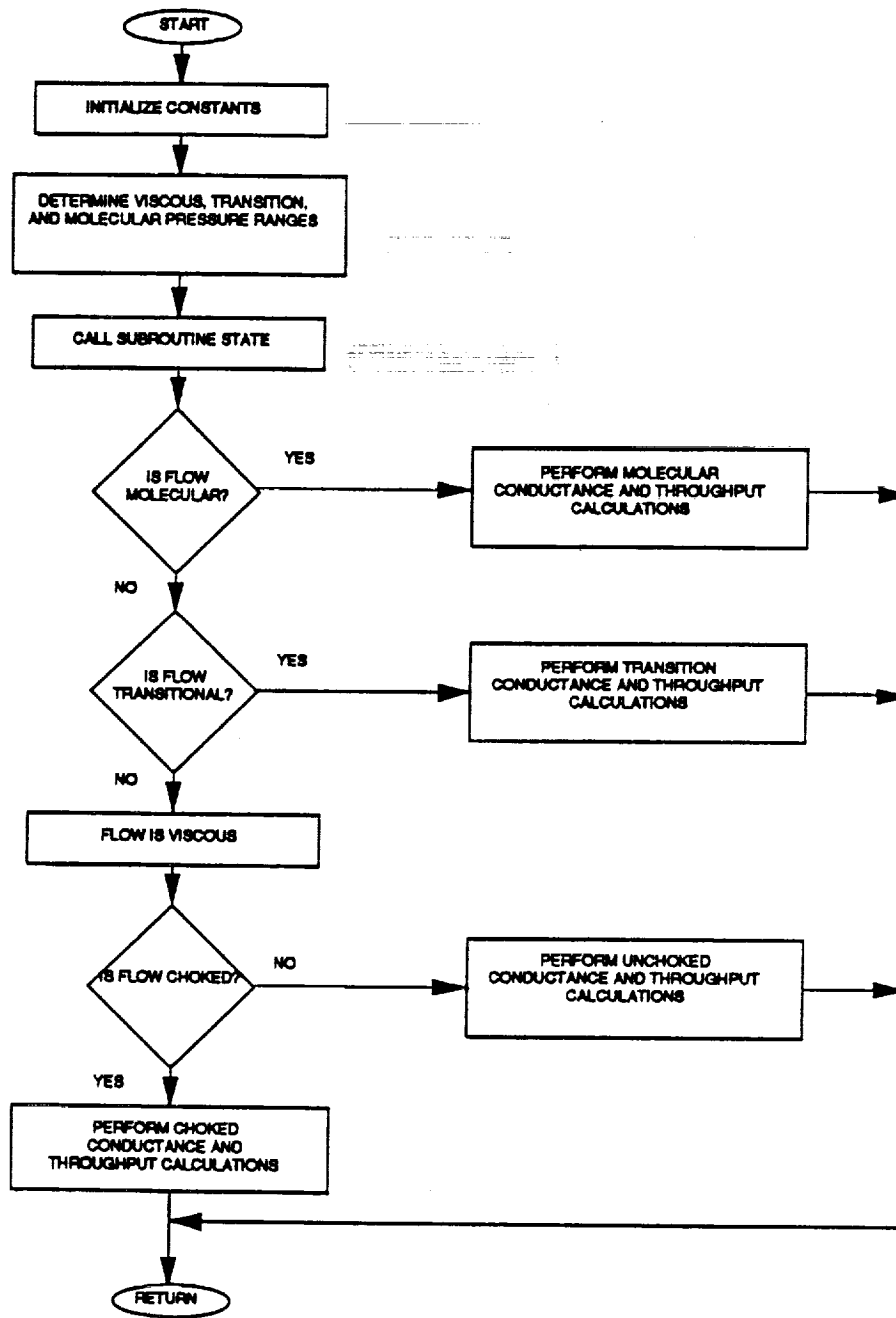Figure 1. Model Overall Logic Flow Chart
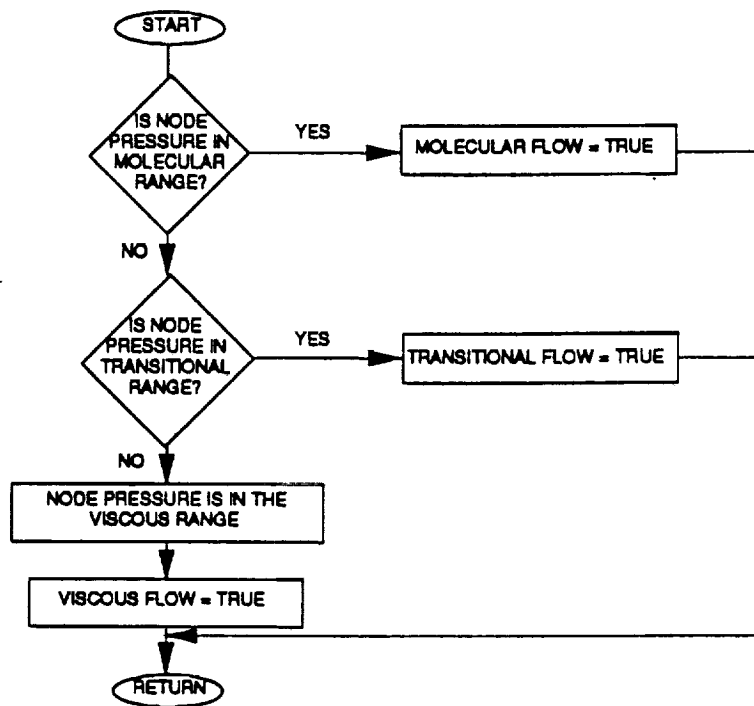
Figure 2. Vent Subroutine Logic Flow
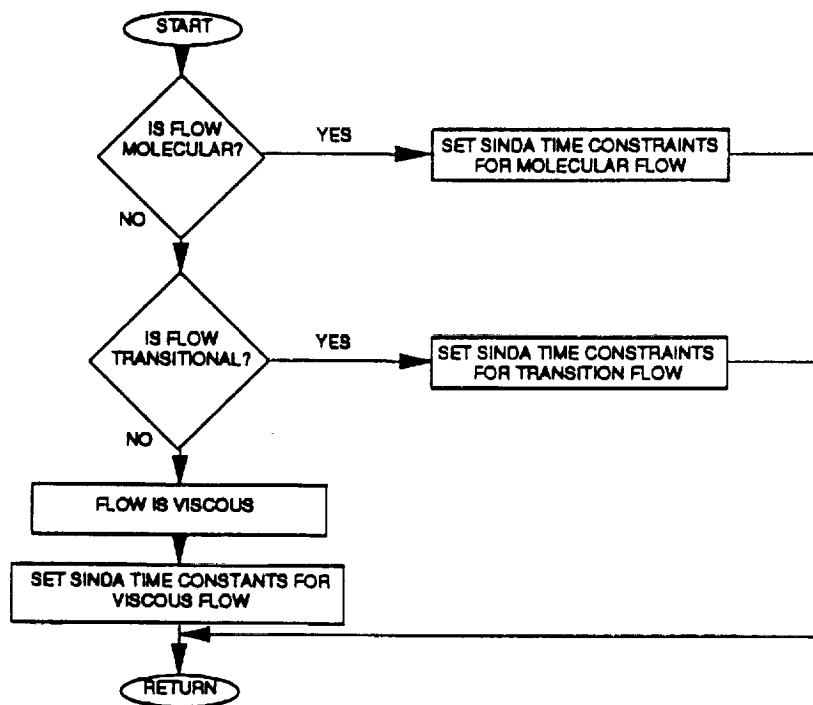
Figure 3. State Subroutine Logic Flow

