

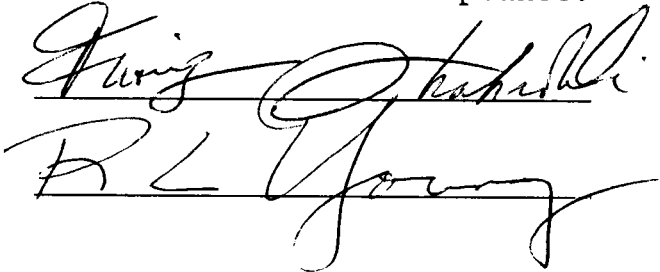
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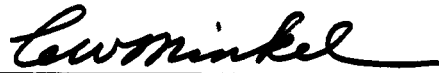


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A MONTE CARLO ANALYSIS OF THE
NASA / ESA SPACELAB VACUUM VENT VALVE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Samuel C. Edwards

December 1989

ABSTRACT

The objective of this thesis is to determine the conductance of the National Aeronautics and Space Administration (NASA) / European Space Agency (ESA) Spacelab vacuum vent valve for gases in the collisionless molecular flow regime.

Since this valve is the only vacuum access afforded to experiments residing inside the pressurized spacelab module, the value of its conductance is necessary in calculating the pressures and flow rates available to these experiments. While the conductance of the pipes connecting the experiments to the valve can be determined using previously published results, the conductance of this valve can not.

For the purposes of this thesis, the gases are assumed to have a Maxwellian speed distribution. The Monte Carlo method of numerical approximation is utilized to determine the valve conductance in this flow regime. This is done by calculating the probability that a particle entering the valve will exit it through the valve exit plane and not be reflected back to exit through its inlet plane.

This probability is approximated by generating a large number of particles at random locations on the valve inlet plane with velocity vectors conforming to the cosine law. The particles are then followed, one at a time, to determine the opening through which they exit.

If the velocity vector of a particle crosses a solid boundary, it is assumed that the particle is absorbed by that solid surface. Further, an absorbed particle is assumed to be ejected from the same location in the solid surface with a velocity vector whose direction follows the cosine law.

Flow visualization is employed to help better understand the flow phenomenon and to help isolate programming errors. To model the solid surface absorption and desorption of each particle, the ray tracing principles and approaches used in high resolution computer graphics modeling are used.

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1. PROBLEM STATEMENT / INTRODUCTION

The objective of this thesis is to determine the conductance of the National Aeronautics and Space Administration (NASA) / European Space Agency (ESA) Spacelab vacuum vent valve for gases in the collisionless molecular flow regime.

In 1987 a materials processing / crystal growth experiment was added to the manifest of the planned NASA / ESA Spacelab Japan (SL-J) pressurized cabin mission. The SL-J experiment integrator requested that NASA allow vacuum access by this experiment for the purpose of purging various gases overboard. The experiment integrator provided NASA with the interface vacuum pressure which the experiment required. NASA granted the experiment integrator's request for access to vacuum, and proceeded to determine whether the experiment interface pressure requirements could be met while staying within the guidelines of the NASA / ESA Spacelab Payload Accommodations Handbook Volume C (SPAH-C) [1]. The calculations showing the compatibility of the vacuum venting requirements of this experiment and spacelab vacuum venting system are documented in SL-J environmental control subsystem compatibility analysis report [2].

The restrictions placed on the spacelab mission integrator by SPAH-C [1] limited the vacuum line outside diameter to approximately two inches. This line outside diameter translates to an approximate inside diameter of 1.875 inches. Due to the location of the experiment inside the spacelab module, the vacuum line length was determined to be approximately 140 inches. The spacelab butterfly type vacuum vent valve had to be used due to the SPAH-C [1] requirements and restrictions. A sketch of this valve is presented as Figure 1.1.

This butterfly type valve fulfills three roles during a typical spacelab mission. These roles are: 1) emergency pressure relief, 2) emergency module air evacuation in case of fire, and 3) vacuum access point for the experiments.

The mission integrator, therefore, used the two inch outside diameter line and the spacelab vacuum vent valve to provide vacuum access to the furnace experiment. The experimenter was then to be provided with the performance specifications of the system to which his experiment was interfacing. In doing so, the integrator had to determine the flow rates through the vent line and through the vacuum vent valve in the molecular flow regime.

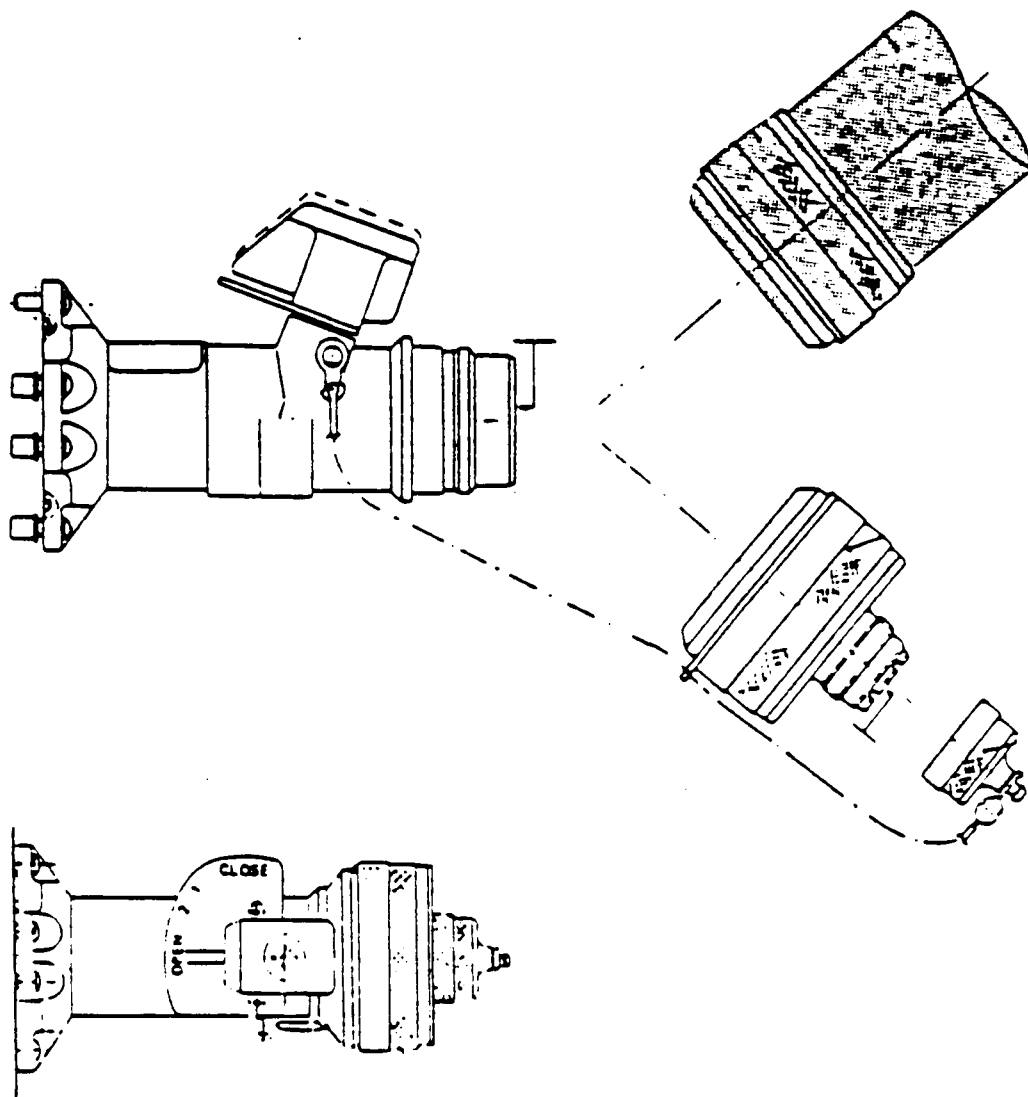


Figure 1.1 - Sketch of the NASA/ESA Spacelab Vacuum Vent Valve from SPAH-C [1]

To determine the overall flow rate, the conductance of the vacuum vent valve in this flow regime had to be determined. After consulting with the manufacturer and checking the applicable documentation (such as the SPAH-C [1]), it was determined that the NASA / ESA vacuum vent valve conductance in the molecular flow regime had never been determined. At that point an approximate value was calculated using a cylinder and an orifice.

Since the spacelab vacuum vent valve is the only approved method for experiments inside the pressurized spacelab module to access vacuum venting, and due to the ever increasing number of experimenters which require such access, it was decided that a more accurate conductance value for the vent valve was needed.

In the Fall of 1987 Dr. Frank G. Collins (University of Tennessee - Space Institute, Tullahoma, Tennessee) was approached with this problem. He suggested a literature search and a numerical approximation method called Monte Carlo.

The Monte Carlo statistical analysis method for modeling molecular flows has been in use for over three decades (Davis [3]). This method suggests that if the history of a large enough number of particles entering the

valve is known, then the conductance of the valve may be approximated by dividing the number of the particles which exited the valve through its exit plane with the total number of particles modeled.

To generate the history of a particle, its interaction with other particles and the solid boundary has to be known. According to the SL-J vacuum venting documentation [2], the flow through the valve is of the collisionless molecular flow type. The behavior of a particle in this flow regime is defined by its position and velocity vectors. It is assumed that position and velocity vectors of the particles entering the valve inlet are independent of the flow in other parts of the vacuum vent system and that they follow the Maxwell distribution law (i.e., are Maxwellian).

With the behavior of a single particle defined, the generation of a particle history involves following the particle from where it enters, through possible collisions with solid boundaries, until it exits through either the valve inlet or outlet. After a particle exits the valve, its history is terminated and a new particle is generated and followed, as before.

To perform the task of following a particle through collisions with the curved surface of a cylinder or the flat

disk shape of a butterfly valve which may be at any angle to the axisymmetric center of the cylinder, the mathematics of three-dimensional coordinate axis transformation should be mastered. Due to the perspective difficulties that were encountered with the axis transformation in the three dimensions during the initial attempts at modeling the problem, it was decided to enlist the aid of flow visualization and ray tracing methods. The mathematics involved in this type of coordinate transformation are very similar to those used for high resolution computer graphics with ray tracing.

The task of locating a software that would permit ready modeling of the valve and the tracing of the particles took some time. The resultant software, Acrospin by Acrobats [4], has all the capabilities that were needed for visualizing this type flow. During this period, a search for literature on ray tracing modeling was also performed. The book which was found to be of most use in this field rigorously explained the techniques necessary for this type modeling (Angell and Griffith [5]).

With the aid of these two visualization tools, a second attempt was made at solving the Monte Carlo problem. By this time an excellent engineering book on molecular flow in complex geometries by Saksaganskii [6] was translated

from Russian and recommended as reference. Using these three tools, a FORTRAN program was written to determine the conductance of the NASA / ESA spacelab vacuum vent valve. The conductance of this valve to molecular flow versus valve angle is listed in Table 1.1 and plotted in Figure 1.2.

The program results were validated by running pipe flow simulations. The program results for the simple pipe flow were in good agreement with those published in the literature [3,6]. These results, along with some of the results documented in the literature, are presented in Table 1.2. The program, as implemented, may be easily modified for different internal or external flow geometries. It also has the ability to simulate different surface sticking coefficients. The program may be easily modified for non-Maxwellian flows and non-engineering surfaces (ones which do not return particles with velocity vectors following the cosine probability law). Other than the simple pipe flow, however, these modifications were not performed.

To perform the Monte Carlo statistical analysis, the program uses random numbers as provided to it by the compiler. The generation of a random number by the compiler for the first time requires the input of a seed. Given the same seed, the same set of random numbers are generated.

Table 1.1 - Conductance of the NASA/ESA Spacelab Vacuum Vent Valve to Flow in the Collisionless Molecular Flow Regime as a Function of Valve Angle, Using 100,000 Particle Monte Carlo Simulation.

Valve Angle (Degrees)	Conductance	Valve Angle (Degrees)	Conductance
0.0	0.00000	41.0	0.27121
1.0	0.05416	42.0	0.27667
2.0	0.06110	43.0	0.27804
3.0	0.06602	44.0	0.28126
4.0	0.07139	45.0	0.28594
5.0	0.07730	46.0	0.28676
6.0	0.08261	47.0	0.28859
7.0	0.08808	48.0	0.29282
8.0	0.09507	49.0	0.29268
9.0	0.10032	50.0	0.29249
10.0	0.10650	51.0	0.29293
11.0	0.11168	52.0	0.29309
12.0	0.11859	53.0	0.29030
13.0	0.12299	54.0	0.29309
14.0	0.12917	55.0	0.29125
15.0	0.13456	56.0	0.29208
16.0	0.13793	57.0	0.29185
17.0	0.14727	58.0	0.28988
18.0	0.15151	59.0	0.29438
19.0	0.15971	60.0	0.29164
20.0	0.16483	61.0	0.29186
21.0	0.16946	62.0	0.29051
22.0	0.17612	63.0	0.29085
23.0	0.17985	64.0	0.29272
24.0	0.18668	65.0	0.28844
25.0	0.19351	66.0	0.29239
26.0	0.19821	67.0	0.29286
27.0	0.20318	68.0	0.29275
28.0	0.20964	69.0	0.29247
29.0	0.21513	70.0	0.29347
30.0	0.21959	71.0	0.29011
31.0	0.22589	72.0	0.29332
32.0	0.23008	73.0	0.29194
33.0	0.23241	74.0	0.28939
34.0	0.23992	75.0	0.29136
35.0	0.24495	76.0	0.29295
36.0	0.24869	77.0	0.29095
37.0	0.25518	78.0	0.29149
38.0	0.25908	79.0	0.29217
39.0	0.26328	80.0	0.29436
40.0	0.26719	81.0	0.29200

Table 1.1 - (Continued)

Valve Angle (Degrees)	Conductance	Valve Angle (Degrees)	Conductance
82.0	0.29128	87.0	0.29230
83.0	0.28973	88.0	0.29128
84.0	0.29196	89.0	0.29195
85.0	0.28889	90.0	0.29287
86.0	0.29127		

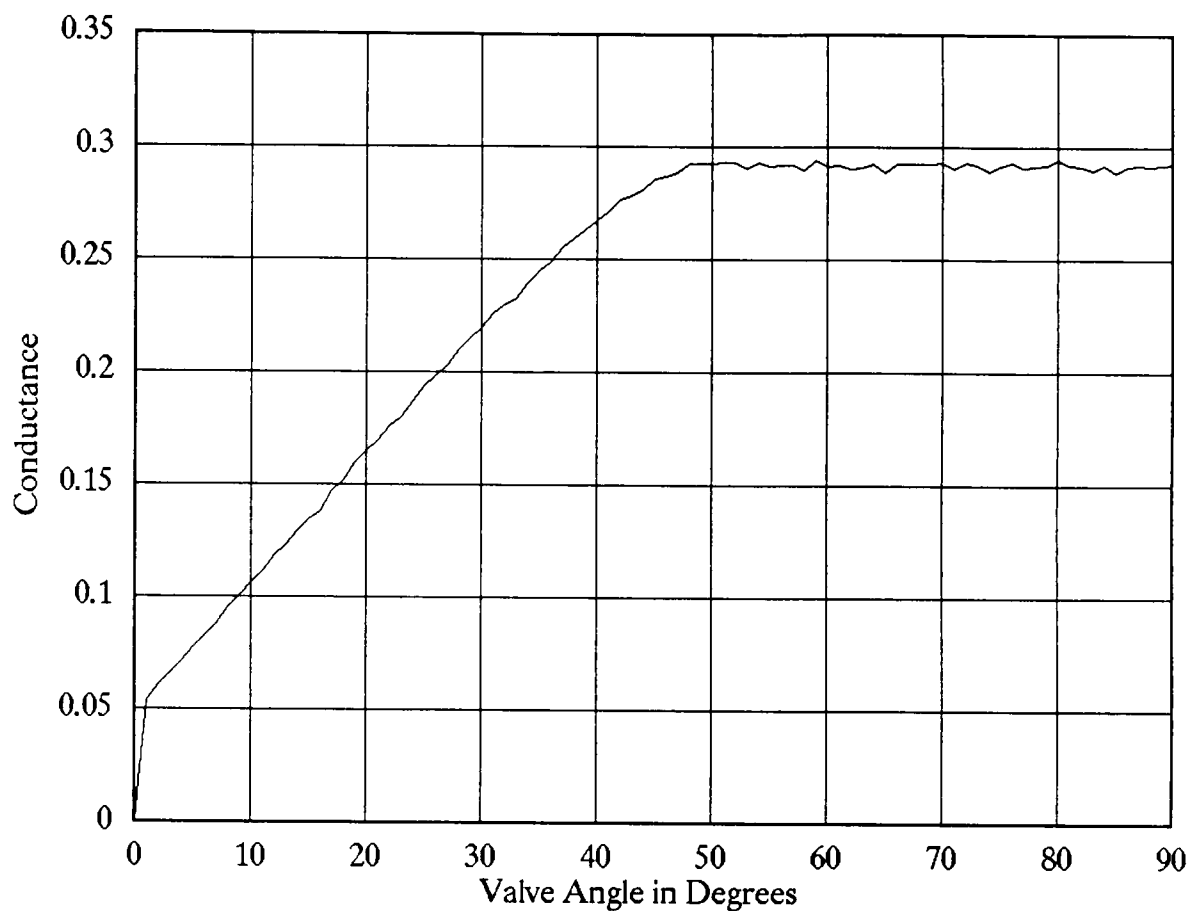


Figure 1.2 - Conductance of the NASA/ESA Spacelab Vacuum Vent Valve to Flow in the Collisionless Molecular Flow Regime as a Function of Valve Angle, Using 100,000 Particle Monte Carlo Simulation.

Table 1.2 - Comparison of Calculated Pipe Conductances Using
10,000 Particle Monte Carlo Analysis With Those
Reported by Davis [3], Saksaganskii [6], and
Van Atta [7]

L/R	K M	K C	K D	K K
0		1.0000		1.000
0.1	0.9542	0.9524		
0.2	0.9089	0.9092		
0.3	0.8685	0.8699		
0.4	0.8337	0.8341		
0.5	0.7983	0.8013	0.804	
0.6	0.7750	0.7711		
0.7	0.7479	0.7434		
0.8	0.7283	0.7177		
0.9	0.6928	0.6940		
1.0	0.6684	0.6720	0.678	0.727
1.1	0.6589	0.6514		
1.2	0.6365	0.6320		
1.3	0.6108	0.6139		
1.4	0.6066	0.5970		
1.5	0.5901	0.5810	0.571	
1.6	0.5703	0.5659		
1.7	0.5597	0.5518		
1.8	0.5441	0.5384		
1.9	0.5215	0.5256		
2.0	0.5177	0.5136	0.522	0.571
2.2	0.4901	0.4914		
2.4	0.4809	0.4711		
2.5	0.4494		0.460	
2.6	0.4572	0.4527		
2.8	0.4348	0.4359		
3.0	0.4192	0.4205	0.425	
3.2	0.4082	0.4062		
3.4	0.3992	0.3931		
3.6	0.3765	0.3809		
3.8	0.3764	0.3695		
4	0.3597	0.3589	0.361	0.400
5	0.3119	0.3146	0.315	
6	0.2740	0.2807		0.307
7	0.2475	0.2537		
8	0.2330	0.2316		0.250
9	0.2109	0.2131		
10	0.1986	0.1973		
12	0.1699	0.1719		0.182
14	0.1481	0.1523		
16	0.1358	0.1367		
18	0.1226	0.1240		

Table 1.2 (Continued)

L/R	K M	K C	K D	K K
20	0.1091	0.1135		0.117
30	0.0808	0.0797		
40	0.0592	0.0613		0.0625
50	0.0450	0.0499		
60	0.0399	0.0420		0.0425
70	0.0361	0.0363		
80	0.0348	0.0319		0.0322
90	0.0318	0.0285		
100	0.0230	0.0258		0.0260
1000	0.0027	0.002658		
∞		8R/3L		

K = Conductance Value Calculated by Clausing per C
Saksaganskii [6] and Davis [3]

K = Conductance Value Calculated by Davis [3] Using a
Modified Monte Carlo Analysis
D

K = Conductance Value Calculated Using the Monte Carlo
M Simulatin With 10,000 Particle Trajectories per Datum

K = Conductance Value Calculated by Van Atta [7] Using
K Knudsen's Method

2. LITERATURE REVIEW

An extensive literature search was performed at the Redstone Scientific Information Center (RSIC) at NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama.

The objective of the search was to locate all material on the conductance of butterfly valves to internal molecular flow. This search proved unsuccessful.

Having failed to locate any data on the above subject, the scope of the search was increased to include all types of internal molecular flow and vacuum technology. As a result of the new effort and advice from Dr. Collins, several sources of information were located.

These sources covered internal molecular flow through cylindrical elbows and pipes (Davis [3]), molecular flow in complex vacuum systems (Saksaganskii [6]), and general vacuum science and engineering (Van Atta [7]). According to the above references, the Monte Carlo method of simulation has historically been deemed a powerful and valid method of attack for calculating the internal conductance of simple and complex-shaped pipes to gases in the molecular flow regime. A detailed history of the internal vacuum

flow problem and its development is provided by Loeb [8]. The problem is based on the classical kinetic theory (Davis and others [3,5,6,7,8]). These references advanced a generalized approach to solving the problem using the Monte Carlo method. No reference for the molecular flow through a valve was found, however.

The detailed technique of following a particle around inside an object, as required by the Monte Carlo method, was not covered by any of the sources on vacuum technology and molecular flow reviewed. Due to the similarity of the above requirements and the ray tracing methods used in computer generated high-resolution solid modeling graphics, a search was conducted in this area.

The two most helpful tools in this area for the purposes of this simulation were found to be a book by Angell and Griffith [5] on high resolution computer graphics, and the software by Acrobats [4] for three-dimensional wire-frame modeling.

3. METHOD OF ATTACK

Using the analyses performed and documented earlier for the NASA SL-J mission [2], it was evident that the gases reaching the vacuum vent valve were well in the collisionless molecular flow regime. The design of this vacuum system calls for a 1.875 inch diameter, 140 inch long pipe to connect the experiment rack interface to the spacelab vacuum vent valve. The pressure required at this interface is stated as 0.001 torr. The NASA / ESA vacuum vent valve is 5.5 inches long and has a two inch internal diameter. The valve butterfly is located halfway between the valve inlet plane and its exit plane. This configuration results in a valve length to diameter ratio (L/D) of 2.75.

The equation for calculating the molecular free path is given by Van Atta [7] as:

$$\beta = \frac{k * T}{\sqrt{2} * \pi * d^2 * P} \quad (3.1)$$

where β is the molecular free path, T is the gas temperature in absolute degrees, d is the molecular diameter, P is the gas absolute pressure, and k is equal to 1.3805E-16 erg/°K. Using this equation, a molecular free path length may be

calculated for each of the four gases vented by this experiment through the valve. The four experiment vent gases are air, argon, helium and krypton.

The flow Knudsen number can be calculated by using the available data for each of the vent gases. The Knudsen number is defined as:

$$Kn = \beta / D \quad (3.2)$$

where Kn is the Knudsen number, β is the molecular free path length, and D is the hydraulic diameter of the pipe. The molecular flow onset pressure for the aforementioned four vent gases at seventy degrees Fahrenheit and a Knudsen number of ten was calculated for pipe diameters of 1.875 and two inches and is presented in Table 3.1.

Table 3.1 - Molecular Flow Onset Pressure at Kn=10 and 70°F

Gas	Molecular Diameter cm x E-08	Pressure (torr x E-07)	
		Diameter (in)	
		1.875	2.00
Air	3.76	3.46	3.25
Argon	2.94	5.66	5.31
Helium	2.62	7.13	6.68
Krypton	3.16	4.19	4.59

According to Van Atta [7], flows above a Knudsen number of 0.8 are assumed to be molecular in nature.

Based on this earlier finding, an effort was made to determine the valve conductance in this flow regime. The collisionless molecular flow regime, its characteristics and requirements, are well documented in Davis, Saksaganskii, etc [3,6,7].

The method of analysis used here is restricted to the steady flow of collisionless molecules where intermolecular forces may be ignored. The molecular positions and velocity vectors which cross the valve inlet are assumed to be independent of the flow in other parts of the vacuum vent system and to follow the Maxwell distribution law (i.e., are Maxwellian). These conditions exist for high Knudsen number flows.

Since the literature search revealed that the Monte Carlo method of mathematical approximation should be used, a program had to be written for its implementation. The FORTRAN programming language was chosen for this purpose due to the author's familiarity with it and FORTRAN's efficiency, as a higher level language, for performing numerical analysis.

The Monte Carlo method requires the generation of a multitude of particles with random locations and velocity vectors. It also requires that each particle be followed through collisions with solid boundaries until it exits through the valve inlet or outlet. A graphical visualization of the phenomenon was deemed useful in both better understanding the phenomenon, and in correcting any possible programming errors. After researching the available software on the market, the AcroSpin dynamic three-dimensional wire-frame modeling software by Acrobits [4] was found to be the most effective for this type of flow visualization.

Further, the ray tracing methods used in high resolution computer graphics, as outlined by Angell and Griffith [5], were put to use. These methods are similar to the methods needed for modeling the absorption / desorption of particles in molecular flow, as modeled using the Monte Carlo method.

3.1 Monte Carlo Method

To implement the Monte Carlo method, random numbers are used to generate a set of particles. Each particle is then followed until it exits from an opening. The ratio of the number of particles generated to the number of particles

which exited each opening is then used to estimate the probability that a particle will exit that opening.

Following Davis [3], using the conservation of particles, and using earlier stated assumptions about the flow, one can write the following equation for the flow rate through the valve:

$$F_i = K_i P_{i-i-j} - K_j P_{j-j-i} \quad \begin{matrix} i, j = 1, 2 \\ i \neq j \end{matrix} \quad (3.1.1)$$

where F_i is the net number of particles that flow through opening i per unit time, K_i is the number of particles entering the valve through opening i per unit time, and P_{i-j} is the probability that a particle which entered through the opening i will exit through the opening j .

As stated in section 3., the analysis documented here makes three assumptions about the flow and is therefore restricted by them. The first assumption is that the flow is steady and the particles do not collide with one another, so the intermolecular forces may be ignored. The second assumption is that the molecular positions and velocity vectors which cross the valve inlet are independent of the flow in other parts of the vacuum vent system. The third assumption is that the particle position and velocity vectors follow the Maxwell distribution law (i.e., are

Maxwellian). Using the second and the third assumptions as stated above, it therefore follows that the probabilities P_{i-j} are independent of the flow in the rest of the system. According to Davis [3]:

These Probabilities depend only on the distribution of the position and angle at which the molecules enter the pipe at an opening, and the mechanics of a single molecule in the pipe. The effect on the flow rate of such quantities as the pressure and temperature of the gas is contained in the factors K_i . The geometrical dependence of the flow rate is contained in the factors P_{i-j} .

According to Maxwellian flow assumptions, the probability that a particle enters an area is proportional to the area, and the probability that a particle enters it at a certain angle is proportional to the cosine of the angle which it makes with the normal vector to that surface (cosine law).

Using this type probability, the position coordinates and velocity vectors for a number of particles are generated at opening i (inlet). Each particle is followed until it collides with a solid boundary or exits through the inlet or outlet. If it collides with a solid boundary, the collision coordinates are calculated and a new set of velocity vectors are generated using the same equations used for initial particle generation. The particle path is once

again checked for solid boundary collision or exit through an opening. The last two steps are repeated until the particle exits through an opening. When a particle exits through an opening, the proper counter is advanced and a new particle at the valve inlet is generated. This process is continued until the requested number of particles have been generated.

The estimated probability P_{i-j} is then given by Davis [3] as:

$$P_{i-j} = N_{i-j} / N_i \quad (3.1.2)$$

where N_i is the total number of particles generated at opening i , and N_{i-j} is the number of those particles which exited through opening j .