Figure 4. Timestep Subroutine Logic Flow

was lumped into the tank node, and the line nodes were modeled as arithmetic nodes. (See Reference 4 for further definition of an arithmetic node and the Header Node Data section.)

Again, as with all SINDA'85/FLUINT models, this is the section where the conductor designations are made. The following is the Conductor Data section from the test case model;

```
C *****************************************************************
HEADER CONDUCTOR DATA, VAC
C *****************************************************************
C
C  Main Vent Line
         GEN 1, 5, 1, 1, 1, 2, 1, 1.0    $ Vent Line Conductors
             6,        6, 9999,    1.0    $ G B/t Vent Valve And Space
```

Since the actual conductor values are calculated by the user subroutines developed in this exercise, this section serves mainly to generate and designate the conductors between the nodes defined in the Header Node Data section. Again, the normal rules for developing SINDA'85/FLUINT models is followed in this section. (See Reference 4 for further details concerning SINDA'85/FLUINT models.)

The Header Control Data section of any SINDA'85/FLUINT model is the section where convergence is controlled. Therefore, this is a very important section of the model, especially since the pressure differences in the molecular region can be as small as 1×10^{-6} Torr. Therefore, the tolerances must be very tight or the numerical solution will converge to quickly yielding incorrect results. On the other hand, if the tolerances are set to tight, the solution will require several loops and a large amount of computer time to converge. The control data section of the test case model is as follows;

```
C *****************************************************************
Header Control Data,  Global
C *****************************************************************
C
C      Time in Minutes
       ARLXCA  =  1.E-6
       DRLXCA  =  1.E-6
       TIMEO   =  0.0
       TIMEND  =  200.0
       OUTPUT  =  0.01667
       NLOOPT  =  500
       UID     =  SI
       PATMOS  =  0.00
       ABSZRO  =  0.0
```

As with all SINDA'85/FLUINT models, ARLXCA defines the relaxation criteria for the arithmetic nodes defined in the Header Node Data section. In the same way, DRLXCA defines the relaxation criteria for the diffusion nodes defined in the Header Node Data. It should be noted that ARLXCA and DRLXCA are set equal to 1×10^{-6} Torr. Since the test case yielded tank pressures of 1×10^{-4} Torr, two orders of magnitude lower than the lowest expected pressure is a good first guess. It is not uncommon for it to require 50 to 100 loops for the solution to converge. Therefore, NLOOPT should be set to 200 to 500 loops. In addition, ABSZRO is used in thermal models to tell SINDA that the model requires the absolute temperature scale. Since we are working in an absolute pressure scale and the pressures should never be less than zero, ABSZRO should be set to 0.00. UID, PATMOS, TIMEO, and TIMEND have the same meaning as in any other SINDA'85/FLUINT model. (See Reference 4 for further details concerning SINDA'85/FLUINT models.)

The HEADER USER DATA. Sbn section of the model is used to initialize the flow through each node so that the model does not fail on the first loop when the flow is just getting started. The flow should be initialized at a very low value but some value greater than zero. From the test case the Header User Data section is as follows;

```
C ***********************************************************************
Header User Data,  VAC
C ***********************************************************************
C
C  Initialize Nodal Throughput Values
            1 = 0.0001
            2 = 0.0001
            3 = 0.0001
            4 = 0.0001
            5 = 0.0001
            6 = 0.0001
C
```

Note that each node except the boundary node must be initialized.

The Header Variables 1 section of the Vacuum System Analysis Model is the most important. In this section, outgassing rates are defined, the vent subroutines are called, the pump subroutine is called, and the timestep subroutine is called. A detailed explanation of each of these subroutines is included in this paper. The Variables 1 section of the test case is as follows;

```
C ***********************************************************************
Header Variables1, VAC
C ***********************************************************************
C
C  Outgassing Rates For Tubes, Pumps, Flexlines
          Q1 = 2.358E-1
          Q2 = 7.688E-1
          Q3 = 7.688E-1
          Q4 = 1.24E-1
          Q5 = 2.00E-2
          Q6 = 2.00E-2
C
C  CALL STATEMENT FOR SUBROUTINE - VENT(G, TI, TJ, MDOT, DIA, L)
C  DETERMINES IF THE FLOW IS IN THE TRANSITION PRESSURE RANGE AND        C
CALCULATES A CONDUCTANCE (G), AND MDOT.
C
C  G - CONDUCTANCE (mL/MIN)
C  TI - DOWNSTREAM PRESSURE (TORR)
C  TJ - UPSTREAM PRESSURE (TORR)
C  MDOT - MASS FLOWRATE (KG/MIN)
C  DIA - DIAMETER (CM)
C  L - LENGTH (CM)
C
M     CALL MEPUMP(T9999, TIMEN,DTIMEU)
M     CALL VENT(G1, T1, T2, XK1, 3.81,327.66,ITEST)
M     CALL VENT(G2, T2, T3, XK2, 9.76,523.875 ,ITEST)
M     CALL VENT(G3, T3, T4, XK3, 9.76,1047.75,ITEST)
M     CALL VENT(G4, T4, T5, XK4, 9.76,287.6 ,ITEST)
M     CALL VENT(G5, T5, T6, XK5, 9.76,77.3,ITEST)
M     CALL VENT(G6, T6, T9999, XK6, 3.81, 50.,ITEST)
M     CALL TIMESTEP(T1, 4.76, DTIMEH, OUTPUT)
C
F     ITEST = ITEST + 1
C
```

Outgassing is defined as the release of gases or vapor absorbed by a material. Outgassing rates are a characteristic of the piping material. In the test case the material was stainless steal with an outgassing rate of 1×10^{-9} Torr-liters/sec-cm^2. Therefore, to calculate the outgassing rate for a single node the surface area represented by the node is multiplied by the outgassing rate of the pipe material.