The standard deviation of the approximate probability from that of the actual probability is given by Davis [3] as:

$$\sigma = \sqrt{P_{i-j} (1 - P_{i-j}) / N_i} \quad (3.1.3)$$

The details of the implementation of the Monte Carlo method are described in Appendix A.

3.2 Flow Visualization

Flow visualization was deemed to be an extremely useful and almost necessary tool to help better understand the flow phenomenon and to help isolate and resolve programming errors.

The three-dimensional nature of the flow modeled, and the existence of internal obstacles to the flow which could hamper visualization, called for a visualization software capable of conveniently rotating and translating an object in all six translational and rotational dimensions. To make visualization even more convenient, such software had to be able to selectively hide certain surfaces from view. It had to allow the user to look through solid surfaces. The software had to be able to represent each surface, or vector, by a specified color (color coding). Most important of all, it had to have an uncomplicated input file format to simplify the generation of surfaces and vectors representing particles.

The most readily available and convenient three-dimensional dynamic visualization software which met or surpassed all of the above requirements was found to be the Acrospin software by Acrobats [4].

To use this software, a FORTRAN program was written for the sole purpose of generating the wire-frame graphical representation of the butterfly valve (i.e., a disk inside a cylinder). This program is documented in Appendix F.

Simply stated, given the cylinder length and radius and the valve angle and radius, the program generates the points in three dimensions to represent the two objects. It then connects the proper points to generate the correct representation using appropriate Acrospin [4] data representations. An example input listing to this program is in Appendix G with the corresponding output listing in Appendix H.

The output listing in Appendix H generates a butterfly valve inside a cylinder. The radius of both the butterfly and the cylinder are equal and the total length of the cylinder is twice this value. The butterfly is located at the center of the cylinder and is at 45 degrees angle to it. Figure 3.1 is the corresponding view of this setup.

Once the proper butterfly valve and cylinder graphics data file is generated, the conductance analysis program optionally appends this file with the required graphics data representing the modeled particles and their encounters with the boundaries. This program color codes the vectors representing the path traveled by each particle depending

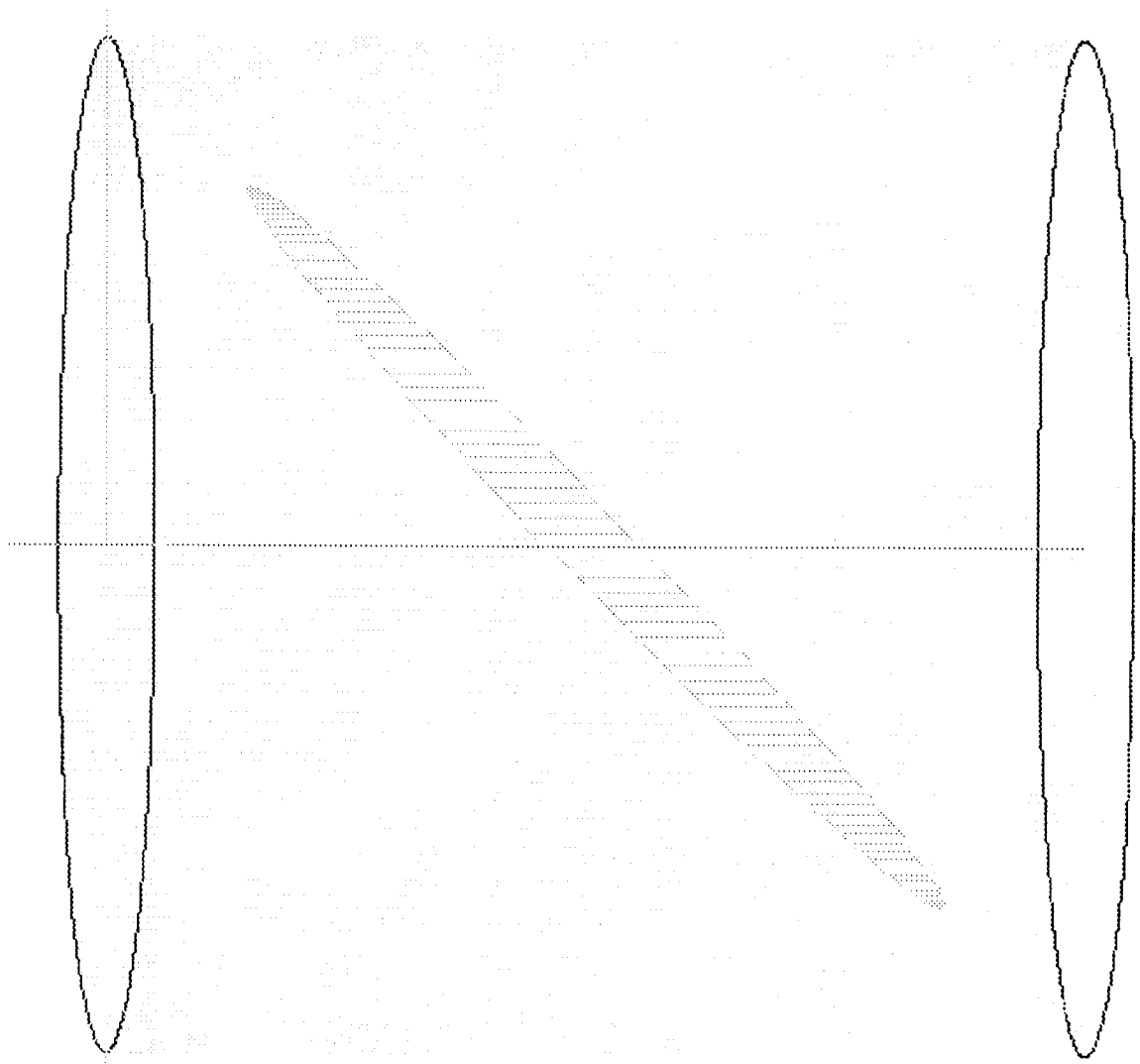


Figure 3.1 - Vacuum Vent Valve Model with 45° Butterfly Angle

on its starting and ending boundaries to further aid in flow visualization. The data that would be appended for the first ten particles simulated for the vent valve setup described above is documented in Appendix I. By appending this data to those in Appendix H, and providing it to the Acrospin program [4], the behavior of the first ten particles generated by the conductance analysis program inside the valve can be visualized. The combined valve and Monte Carlo visualization file (Appendix H and I) would generate a view in the screen similar to Figure 3.2.

3.3 Ray Tracing and Axis Transformation

The ray tracing method is used to determine which boundary has been crossed by the particle. This is done by determining which surfaces are crossed by the particle velocity vector. The distance that the particle would have to travel to collide with each surface is then determined. The shortest collision distance is the surface with which the particle will collide. The location in the three dimensions of where the collision takes place is then determined. The particle coordinates are translated to the collision location. The particle coordinates are then rotated such that the particle x-axis is along the normal vector to the surface. If the particle has crossed the butterfly, then the x-axis is either in the direction of the rotated x-axis

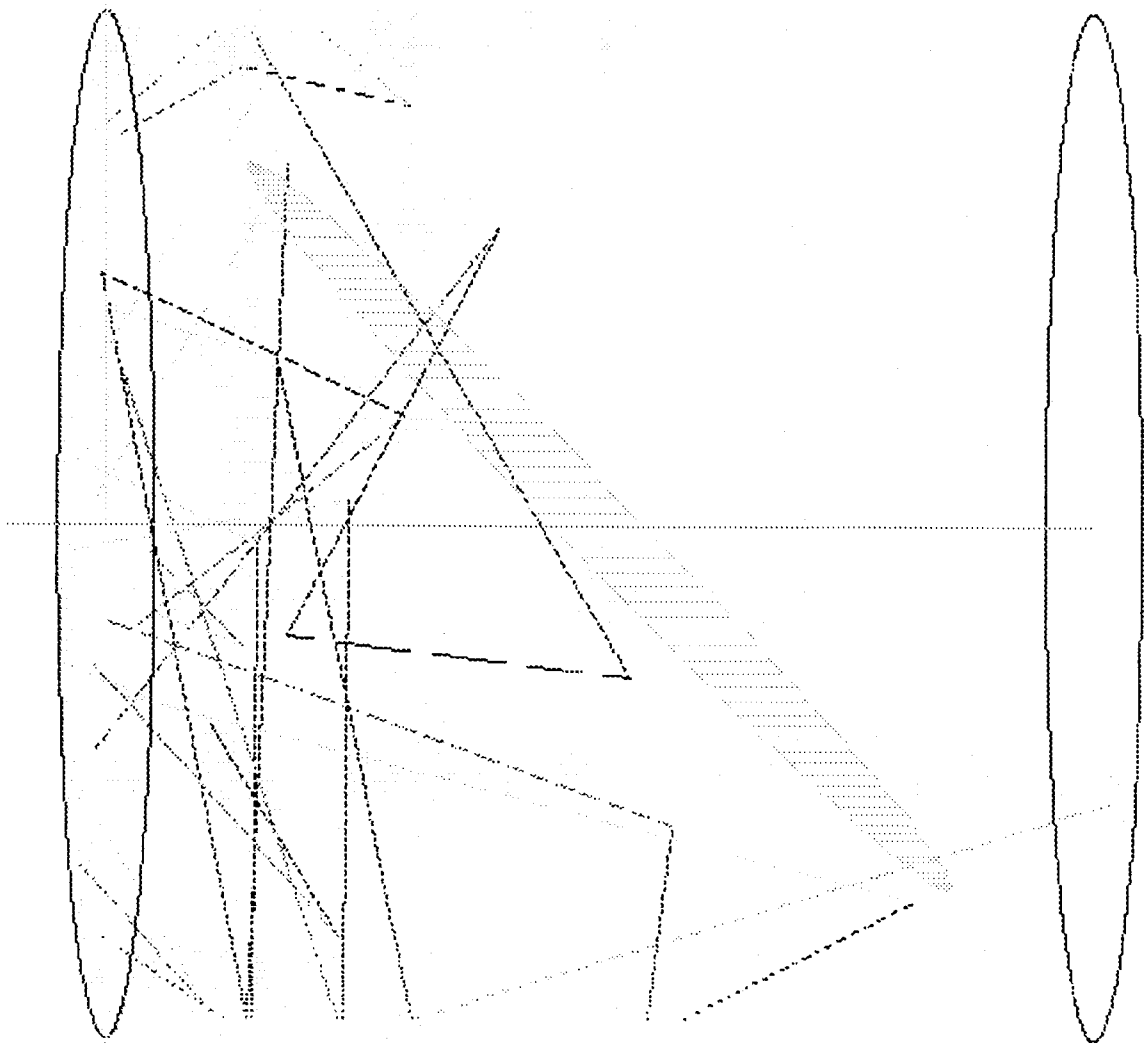


Figure 3.2 - Ray Tracing Visualization of Monte Carlo Simulation of the Flow of Ten Particles Entering The Vacuum Vent Valve From Left, With the Valve Butterfly at 45° Angle.

of the valve, or 180° opposite to it. If it is in the direction of the valve x-axis, then the three axes of the particle follow the directions of the valve axes. If the x-axis of the particle is 180° opposite to the valve x-axis, then the y-axis of the particle is kept common to that of the valve, and its z-axis is rotated to follow the right-hand-rule.

If the particle has crossed the valve body, then the particle x-axis is towards the valve body centerline (and normal to it). In this situation, the particle z-axis is towards the valve inlet and parallel to the valve body. The direction of the particle y-axis depends on where the particle has crossed the valve body.

Using the new particle coordinate system and in accordance with the cosine law, a new particle velocity vector is generated. The new particle must be rotated back to the valve-body-central coordinate system before the next collision can be calculated.

The need for axis transformation arises when a particle has hit a surface, been absorbed by it, and is then to be ejected from it. To use the same subroutine that generated the initial random velocity vector, it is required for the x, y, and z axes to be rotated to conform to the plane of

the surface crossed. For example, if the particle has collided with the butterfly valve, the axes has to be rotated such that the particle may be ejected properly off of the same side of the valve as the collision took place. The rotation also has to take into account the angle between the butterfly valve and the primary axes to ensure that the new velocity vectors do not cross the butterfly. Figure 3.2 illustrates this concept.

Using the graphics book by Angell and Griffith [5] and the Monte Carlo method, a program was written to simulate the flow of molecular particles through the butterfly valve. For the sake of keeping the program general enough to be useful as a possible future tool, it was determined that the program should be able to handle a variety of different geometries. However, due to the limited available time, only cylindrical and disk type surface model subroutines were coded. The possibility of adding other surface types in the future does exist.

The program, as it exists today, is able to simulate any length of down stream or upstream pipe and any size disk, simulating the butterfly valve. It is therefore possible to simulate a situation where the butterfly valve has a radius smaller than the surrounding pipe, or one in which the valve exactly slices the cylinder, giving a

semicylinder and a flat surface as the internal walls seen by the flowing molecules.

There are several cases in addition to the Spacelab Vacuum Vent Valve case analyzed here. These cases show the effect of the ratio of the pipe length to its diameter (L/D) on the valve conductance, the effect that increasing or decreasing the total number of particles simulated has on the final results, the effect of the valve angle on the valve conductance, and the effect of the random number generator seed on the calculated valve conductance.

4. PRESENTATION AND DISCUSSION OF RESULTS

Several butterfly and valve configurations were modeled. These configurations included the valve conductance as a function of valve angle, and the valve conductance as a function of valve cylinder length - with both equal and unequal upstream and downstream lengths.

4.1 Pipe Flow Comparison With Other Investigators

To verify the program accuracy, the initial case studied was that of a hollow pipe. The pipe was generated by specifying a very small valve radius ($1.E-20$) as compared to the valve body lengths (total lengths from 0.1 to 1000 pipe radii). The pipe conductances calculated for 10,000 particle trajectory simulations per datum, along with those of Knudsen as presented by Van Atta [7], Clausing's results as reported by Saksaganskii, and those results obtained by Davis [3] using Monte Carlo analysis are presented in Table 1.1, page 7. The calculated conductances are plotted in Figure 4.1. As may be determined by inspecting Table 1.1 (page 7) these results are very similar. The differences are within computational uncertainty and round-off error.

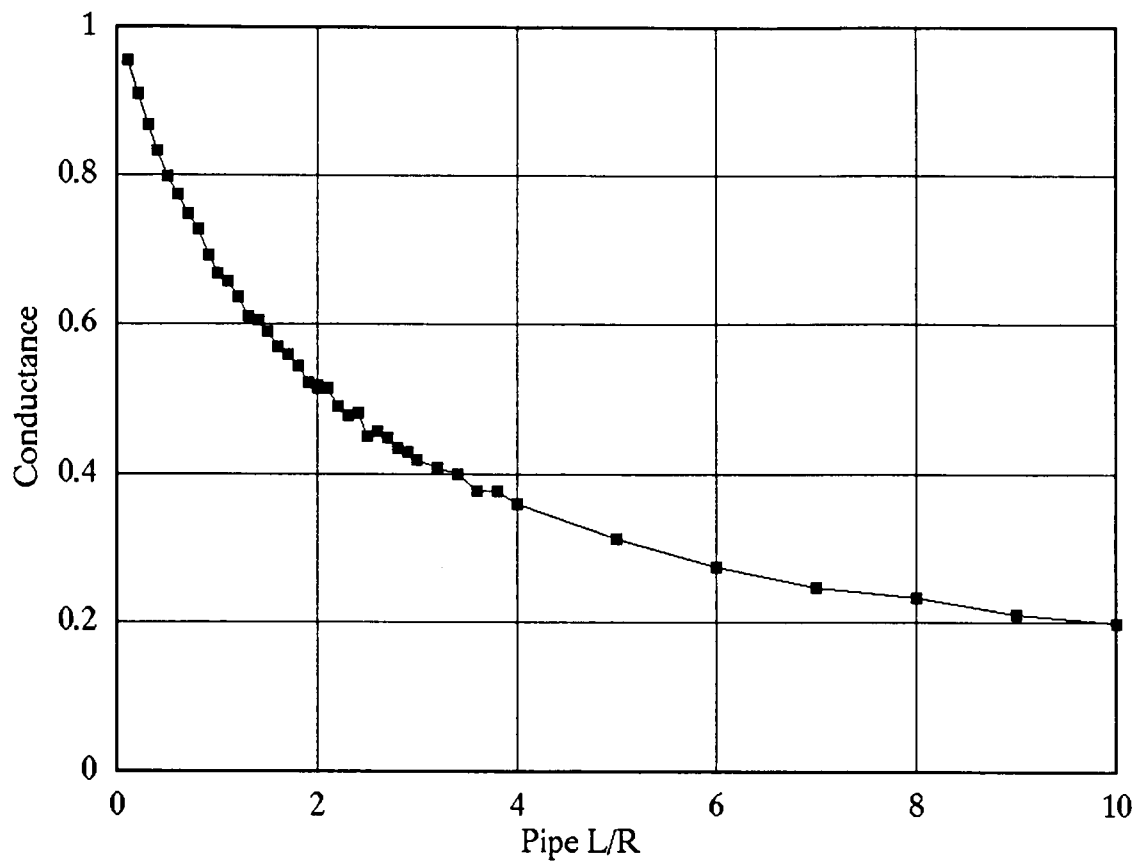


Figure 4.1 - Calculated Pipe Conductances Using Monte Carlo Analysis with 10,000 particles simulated per datum

4.2 Butterfly Valve

Having shown the validity of the modeling technique and the accuracy of the simulation program, several parametric studies were performed.

In the first study the valve upstream and downstream lengths were kept equal. Here, a comparison of the overall conductance as a function of length at various butterfly angles was made by modeling 10,000 particle trajectories for each datum. The results for pipe lengths equal to one to six times the valve (pipe) radii and angles from zero to ninety degrees at five degree intervals are presented in Table 4.1 and plotted in Figure 4.2. Figure 4.3 is a plot of these conductances for valve angles from zero to forty degrees. Also presented are the results obtained for the above valve angles and pipe lengths equal to two to seven times the valve (pipe) radii when modeling 100,000 particle trajectories per datum. These results are presented in Table 4.2 and are plotted from zero to ninety degrees in Figure 4.4. Figure 4.5 is the plot of the same data for valve angles from zero to forty degrees. As can be deduced, at low valve angles (valve beginning to open) the conductance is almost a sole function of the valve angle and not the pipe length. On the other hand, at large valve angles

Table 4.1 - Effects of Total Pipe Length on the Calculated Conductance of a Valve Using Monte Carlo Simulation With 10,000 Particles for Valve Angles From Zero to Ninety Degrees

Valve Angle (Degrees)	Conctance			
	L/R=1	L/R=2	L/R=3	L/R=4
0.0	0.0000	0.0000	0.0000	0.0000
5.0	0.0746	0.0663	0.0840	0.0563
10.0	0.1027	0.0928	0.1170	0.0884
15.0	0.1352	0.1279	0.1440	0.1163
20.0	0.1698	0.1574	0.1707	0.1544
25.0	0.2041	0.1960	0.2011	0.1886
30.0	0.2524	0.2322	0.2338	0.2106
35.0	0.3220	0.2546	0.2632	0.2467
40.0	0.3747	0.2939	0.3083	0.2828
45.0	0.4317	0.3379	0.3247	0.3011
50.0	0.4786	0.3681	0.3587	0.3283
55.0	0.5113	0.4062	0.3933	0.3511
60.0	0.5286	0.4247	0.4005	0.3572
65.0	0.5575	0.4552	0.4183	0.3587
70.0	0.5767	0.4771	0.4193	0.3557
75.0	0.5749	0.4929	0.4356	0.3554
80.0	0.5943	0.5147	0.4151	0.3629
85.0	0.6035	0.5158	0.4222	0.3567
90.0	0.6104	0.5100	0.4246	0.3528
	L/R=5	L/R=6	L/R=7	L/R=8
0.0	0.0000	0.0000	0.0000	0.0000
5.0	0.0740	0.0794	0.0752	0.0512
10.0	0.1024	0.1099	0.1030	0.0822
15.0	0.1292	0.1311	0.1405	0.1217
20.0	0.1599	0.1645	0.1621	0.1458
25.0	0.1891	0.1929	0.1917	0.1739
30.0	0.2241	0.2212	0.2179	0.1957
35.0	0.2510	0.2437	0.2362	0.2031
40.0	0.2747	0.2639	0.2399	0.2223
45.0	0.2934	0.2724	0.2404	0.2212
50.0	0.3144	0.2791	0.2484	0.2246
55.0	0.3058	0.2775	0.2478	0.2261
60.0	0.3142	0.2767	0.2445	0.2226
65.0	0.3065	0.2791	0.2440	0.2191
70.0	0.3109	0.2690	0.2473	0.2312
75.0	0.3113	0.2749	0.2464	0.2243
80.0	0.3113	0.2696	0.2466	0.2229
85.0	0.3128	0.2746	0.2470	0.2330
90.0	0.3100	0.2717	0.2493	0.2289

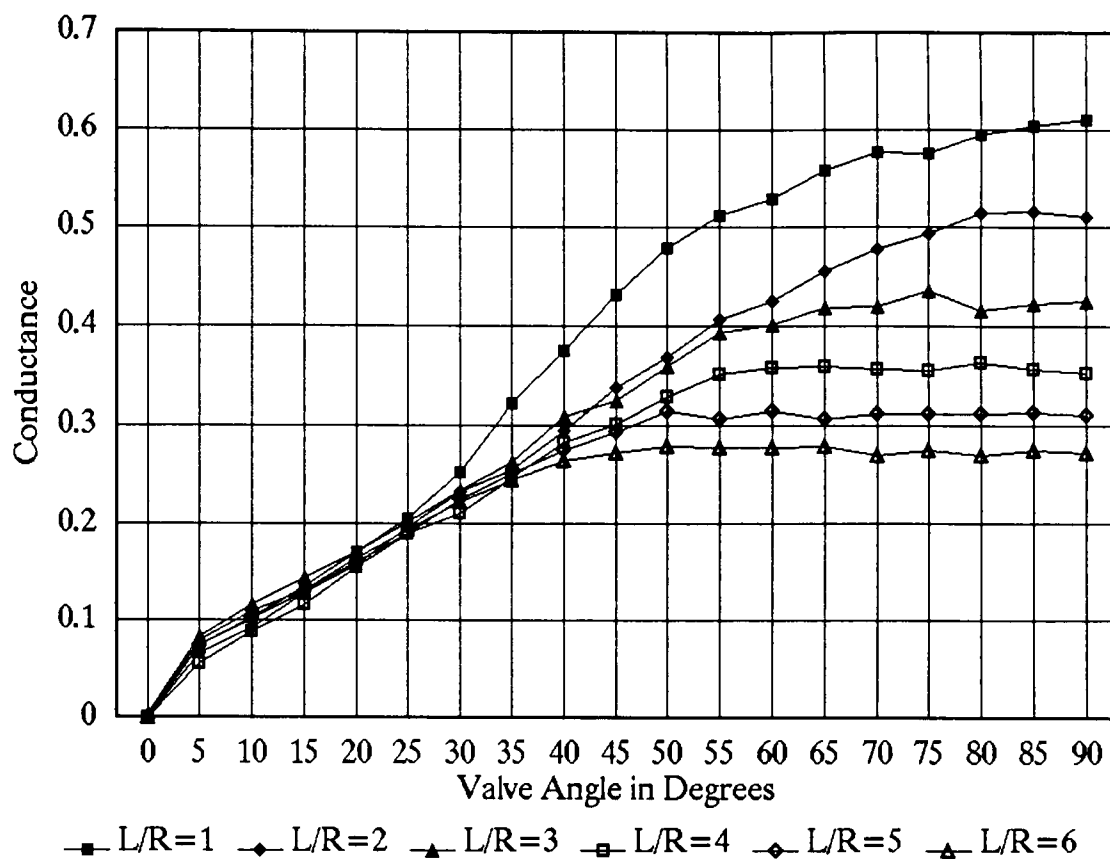


Figure 4.2 - Effects of Total Pipe Length on the Calculated Conductance of a Valve Using Monte Carlo Simulation With 10,000 Particles for Valve Angles From Zero to Ninety Degrees

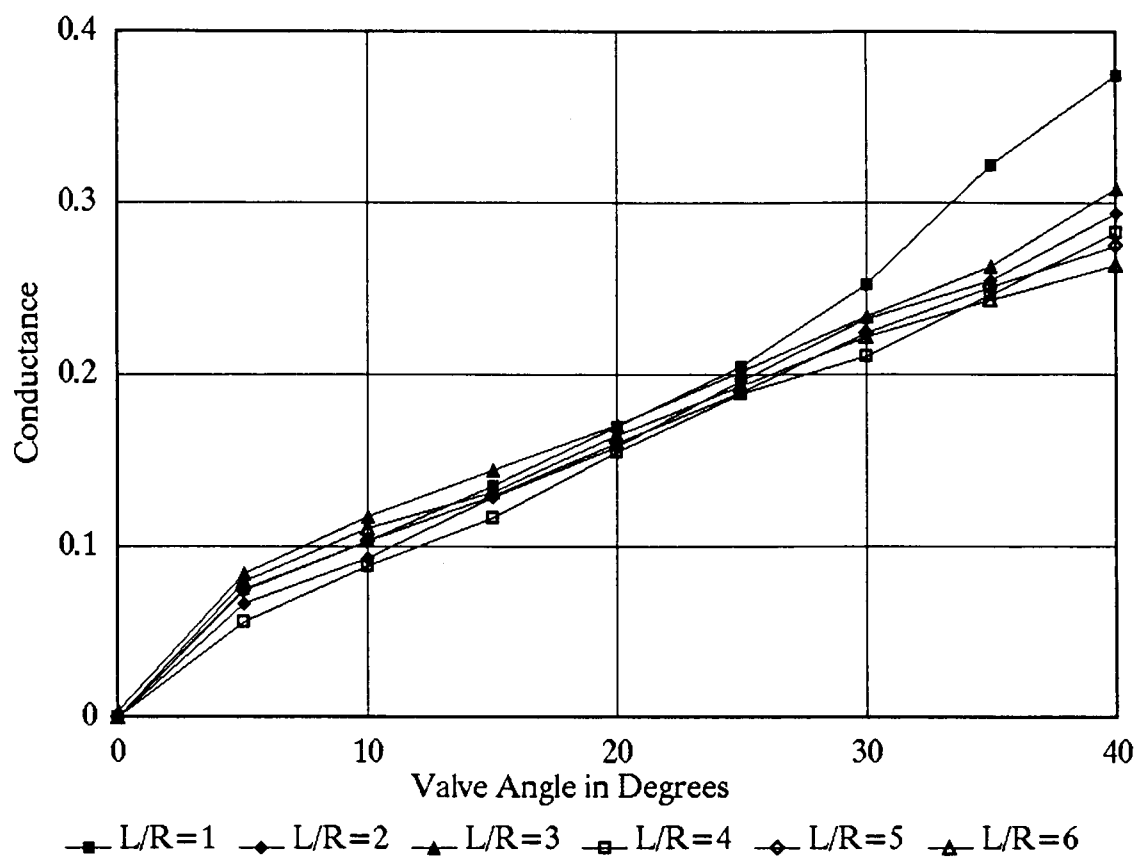


Figure 4.3 - Effects of Total Pipe Length on the Calculated Conductance of a Valve Using Monte Carlo Simulation With 10,000 Particles for Valve Angles From Zero to Forty Degrees

Table 4.2 - Effects of Total Pipe Length on the Calculated Conductance of a Valve Using Monte Carlo Simulation With 100,000 Particles