The first subroutine called is the MEPUMP subroutine which is used in the test case to determine the pressure of the pump based on the pump curve. The user must make sure that the node representing the pump (in this case 9999) is included with a preceding T as the first entry in the MEPUMP call statement.

Each conductor defined in the Header Conductor Data section must have a corresponding call statement as follows;

M   CALL VENT(Gn, Tn1, Tn2, XKn1, D,L ,ITEST)

> Where;
>
> Gn1   = Number designation of the conductor to be calculated
> Tn1   = Node number of the first node in the conductor
> Tn2   = Node number of the second node in the conductor
> XKn1   = Designation for the throughput at the first node in the conductor
> D   = Diameter of the pipe between the node centers (cm)
> L   = Distance between the node centers (cm)
> ITEST = Dummy variable that flags the first timestep.

In order to aid in convergence and reduce the required computation time, the time step is different for each flow regime. The timestep should be smallest in the viscous flow regime, larger in the transition regime and largest in the molecular flow regime. In order to insure that the best time step is chosen for the solution, the user should choose the node most distant from the space node or pump boundary to base the time step calculation. In the call statement;

M   CALL TIMESTEP(T1, 4.76, DTIMEH, OUTPUT)

The user must enter the number of the node on which the time step is to be based preceded by a "T" (T1 in this case) and the diameter of the tank or pipe that the node represents (4.76cm in this case) in centimeters.

The Header Subroutine Data section of the model is the section that was written to provide SINDA'85/FLUINT with the ability to model vacuum systems. Therefore these subroutines are the heart of the model. The user does not have to provide any input into the TIMESTEP subroutine. However, the MEPUMP & VENT subroutines require the user to input a representation of the pump curve and material constants of the gas.

The vent subroutine is a FORTRAN code that uses the equations discussed in the theory section of this document to calculate the conductance between the two nodes in the call statement The calculations for the conductance are based on the pressure results from the previous time step. The first portion of the routine initializes the material properties of the gas. In the test model the gas was air and the vent subroutine is as follows;

```
C
F          SUBROUTINE VENT(G, TI, TJ, MDOT, D, L, ITEST)
C
FSTART
C
C          THIS SUBROUTINES DETERMINES THE CONDUCTANCE (G) AND MDOT OF THE FLOW
C          UNITS:  G(mL/MIN), TI(TORR), TJ(TORR), MDOT(KG/MIN), D(CM), L(CM)
C
C   DECLARE REAL AND LOGICAL VARIABLES
```

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```fortran
      REAL G,TI,TJ,MDOT,D,L,RBAR,MBAR,PI,T,VISC
      REAL AC,LC,F,GRAV,GAM,RA,LP,Z,K,COM,QM,QV,QT
C     REAL K1,K2
C
C
C  INITIALIZE CONSTANTS AND SET AIR PROPERTIES:
C  MBAR(MOL.WT KG/KMOLE),RBAR(UNIV.GAS CONST.(KN-CM/KMOL-K),
C  T(TEMP K),VISC(POSSIONS),AC(THROAT AREA M^2), DENS(KG/M^3)
      MBAR = 28.97
      RBAR = 83.144
      T = 300.0
      VISC = 1.85E-4
      GAM = 1.4
      PI = 3.141592654
      GRAV = 32.2
      DELTAP=TI-TJ
      IF (DELTAP .LE. 0.0) DELTAP = 0.001
C
```

If the vent system is being modeled using a fluid other than air MBAR, VISC, T & GAM must be replaced with the appropriate constants. These constants are defined as;

$$\begin{array}{ll}
\text{MBAR} & = \text{ Molecular weight of the gas (Kg/Kmole)} \\
\text{T} & = \text{ Average temperature of the gas (°K)} \\
\text{VISC} & = \text{ Viscosity of the gas (Poissions)} \\
\text{GAM} & = \text{ Ratio of specific heats for the gas}
\end{array}$$

In some cases, the user may want to adjust the time steps used to calculate the transient pressure solution. Since each subroutine stands alone in SINDA'85/FLUINT and variables must be specifically called out in the call statement, the values of MBAR, VISC, and T must be entered into the TIMESTEP subroutine also. The subroutine that controls the timestep is as follows;