Valve Angle (Degrees)	Conctance		
	L/R=2	L/R=3	L/R=4
0.0	0.00000	0.00000	0.00000
5.0	0.06675	0.08454	0.05836
10.0	0.09603	0.11150	0.08800
15.0	0.12856	0.14346	0.12230
20.0	0.16218	0.17314	0.15295
25.0	0.19365	0.20244	0.18453
30.0	0.22843	0.23641	0.21823
35.0	0.26314	0.26672	0.24680
40.0	0.30082	0.29655	0.27807
45.0	0.33065	0.33148	0.30615
50.0	0.36980	0.35802	0.33493
55.0	0.40388	0.38435	0.35291
60.0	0.42911	0.40453	0.35346
65.0	0.45543	0.41920	0.35975
70.0	0.47844	0.41939	0.35487
75.0	0.49577	0.41924	0.35713
80.0	0.50849	0.42030	0.35561
85.0	0.51418	0.42019	0.35820
90.0	0.51441	0.42275	0.35640
	L/R=5	L/R=6	L/R=7
0.0	0.00000	0.00000	0.00000
5.0	0.07546	0.07952	0.07891
10.0	0.10105	0.10689	0.10943
15.0	0.13177	0.13572	0.13692
20.0	0.16056	0.16529	0.16758
25.0	0.19141	0.19305	0.19555
30.0	0.22040	0.21736	0.21842
35.0	0.24833	0.24379	0.23277
40.0	0.27396	0.26104	0.24947
45.0	0.29591	0.27404	0.24506
50.0	0.30983	0.27654	0.24579
55.0	0.31204	0.27070	0.24771
60.0	0.30997	0.27667	0.24759
65.0	0.31123	0.27254	0.24937
70.0	0.31005	0.27415	0.24742
75.0	0.30972	0.27550	0.24703
80.0	0.31145	0.27466	0.24891
85.0	0.31039	0.27508	0.24848
90.0	0.31255	0.27725	0.24791

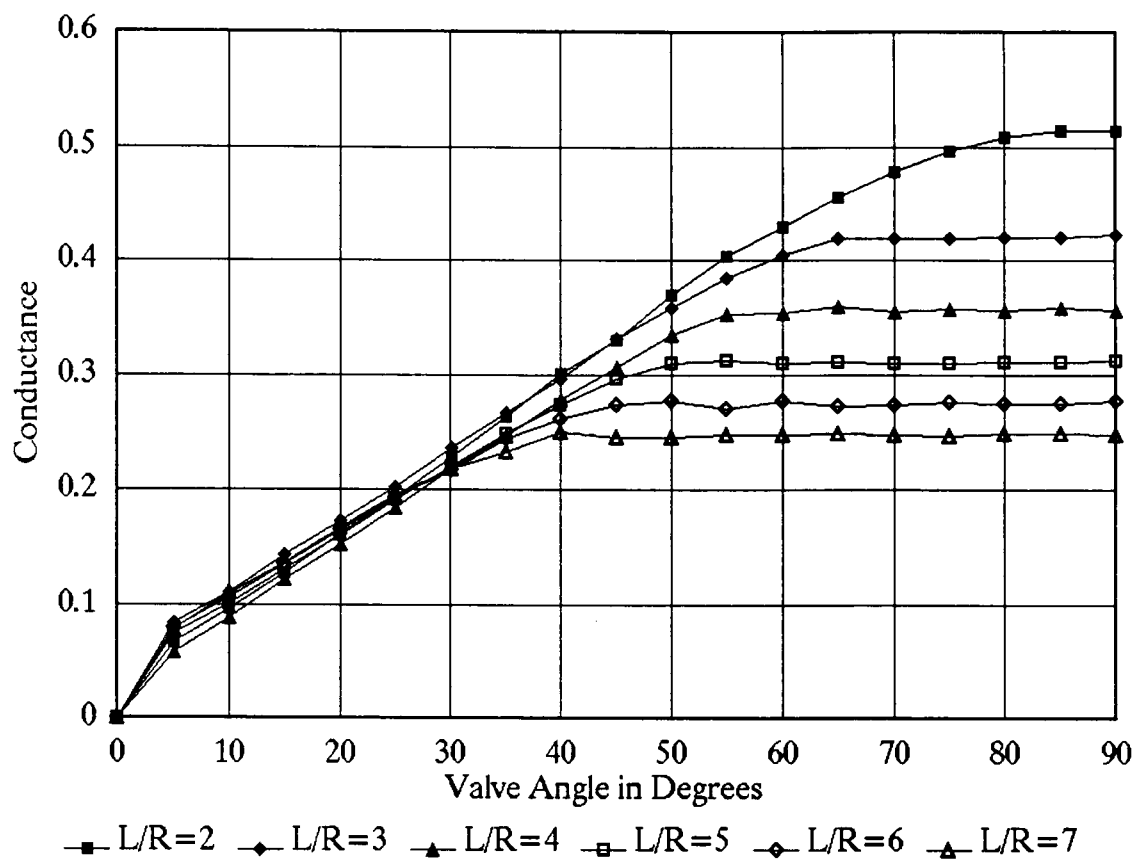


Figure 4.4 - Effects of Total Pipe Length on the Calculated Conductance of a Valve Using Monte Carlo Simulation With 100,000 Particles for Valve Angles From Zero to Ninety Degrees

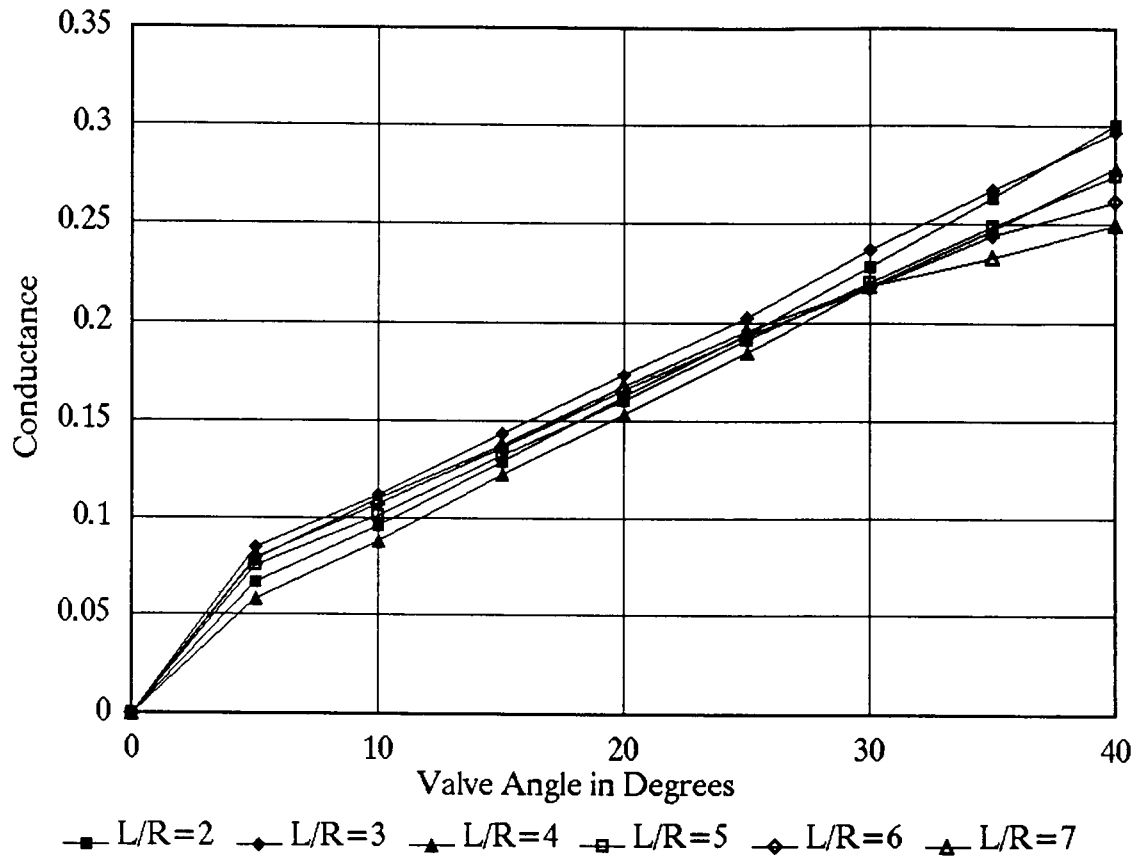


Figure 4.5 - Effects of Total Pipe Length on the Calculated Conductance of a Valve Using Monte Carlo Simulation With 100,000 Particles for Valve Angles From Zero to Forty Degrees

(valve almost wide open) the conductance seems to be a sole function of the pipe length. (The conductance of a pipe as a function of its length and diameter is presented in Table 1.1 on page 7 and plotted in Figure 4.1 on page 28.)

For the second study, the valve upstream and downstream lengths were kept unequal and the valve conductance for several valve angles was determined. Here, six cases were analyzed. Case 1 has an upstream pipe length equal to seventeen valve radiuses and a downstream pipe length equal to the valve radius. Each of the next five cases added 0.5 valve radii to the upstream length and 0.5 radii to the downstream length. All cases used 10,000 iterations per datum. The conductance fluctuations present in this figure are due to the error caused by modeling with 10,000 particles. As apparent in the previous study, increasing the number of simulated particles per datum by a factor of ten results in a smoother curve. These results are presented in Table 4.3 and Figure 4.6.

In the third study, the effect of the number of particles generated on the conductance value calculated was determined. This study was performed on the spacelab vacuum vent valve case. This valve has an upstream length equal to 1.375 valve diameters and a downstream length equal to

Table 4.3 - Effects of Lengthened Upstream Pipe on the
Calculated Conductance of a Valve Using Monte
Carlo Simulation With 10,000 Particles

Valve Angle (Degrees)	Conctance			
	L/R=18	L/R=19	L/R=20	L/R=21
5.0	0.0656	0.0663	0.0672	0.0698
10.0	0.0929	0.0936	0.0891	0.0848
15.0	0.1066	0.1095	0.0983	0.0992
20.0	0.1142	0.1142	0.1101	0.1079
25.0	0.1232	0.1170	0.1064	0.1125
30.0	0.1213	0.1112	0.1109	0.1010
35.0	0.1188	0.1201	0.1135	0.1061
40.0	0.1177	0.1132	0.1098	0.1037
45.0	0.1176	0.1111	0.1055	0.1077
50.0	0.1202	0.1149	0.1095	0.1034
55.0	0.1139	0.1115	0.1102	0.1023
60.0	0.1210	0.1161	0.1037	0.0963
65.0	0.1150	0.1151	0.1096	0.0990
70.0	0.1215	0.1147	0.1066	0.1055
75.0	0.1231	0.1163	0.1124	0.1068
80.0	0.1228	0.1094	0.1136	0.1040
85.0	0.1235	0.1154	0.1105	0.1092
90.0	0.1227	0.1140	0.1114	0.1043
	L/R=22	L/R=23	L/R=24	L/R=25
5.0	0.0708	0.0689	0.0694	
10.0	0.0839	0.0883	0.0859	
15.0	0.0961	0.0926	0.0916	
20.0	0.0927	0.0956	0.0944	
25.0	0.1034	0.0985	0.0929	
30.0	0.0981	0.0993	0.0949	
35.0	0.1022	0.1015	0.0904	
40.0	0.1038	0.0972	0.0889	
45.0	0.1027	0.0989	0.0930	
50.0	0.0995	0.0937	0.0932	
55.0	0.1000	0.1003	0.0955	
60.0	0.0951	0.0959	0.0921	
65.0	0.1017	0.0954	0.0921	
70.0	0.0969	0.0901	0.0954	
75.0	0.1024	0.0916	0.1000	
80.0	0.1014	0.0976	0.0916	
85.0	0.1047	0.0969	0.0977	
90.0	0.1037	0.0987	0.0945	0.0975

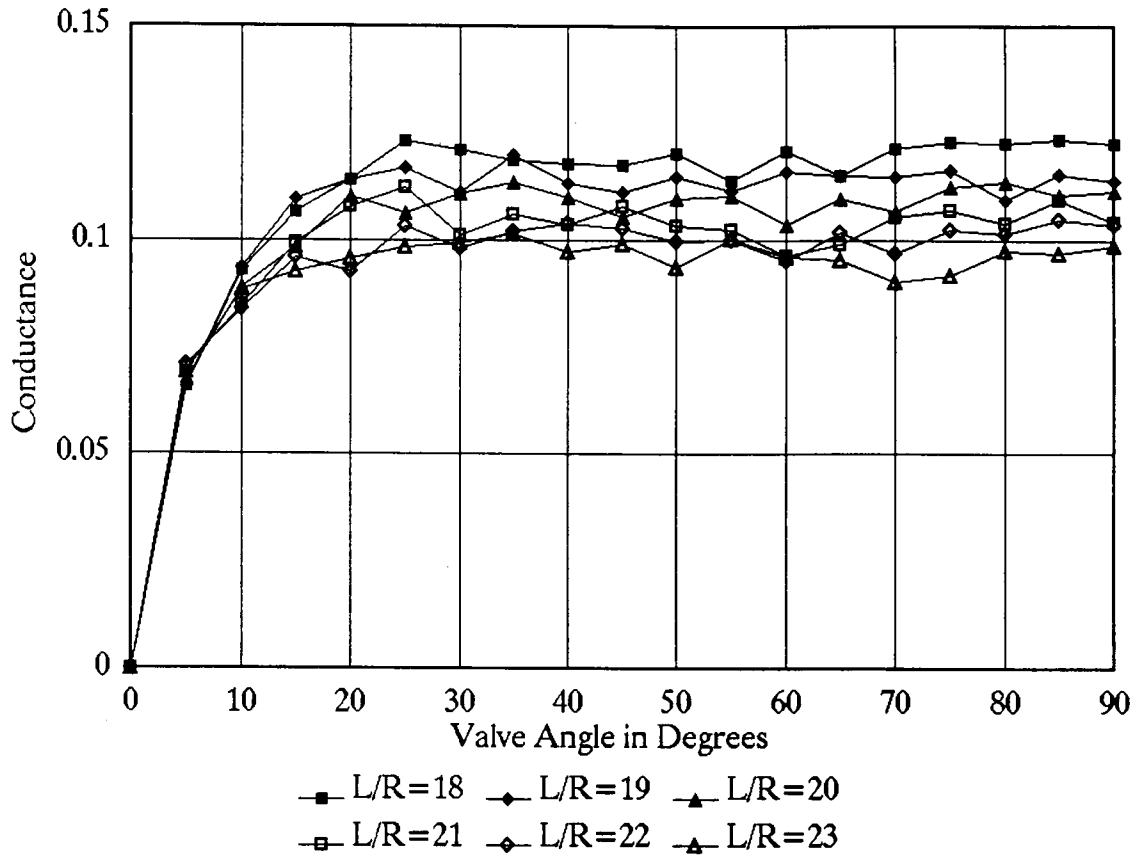


Figure 4.6 - Effects of Lengthened Upstream Pipe on the Calculated Conductance of a Valve Using Monte Carlo Simulation With 10,000 Particles

1.375 valve diameters. The valve angle was set to twenty degrees from the closed position. The data calculated for this study are actually the results of a single run. The program was asked to calculate a conductance after the least number of iterations were performed and report it. It was then told to continue generating more histories until the next requested total number of iterations were performed. It would then calculate a new approximate value for the conductance. This value was then reported. This scheme was repeated until the highest number of requested iterations have been performed.

The resultant data are plotted in Figure 4.7 and presented in Table 4.4. As may be expected, as the number of simulated particles is increased, the answer seems to converge. Due to computer round-off and inaccuracies in assumptions and theory, the final answer is still inexact. Since, as can be seen from Figure 4.7, increasing the number of iterations beyond 100,000 does not seem to have much effect on the final result, 100,000 loops were used for calculating the conductance of the NASA / ESA vacuum vent valve conductance.

The fourth study looked at the effect of changing the random number generator seed value. For this study, a total of 10,000 random numbers were generated for each case. In

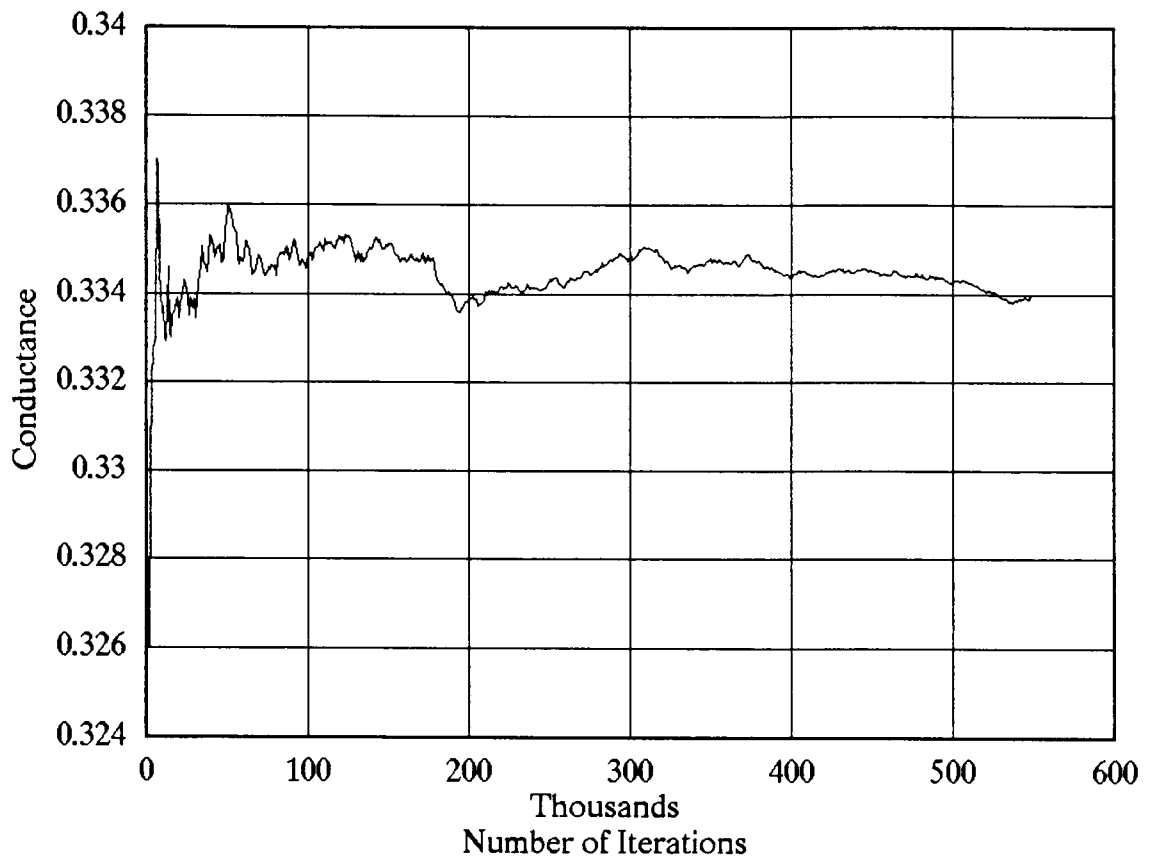


Figure 4.7 - Effect of Increasing the Number of Particles Simulated on the Conductance Value Calculated for the NASA/ESA Spacelab Vacuum Vent Valve With Butterfly at 45° Angle

Table 4.4 - Effect of Increasing the Number of Particles Simulated on the Conductance Value Calculated for the NASA/ESA Spacelab Vacuum Vent Valve With Butterfly at 45° Angle

Iterat.	Cond.	Iterat.	Cond.	Iterat.	Cond.
1000	0.326000	43000	0.334977	85000	0.334859
2000	0.330000	44000	0.335068	86000	0.335070
3000	0.332000	45000	0.335089	87000	0.334954
4000	0.332750	46000	0.334696	88000	0.334761
5000	0.333000	47000	0.334808	89000	0.334944
6000	0.337000	48000	0.335500	90000	0.335144
7000	0.336857	49000	0.335571	91000	0.335220
8000	0.334500	50000	0.335980	92000	0.335109
9000	0.333556	51000	0.335863	93000	0.334817
10000	0.333700	52000	0.335769	94000	0.334628
11000	0.333000	53000	0.335547	95000	0.334705
12000	0.332917	54000	0.335444	96000	0.334781
13000	0.334615	55000	0.335364	97000	0.334680
14000	0.333071	56000	0.334786	98000	0.334582
15000	0.333000	57000	0.334667	99000	0.334768
16000	0.333500	58000	0.334793	100000	0.334840
17000	0.333647	59000	0.334712	101000	0.334931
18000	0.333833	60000	0.334867	102000	0.334745
19000	0.333895	61000	0.335180	103000	0.334874
20000	0.333450	62000	0.335129	104000	0.335000
21000	0.333952	63000	0.334968	105000	0.335048
22000	0.334000	64000	0.334734	106000	0.335057
23000	0.334304	65000	0.334431	107000	0.335150
24000	0.334083	66000	0.334470	108000	0.335056
25000	0.333920	67000	0.334567	109000	0.334954
26000	0.333500	68000	0.334750	110000	0.335255
27000	0.333889	69000	0.334855	111000	0.335108
28000	0.333679	70000	0.334743	112000	0.335170
29000	0.333862	71000	0.334634	113000	0.335142
30000	0.333433	72000	0.334500	114000	0.335158
31000	0.333903	73000	0.334411	115000	0.335078
32000	0.334469	74000	0.334500	116000	0.335009
33000	0.334606	75000	0.334600	117000	0.335188
34000	0.335059	76000	0.334553	118000	0.335186
35000	0.334743	77000	0.334662	119000	0.335303
36000	0.334611	78000	0.334603	120000	0.335225
37000	0.334486	79000	0.334646	121000	0.335281
38000	0.334816	80000	0.334388	122000	0.335115
39000	0.335308	81000	0.334778	123000	0.335341
40000	0.335225	82000	0.334927	124000	0.335266
41000	0.334976	83000	0.334904	125000	0.335304
42000	0.334810	84000	0.334917	126000	0.335206

Table 4.4 (Continued)

Iterat.	Cond.	Iterat.	Cond.	Iterat.	Cond.
127000	0.335087	169000	0.334722	211000	0.334019
128000	0.334906	170000	0.334841	212000	0.334066
129000	0.334721	171000	0.334912	213000	0.333991
130000	0.334846	172000	0.334738	214000	0.334079
131000	0.334939	173000	0.334705	215000	0.334060
132000	0.334720	174000	0.334874	216000	0.334037
133000	0.334902	175000	0.334737	217000	0.334018
134000	0.334709	176000	0.334744	218000	0.334069
135000	0.334785	177000	0.334819	219000	0.334128
136000	0.334897	178000	0.334618	220000	0.334168
137000	0.334985	179000	0.334430	221000	0.334100
138000	0.335029	180000	0.334317	222000	0.334149
139000	0.335014	181000	0.334232	223000	0.334135
140000	0.335129	182000	0.334203	224000	0.334246
141000	0.335199	183000	0.334224	225000	0.334213
142000	0.335282	184000	0.334141	226000	0.334177
143000	0.335154	185000	0.334032	227000	0.334123
144000	0.335215	186000	0.333979	228000	0.334127
145000	0.335062	187000	0.334059	229000	0.334197
146000	0.335000	188000	0.334000	230000	0.334165
147000	0.335020	189000	0.333931	231000	0.334069
148000	0.335101	190000	0.333847	232000	0.334034
149000	0.335074	191000	0.333801	233000	0.334056
150000	0.335140	192000	0.333635	234000	0.334047
151000	0.335126	193000	0.333596	235000	0.334119
152000	0.335092	194000	0.333588	236000	0.334220
153000	0.334980	195000	0.333662	237000	0.334173
154000	0.334890	196000	0.333684	238000	0.334109
155000	0.334858	197000	0.333812	239000	0.334151
156000	0.334795	198000	0.333823	240000	0.334137
157000	0.334720	199000	0.333849	241000	0.334145
158000	0.334804	200000	0.333875	242000	0.334141
159000	0.334786	201000	0.333915	243000	0.334103
160000	0.334800	202000	0.333970	244000	0.334074
161000	0.334733	203000	0.333877	245000	0.334069
162000	0.334784	204000	0.333868	246000	0.334110
163000	0.334877	205000	0.333732	247000	0.334126
164000	0.334884	206000	0.333743	248000	0.334137
165000	0.334800	207000	0.333749	249000	0.334225
166000	0.334759	208000	0.333813	250000	0.334336
167000	0.334796	209000	0.333861	251000	0.334287
168000	0.334756	210000	0.334048	252000	0.334341

Table 4.4 (Continued)

Iterat.	Cond.	Iterat.	Cond.	Iterat.	Cond.
253000	0.334344	295000	0.334898	337000	0.334558
254000	0.334382	296000	0.334855	338000	0.334589
255000	0.334306	297000	0.334848	339000	0.334640
256000	0.334223	298000	0.334802	340000	0.334653
257000	0.334230	299000	0.334763	341000	0.334625
258000	0.334167	300000	0.334847	342000	0.334655
259000	0.334151	301000	0.334857	343000	0.334679
260000	0.334204	302000	0.334768	344000	0.334657
261000	0.334241	303000	0.334815	345000	0.334701
262000	0.334294	304000	0.334868	346000	0.334662
263000	0.334357	305000	0.334902	347000	0.334718
264000	0.334352	306000	0.335003	348000	0.334759
265000	0.334343	307000	0.334971	349000	0.334748
266000	0.334316	308000	0.335032	350000	0.334794
267000	0.334375	309000	0.335065	351000	0.334732
268000	0.334377	310000	0.335035	352000	0.334764
269000	0.334375	311000	0.335045	353000	0.334765
270000	0.334393	312000	0.335048	354000	0.334734
271000	0.334480	313000	0.335022	355000	0.334766
272000	0.334511	314000	0.335000	356000	0.334789
273000	0.334502	315000	0.334940	357000	0.334728
274000	0.334507	316000	0.335022	358000	0.334684
275000	0.334469	317000	0.334997	359000	0.334716
276000	0.334428	318000	0.334906	360000	0.334733
277000	0.334480	319000	0.334859	361000	0.334723
278000	0.334522	320000	0.334850	362000	0.334691
279000	0.334588	321000	0.334766	363000	0.334705
280000	0.334521	322000	0.334727	364000	0.334736
281000	0.334598	323000	0.334737	365000	0.334740
282000	0.334617	324000	0.334701	366000	0.334691
283000	0.334724	325000	0.334634	367000	0.334657
284000	0.334634	326000	0.334577	368000	0.334641
285000	0.334663	327000	0.334615	369000	0.334721
286000	0.334699	328000	0.334665	370000	0.334789
287000	0.334760	329000	0.334638	371000	0.334801
288000	0.334788	330000	0.334636	372000	0.334852
289000	0.334761	331000	0.334653	373000	0.334882
290000	0.334793	332000	0.334605	374000	0.334882
291000	0.334818	333000	0.334610	375000	0.334803
292000	0.334842	334000	0.334599	376000	0.334750
293000	0.334904	335000	0.334549	377000	0.334769
294000	0.334929	336000	0.334479	378000	0.334751

Table 4.4 (Continued)

Iterat.	Cond.	Iterat.	Cond.	Iterat.	Cond.
379000	0.334718	421000	0.334463	463000	0.334523
380000	0.334761	422000	0.334495	464000	0.334558
381000	0.334698	423000	0.334522	465000	0.334527
382000	0.334688	424000	0.334516	466000	0.334453
383000	0.334611	425000	0.334527	467000	0.334463
384000	0.334607	426000	0.334549	468000	0.334425
385000	0.334634	427000	0.334527	469000	0.334407
386000	0.334606	428000	0.334533	470000	0.334438
387000	0.334576	429000	0.334580	471000	0.334380
388000	0.334603	430000	0.334560	472000	0.334422
389000	0.334586	431000	0.334541	473000	0.334423
390000	0.334528	432000	0.334560	474000	0.334397
391000	0.334547	433000	0.334492	475000	0.334385
392000	0.334520	434000	0.334502	476000	0.334410
393000	0.334481	435000	0.334536	477000	0.334474
394000	0.334480	436000	0.334537	478000	0.334418
395000	0.334451	437000	0.334501	479000	0.334392
396000	0.334437	438000	0.334489	480000	0.334412
397000	0.334451	439000	0.334474	481000	0.334455
398000	0.334457	440000	0.334518	482000	0.334378
399000	0.334368	441000	0.334535	483000	0.334373
400000	0.334350	442000	0.334536	484000	0.334329
401000	0.334416	443000	0.334549	485000	0.334365
402000	0.334458	444000	0.334577	486000	0.334420
403000	0.334462	445000	0.334575	487000	0.334402
404000	0.334502	446000	0.334585	488000	0.334398
405000	0.334538	447000	0.334550	489000	0.334348
406000	0.334500	448000	0.334520	490000	0.334392
407000	0.334504	449000	0.334539	491000	0.334373
408000	0.334525	450000	0.334509	492000	0.334364
409000	0.334523	451000	0.334528	493000	0.334367
410000	0.334454	452000	0.334509	494000	0.334356
411000	0.334448	453000	0.334483	495000	0.334313
412000	0.334437	454000	0.334474	496000	0.334315
413000	0.334438	455000	0.334433	497000	0.334280
414000	0.334394	456000	0.334428	498000	0.334249
415000	0.334422	457000	0.334462	499000	0.334257
416000	0.334409	458000	0.334463	500000	0.334282
417000	0.334410	459000	0.334427	501000	0.334283
418000	0.334404	460000	0.334443	502000	0.334307
419000	0.334432	461000	0.334432	503000	0.334316
420000	0.334438	462000	0.334461	504000	0.334294