```fortran
*******************************************************************
F     SUBROUTINE TIMESTEP(TI, D, DTIMEH, OUTPUT)
C
FSTART
C
C  THIS SUBROUTINE DETERMINES THE TIMESTEP IN MINUTES
C  BASED ON THE TANK PRESSURE
C
      MBAR = 28.97
      T = 300.0
      VISC = 1.85E-4
C
C  DETERMINE PRESSURE RANGES
      PT = 95.7 * SQRT(T/MBAR) * (VISC/D)
      PU = 9.91 * PT
      PL = 0.114 * PT
C
C  DETERMINE THE FLOW STATE;  MOLECULAR, TRANSITIONAL, OR VISCOUS
      CALL STATE(PU,PL,TI,IPMOL,IPTRN,IPVISC)
      IF (IPMOL .GT. 1) THEN
         DTIMEH=1.0
         OUTPUT=1.0
      ENDIF
      IF (IPTRN .GT. 1) THEN
         DTIMEH=0.9
```

```
                OUTPUT=0.9
            ENDIF
            IF (IPVISC .GT. 1) THEN
                DTIMEH=0.09
                OUTPUT=0.09
            ENDIF
C
            RETURN
            END
C
FSTOP
C ****************************************************************
```

The user may also wish to change the timestep for the problem solution. The timestep can be changed by changing the DTIMEH and OUTPUT statements above.

The MEPUMP subroutine was included so the model could analyze a pumpdown rather than a blowdown. The pump curve for the pump used in the pumpdown must be included in the MEPUMP subroutine. The MEPUMP subroutine for the test case is as follows;