Table 4.4 (Continued)

Iterat.	Cond.	Iterat.	Cond.	Iterat.	Cond.
505000	0.334297	520000	0.334073	535000	0.333802
506000	0.334320	521000	0.334044	536000	0.333845
507000	0.334314	522000	0.334080	537000	0.333816
508000	0.334270	523000	0.334082	538000	0.333833
509000	0.334271	524000	0.334059	539000	0.333881
510000	0.334243	525000	0.334038	540000	0.333859
511000	0.334239	526000	0.334036	541000	0.333900
512000	0.334230	527000	0.334025	542000	0.333875
513000	0.334232	528000	0.333989	543000	0.333890
514000	0.334204	529000	0.333970	544000	0.333903
515000	0.334192	530000	0.333940	545000	0.333923
516000	0.334163	531000	0.333917	546000	0.333901
517000	0.334124	532000	0.333904	547000	0.333888
518000	0.334106	533000	0.333914	548000	0.333934
519000	0.334094	534000	0.333852	549000	0.333991

each case, however, the random number generator seed was changed. The conductances calculated for the different random numbers are presented in Figure 4.8 and Table 4.5. The valve upstream and downstream lengths for all these cases are equal to the pipe (valve) diameter. Comparing these results with those of the third study, it can be concluded that changing the random number generator initial seed value for calculating the spacelab vacuum vent valve conductance when simulating 10,000 particles has little effect on the final calculated conductance.

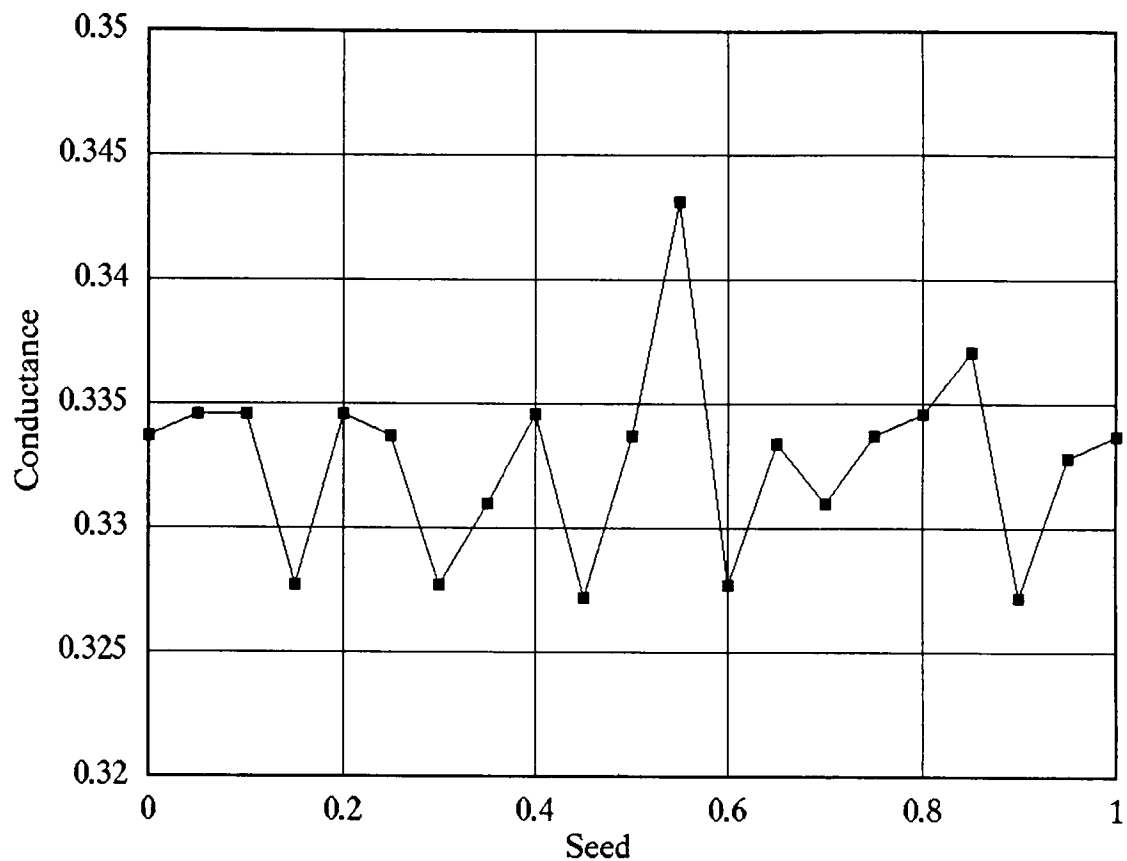


Figure 4.8 - Effect of Different Random Number Generator Seed on the Conductance of the NASA/ESA Spacelab Vacuum Vent Valve With Valve Butterfly Angle at 45° for 10,000 Simulated Particles

Table 4.5 - Effect of Different Random Number Generator Seed on the Conductance of the NASA/ESA Spacelab Vacuum Vent Valve With Valve Butterfly Angle at 45° for 10,000 Simulated Particles

Seed	Conductance	Seed	Conductance
0.00	0.3337	0.55	0.3431
0.05	0.3346	0.60	0.3277
0.10	0.3346	0.65	0.3334
0.15	0.3277	0.70	0.3310
0.20	0.3346	0.75	0.3337
0.25	0.3337	0.80	0.3346
0.30	0.3277	0.85	0.3371
0.35	0.3310	0.90	0.3272
0.40	0.3346	0.95	0.3328
0.45	0.3272	1.00	0.3337
0.50	0.3337		

For the fifth and final study, the exact configuration of the NASA / ESA spacelab vacuum vent valve was investigated and its performance was mapped. This valve has a length to diameter ratio of 2.75. The valve conductance was calculated using 100,000 loops per datum. The initial seed for the valve angle of ninety degrees was zero. The program cycled every five degrees thereafter, until the valve angle was zero, at which point it was ended. Some additional valve angles at one degree intervals were also calculated. All calculated NASA / ESA valve conductance results are presented in Table 4.6 and Figure 4.9.

Table 4.6 - Conductance of the NASA/ESA Spacelab Vacuum Vent Valve as a Function of Butterfly Valve Angle, Using Monte Carlo Analysis and 100,000 Particle Histories per Valve Angle Calculated

Valve Angle (Degrees)	Conductance	Valve Angle (Degrees)	Conductance
0.0	0.00000	41.0	0.27121
1.0	0.05416	42.0	0.27667
2.0	0.06110	43.0	0.27804
3.0	0.06602	44.0	0.28126
4.0	0.07139	45.0	0.28594
5.0	0.07730	46.0	0.28676
6.0	0.08261	47.0	0.28859
7.0	0.08808	48.0	0.29282
8.0	0.09507	49.0	0.29268
9.0	0.10032	50.0	0.29249
10.0	0.10650	51.0	0.29293
11.0	0.11168	52.0	0.29309
12.0	0.11859	53.0	0.29030
13.0	0.12299	54.0	0.29309
14.0	0.12917	55.0	0.29125
15.0	0.13456	56.0	0.29208
16.0	0.13793	57.0	0.29185
17.0	0.14727	58.0	0.28988
18.0	0.15151	59.0	0.29438
19.0	0.15971	60.0	0.29164
20.0	0.16483	61.0	0.29186
21.0	0.16946	62.0	0.29051
22.0	0.17612	63.0	0.29085
23.0	0.17985	64.0	0.29272
24.0	0.18668	65.0	0.28844
25.0	0.19351	66.0	0.29239
26.0	0.19821	67.0	0.29286
27.0	0.20318	68.0	0.29275
28.0	0.20964	69.0	0.29247
29.0	0.21513	70.0	0.29347
30.0	0.21959	71.0	0.29011
31.0	0.22589	72.0	0.29332
32.0	0.23008	73.0	0.29194
33.0	0.23241	74.0	0.28939
34.0	0.23992	75.0	0.29136
35.0	0.24495	76.0	0.29295
36.0	0.24869	77.0	0.29095
37.0	0.25518	78.0	0.29149
38.0	0.25908	79.0	0.29217
39.0	0.26328	80.0	0.29436
40.0	0.26719	81.0	0.29200

Table 4.6 - (Continued)

Valve Angle (Degrees)	Conductance	Valve Angle (Degrees)	Conductance
82.0	0.29128	87.0	0.29230
83.0	0.28973	88.0	0.29128
84.0	0.29196	89.0	0.29195
85.0	0.28889	90.0	0.29287
86.0	0.29127		

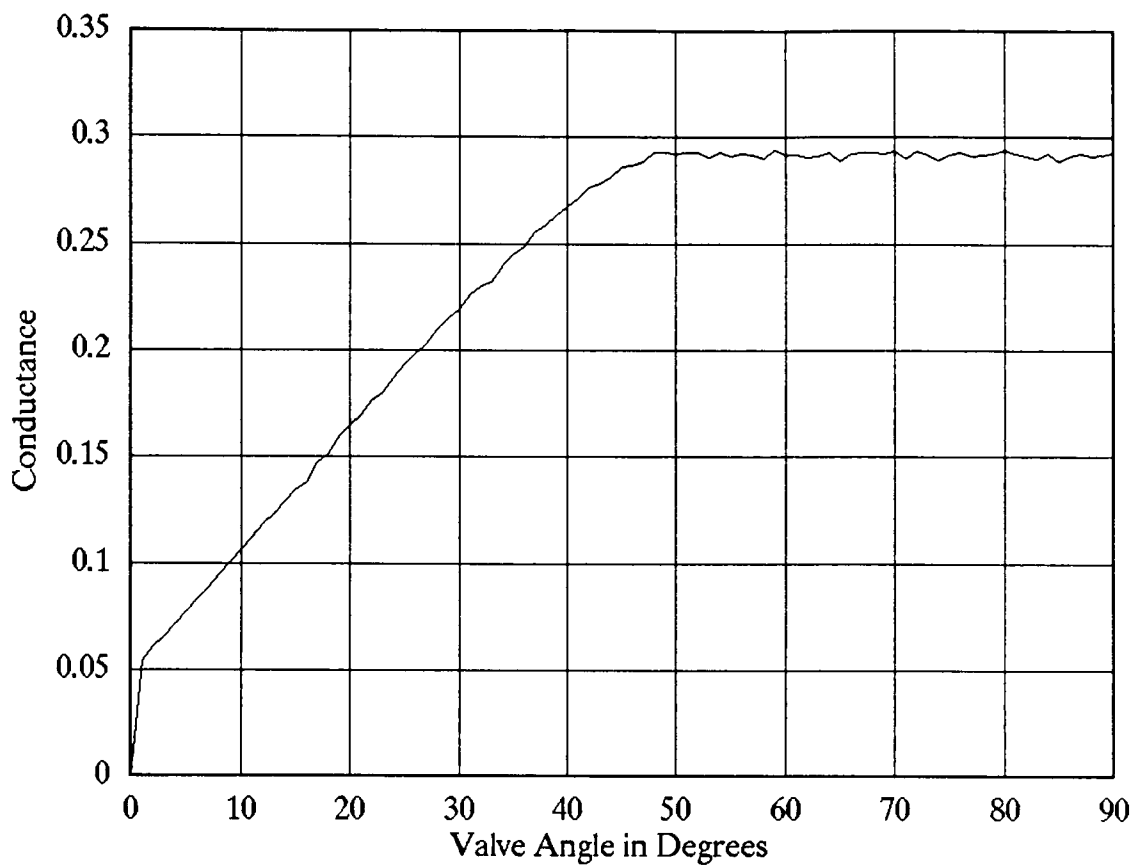


Figure 4.9 - Conductance of the NASA/ESA Spacelab Vacuum Vent Valve as a Function of Butterfly Valve Angle, Using Monte Carlo Analysis and 100,000 Particle Histories per Valve Angle Calculated

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APPENDIXES

APPENDIX A - MONTE CARLO METHOD

The general program flow as suggested by Saksaganskii [6] was followed with some modifications and additions. The resultant program flow diagram is depicted in Figure A.1.