```
F           SUBROUTINE MEPUMP(TI,TIMEN,DTIMEU)
C
FSTART
C
            IF(TI .LT. 1.E-4) TI=1.E-4
C
            IF((TI .LT. 11.5).AND.(TI .GT. 1.E-4)) THEN
                TIOLD=11.5
                DT3=DT3+DTIMEU
                G = 7.7362 - 6.4009*ALOG10(TI)
                G = G *1000.*60.
                TI = TIOLD/EXP((G*DT3/350000.))
            ENDIF
C
C
            IF ((TI .GE.11.5) .AND.(TI .LT. 52.5)) THEN
                PMPSP=1.5815
                TIOLD=52.5
                DT1=DT1+DTIMEU
                G=PMPSP*1000.*60.
                TI=TIOLD/EXP(G*DT1/350000.)
                DT3=0.0
            ENDIF
            IF ((TI .GE.52.5).AND.(TI .LT. 272.5)) THEN
                PMPSP=0.7624
                TIOLD=272.5
                DT2=DT2+DTIMEU
                G=PMPSP*1000.*60.
                TI=TIOLD/EXP(G*DT2/350000.)
                DT1=0.0
            ENDIF
            IF (TI .GE.272.5) THEN
                PMPSP=.4274
                TIOLD=755.
                G=PMPSP*1000.*60.
                TI=TIOLD/EXP(G*TIMEN/350000.)
                DT2=0.0
            ENDIF
```

In the test case, the pump was a pump package that was made up of four individual pumps. Note that the quantity that is calculated in this subroutine is the pressure of the boundary node. In most cases, the pump curve supplied by the pump vendor will be in the form of a G vs P curve. Santeler (Reference 1) develops a method of calculating a pressure vs time curve from this data which is as follows;

$$P = P_0 exp(-Gt/V) \qquad (3.1)$$

Where;

P = New pump pressure (Torr)

P_0 = Pump pressure at previous timestep

G = Conductance from the pump curve (G vs P) @ P_0

t = Timestep (min)

V = System volume

The MEPUMP subroutine used in the test case is discussed further in the next section of this paper.

TEST CASE

The test case was conducted to validate the assumptions, methods, and algorithms described in this paper. The test involved modeling a vacuum test that had two different size pipes, flex lines,valves, and a pump package. The addition of the pump package complicated the modeling because the vendor data was not complete and the pump package contained 4 different pumps that became effective at different pressure ranges.

The layout of the test setup is shown in Figure 5 . The test fixture consisted of a 250 liter chamber connected to the VES1 header (9.78cm I.D.x101.60cm) by a 3.81cm I.D. x 91.44 cm branch line (similar to the line used to attach Space Station payloads to the Vacuum Exhaust System). Also included in the test setup was a pump package connected to the VES1 header by a 3.81cm I.D. X 91.44 cm branch line. The object of the test was to pump the vacuum chamber from atmospheric conditions (760 Torr) down to $1x10^{-4}$ Torr. The tank was filled with air and the VES1 header was made of stainless steal. The pump was a Trybodyne pump package that is made up of four pumps. Data collection consisted of vacuum pressure measurements recorded at the vacuum chamber. Bourdon , cold cathode, and Pirani gauges were use to measure pressure from 760 torr to 10^{-7} torr. Cold cathode gauges were the inverted magnetron design with a pressure range of 10^{-2} to 10^{-11} torr. Pirani gauges measured pressure from 200 torr to 10^{-4} torr. The bourdon gauge measured pressure from 30 psig to 0 mm Hg. The entire system was leak checked with a helium leak detector to 10^{-8} tl/s sensitivity with no measurable leaks indicated. Residual gas analysis was performed to qualify any contamination in the system. Pressure measurements were recorded manually from the gauge controller display and electronically from the gauge controller analog signal. Electronic data recording converted the raw analog signal to pressure units using a curve fit algorithm provided by the manufacturer. Data stored in the computer were then converted to Microsoft Excel and Cricket Graph format for reporting and graphics purposes.

As discussed in above, the pump package presented a modeling challenge due to the design of the Trybodyne pump. This particular model pump consists of 4 pumps in series that are effective at different pressure levels. The pump curve is shown in Figure 6. From Figure 6 we see as the pressure approaches 0 the pump curve goes to infinity and above 11.5 Torr the pump data was found to be inaccurate in previous testing.
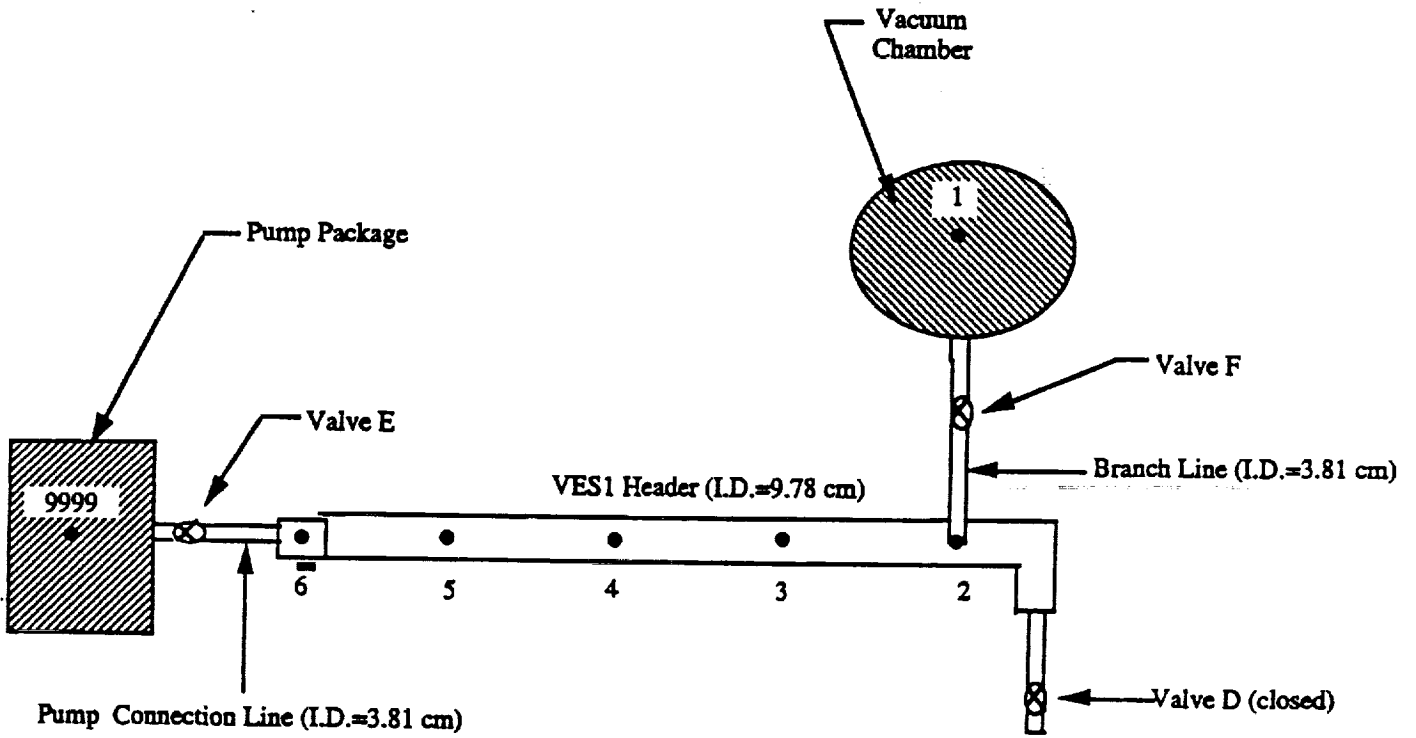
Figure 5. Vacuum Vent Test System Schematic

When the test was performed, it was found that the pump did not provide a pressure of less than 1×10^{-4} Torr. In order to model the pump in the pressure range of 760 Torr down to 11.5 Torr, the conductance was assumed to be step wise linear. With this assumption, the pump speed was calculated using equation 3.1 and pump test data. The steps over which the pump conductance was calculated were as follows;

760 Torr to 272.5 Torr
pump speed = 0.4274 l/sec

272.5 Torr to 52.5 Torr
pump speed = 0.7624 l/sec

52.5 Torr to 11.5 Torr
pump speed = 1.5812 l/sec

After the pressure of the system dropped below 11.5 Torr, the pump curve shown in Figure 6 was used to predict the conductance of the pump. It should be noted that, in a blowdown or a pumpdown, the boundary is the driver for the system and any error associated with the pump curve will translate into an error in the analysis. Therefore, it is very important to have accurate data concerning the pump performance when doing this type of analysis. The method used here to model the pump was expected to induce some error into the analysis in the pressure range from 760 Torr to 10 Torr. Greater accuracy might have been achieved if the pressure range had been divided into more steps.
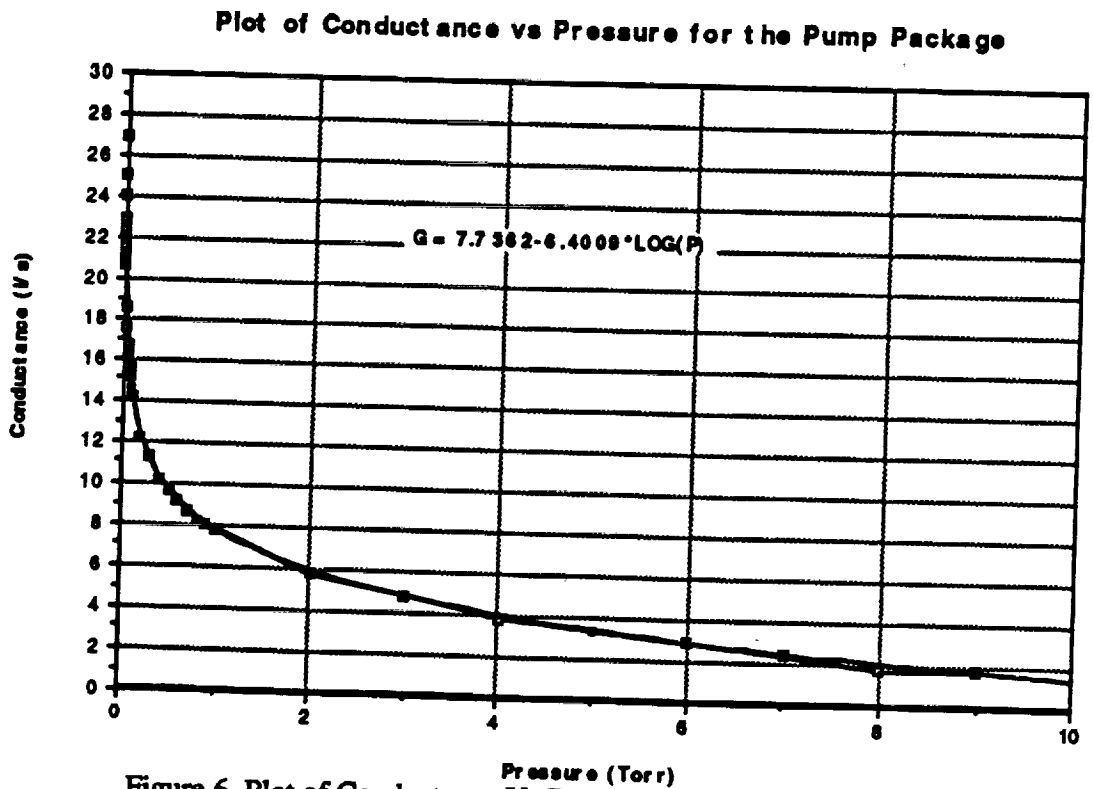

Figure 6. Plot of Conductance Vs Pressure For the Pump Package.

RESULTS AND CONCLUSIONS

Figure 7 shows the correlation between the test data and analytical results. The flow remained in the viscous regime for 33.5 minutes and was in transition for 12 minutes before molecular flow began. Results from the analytical model predicted that the tank pressure would reach steady state at 1.095×10^{-4} Torr. Test results indicate that the tank pressure would reach steady state at 1.06×10^{-4} Torr, yielding an error of 3.3 %. In addition, the trend of the results compares favorably with the test data. The largest deviation was found to be approximately 10 minutes occurring at a pressure of 20 torr. This can be attributed to the assumption of a constant pump speed in this pressure range. A review of the actual test data has shown that speed inflections did occur in this pressure range for the pump.

The results of the correlations support the validity of vacuum flow analysis using numerical solution methods. Any deviations between the test and analysis is largely due to insufficient pump data. The pump in this case was the controlling factor and any discrepancies in pump modeling would have a direct impact on the results. In situations where the evacuation process is due to a blowdown, the analytical results should show greater accuracy. This is because, in a blowdown process the boundary node would remain at a constant pressure and not be based on a pressure vs time dependency such as a pump.

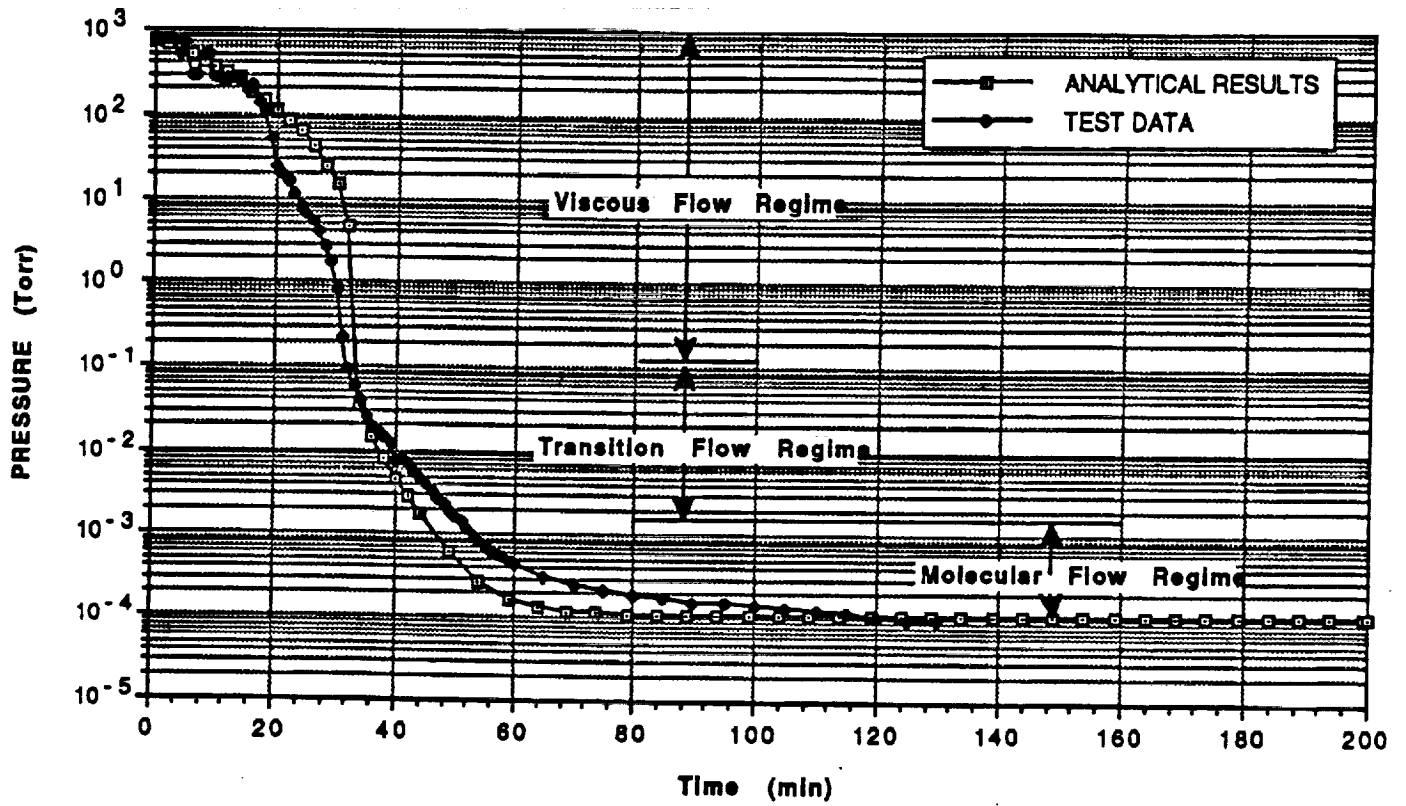# Plot of Pressure Vs Time For the Vacuum Chamber Node

Figure 7. Plot of Analytical Results and Test Results

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