After initiallizing the variables, a particle is generated. The particle is set to enter the valve inlet plane. Its position in the y-z plane is then generated using the following methods and equations as described by Saksaganskii, etc, [3,6,7]. Following Saksaganskii [6], it can be stated that for an opening of radius R, the number of particles to reach a ring of radius Ω is:

$$\frac{dN}{d\Omega} = 2 * \pi * N * \Omega * d\Omega / \pi * R^2 \quad (A.1)$$

where $d\Omega$ is the width of the ring and N is the total number of particles. Setting up the coordinate system per Figure A.2, with the x-axis along the valve body central axis and the valve pivoting around the y-axis and assuming a probability density of:

$$P(\Omega) = 2 * \Omega / R^2 \quad (A.2)$$

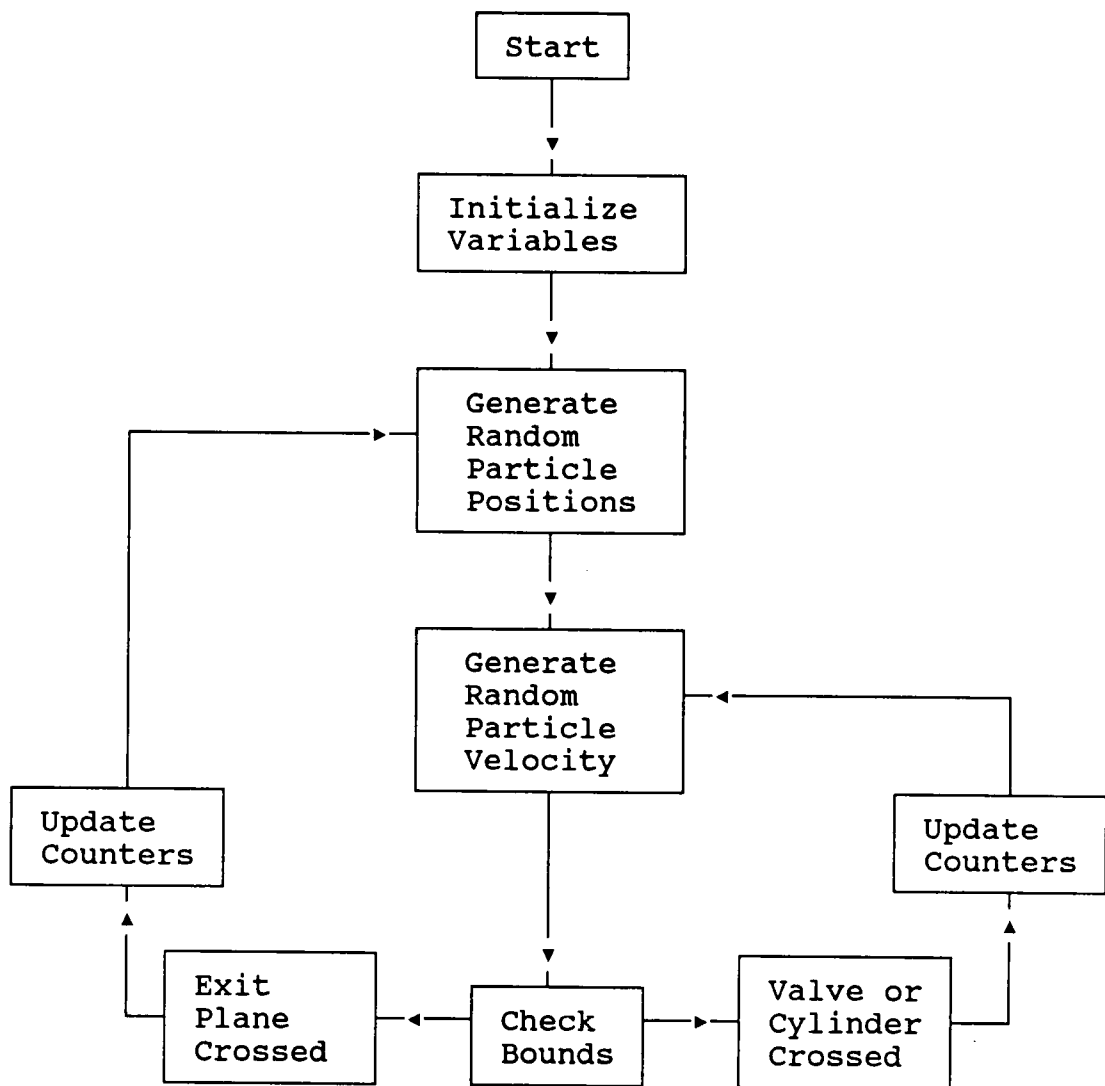


Figure A.1 - Program Flow Chart

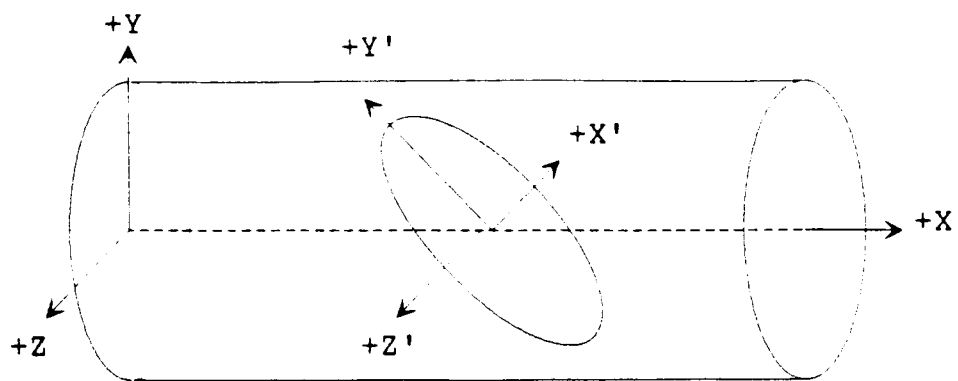


Figure A.2 - Problem Coordinate System Definition

and since:

$$\int_0^{\Omega} P(\Omega) d\Omega = f \quad (\text{A.3})$$

where f is a random number between zero and one, the particle radial position equation at the entrance becomes:

$$\Omega = R * \sqrt{f} \quad (\text{A.4})$$

f is generated by the FORTRAN compiler and has a different value for each equation. Since the particles are distributed uniformly over the entrance area, the particle position polar angle, Φ , can take on any arbitrary value:

$$\Phi = 2 * \pi * f \quad (\text{A.5})$$

where Φ is defined positive in the counter-clockwise direction. The initial particle position is then calculated in the three dimensions using the following equations:

$$X. = 0 \quad (\text{A.6})$$

$$Y. = \Omega * \sin(\Phi) \quad (\text{A.7})$$

$$Z. = \Omega * \cos(\Phi) \quad (\text{A.8})$$

where X., Y., and Z. are the three initial positions of the particle in the x, y, and z axes respectively. After generating the particle initial position, its initial unit velocity vector into the valve is generated.

The particle velocity vectors are also generated using the equations and guidelines as set forth by Saksaganskii and others [3,6,7]. Following Saksaganskii [6] and assuming a diffusion distribution of the particles at the entrance and upon ejection from solid boundaries, an elementary solid angle is defined as:

$$d\alpha = 2 * \pi * \sin \mu * d\mu \quad (\text{A.9})$$

The number of particles that have reached this elementary angle, dN_{μ} , is proportional to $\cos \mu$:

$$dN_{\mu} = N * d\alpha * \cos \mu \quad (\text{A.10})$$

Assuming a probability density of:

$$P(\mu) = A * \sin \mu * \cos \mu \quad (\text{A.11})$$

and due to the normalization:

$$\int_0^{\pi/2} P(\mu) * d\mu = 1 \quad (\text{A.12})$$

Saksaganskii [6] states that the coefficient A is determined to be equal to 2. Since

$$\int_0^{\mu} P(\mu) * d\mu = f \quad (\text{A.13})$$

it therefore follows that:

$$\mu = \arcsin \sqrt{f} \quad (\text{A.14})$$

As with Φ , the angle σ is calculated arbitrarily as:

$$\sigma = 2 * \pi * f \quad (\text{A.15})$$

Here, μ is the angle which the unit velocity vector makes with the x-axis and σ is the angle between the unit velocity vector and the z-axis. The three velocity vector components are then calculated using μ and σ as follows:

$$V_x = \cos (\mu) \quad (\text{A.16})$$

$$V_y = \sin (\mu) * \sin (\sigma) \quad (\text{A.17})$$

$$V_z = \sin(\mu) * \cos(\sigma) \quad (A.18)$$

where V_x , V_y , and V_z are along the x, y, and z axis, respectively.

Once the particle position and velocity vector are known, the program determines which boundary has been crossed, and where it has been crossed by the particle. (The boundaries in this problem consist of the outlet, the inlet, the butterfly, and the valve body.) To do this, the program first determines the points of intersection between the velocity vector and the various boundaries. This is done by first checking for the particle crossing the inlet (backscatter), then the outlet (passed through), the valve butterfly (bounced), and finally the valve body (bounced). The distance the particle has to travel to cross each crossed boundary is then compared. The shortest distance traveled to a boundary points to the actual boundary crossed. If the boundary is the valve exit plane, the counter indicating the number of particles exited is advanced by one and another particle at the valve inlet is generated, repeating the process. If the inlet plane was crossed, the particle is presumed to be backscattered. In this case the backscatter counter is advanced by one and a new particle at the valve inlet is generated, repeating the

process. If, however, the valve body or butterfly have been crossed, the point in three dimensions where the particle velocity vector crosses the solid surface is saved and a new particle velocity vector in the three dimensions is generated at that location. (The process of generating a velocity vector for a particle on a boundary is described in Appendix B.) The saved crossing point is then used as the initial position for the particle with the newly generated velocity vector and all boundaries are once again checked for crossing and the secondary loop is executed ad infinitum until the particle either crosses the valve inlet or outlet.

After the requested number of particles have been simulated, the resultant probability of a particle starting at the valve inlet and exiting at the valve outlet may be determined. This value is equal to the number of particles which exited through the valve exit plane divided by the total number of particles simulated. The resultant number would be the valve conductance.

The valve backscatter coefficient is defined by the ratio of the number of particles which exited from the inlet plane to the total number of particles simulated. The sum of the backscatter coefficient and the conductance coefficient must equal one, except for round off error in

division. In any case, the valve resistance is defined as the inverse of the valve conductance.

APPENDIX B - COORDINATE TRANSFORMATIONS

Since the Monte Carlo analysis of the valve problem requires following a single particle at a time and bouncing it off of different surfaces, the similarity of the problem with that of following rays of light in a three-dimensional graphics environment (ray tracing) became apparent.

The approach used here requires extensive use of coordinate rotation and translation. These tasks are performed using methods set forth by Angell and Griffith [5]. The particle P is thus represented by its coordinates¹ in the three dimensions as:

$$P_1 \equiv (x_1, y_1, z_1) \quad (B.1)$$

where x_1 is its distance from the valve entrance, and y_1 and z_1 are its coordinates on the y - z plane. The coordinate¹ system origin is set up at the valve entrance plane. The x -axis runs along the center of the cylinder representing the valve body and the y - z plane is co-planar with the valve entrance with the butterfly pivoting around the y -axis.

The particle velocity vector, V_1 , is defined by its direction cosines:

$$V_1 \equiv (V_{1x}, V_{1y}, V_{1z}) \quad (B.2)$$

where:

$$V_{1x} \equiv \cos \Omega_x$$

$$V_{1y} \equiv \cos \Omega_y \quad (B.3)$$

$$V_{1z} \equiv \cos \Omega_z$$

and Ω_x , Ω_y , and Ω_z are the angles which V_1 makes with the x, y, and z axes, respectively. Multiplication of a vector by a scalar is represented by the "*" symbol and is defined as:

$$\mu * V \equiv \mu V_x + \mu V_y + \mu V_z \quad (B.4)$$

where V is the vector and V_x , V_y , and V_z are its components in the x, y, and z directions. The dot product (sometimes referred to as scalar product) of two vectors is represented by the symbol "." and is defined as:

$$L_1 \cdot L_2 = (L_{1x} * L_{2x}) + (L_{1y} * L_{2y}) + (L_{1z} * L_{2z}) \quad (B.5)$$

The angle between two direction vectors V_1 and V_2 is represented by Ω and is defined as:

$$\cos \Omega = \frac{V_1 \cdot V_2}{|V_1| |V_2|} \quad (B.6)$$

Further, the length of a vector $V \equiv (V_x, V_y, V_z)$ (sometimes called the modulus, or absolute value) is represented as $|V|$ and is defined as its distance from the origin, or:

$$|V| \equiv \sqrt{V_x^2 + V_y^2 + V_z^2} \quad (B.7)$$

A vector having a length equal to one is called a unit vector. In this system of representation, a straight line is defined as:

$$L(\mu) \equiv P_1 + \mu * V_1 \quad (B.8)$$

where μ is the line length and P_1 is called the base vector and is where the line begins. A plane is represented by the equation:

$$N \cdot R = k \quad (B.9)$$

where N is the unit normal vector to the plane, R is the coordinates of a point on the plane, and k is a scalar value. If a line and plane are not parallel to each other,

there exists a unique value, μ , which would define where the two cross. This value has to be found such that:

$$N \cdot (P_1 + \mu * V_1) = k \quad (B.10)$$

The value for μ is given by Angell and Griffith [5] as:

$$\mu = \frac{k - N \cdot V_1}{N \cdot P_1} \quad (B.11)$$

If $N \cdot V_1 = 0$, then the cosine of the angle that V_1 makes with the unit normal vector to the surface is zero. This is true if and only if the unit normal vector to the surface, N , is also normal to P_1 . Thus, if $N \cdot P_1 = 0$, the line and the plane are parallel and there is no unique solution for μ . If a solution for μ can be found, the point, P_2 , in three dimensions where the line crosses the plane may be determined by using:

$$P_2 = P_1 + \mu * V_1 \quad (B.12)$$

It is necessary to analytically represent the surfaces of interest in vector format. Using Angell and Griffith [5], a surface may be represented as:

$$f(R) \equiv N \cdot R - k \quad (B.13)$$

The space with respect to $f(R)$ may now be represented by three sets of points: those with $f(R) = 0$ (the zero set), those with $f(R) < 0$ (the negative set), and those with $f(R) > 0$ (the positive set). A point P_1 lies on the surface if and only if $f(P_1) = 0$. For a sphere of radius r , $f(R)$ is defined as:

$$f(R) \equiv r^2 - |\tau|^2 \quad (B.14)$$

or:

$$f(x,y,z) \equiv r^2 - x^2 - y^2 - z^2 \quad (B.15)$$

Here, if $f(P_1) = 0$, P_1 is on the surface, if $f(P_1) > 0$, P_1 is inside the sphere, and if $f(P_1) < 0$, P_1 is outside the sphere. Applying the same conventions to a cylinder of radius r , we have:

$$f(x,y,z) \equiv r^2 - y^2 - z^2 \quad (B.16)$$

and

$$0 \leq x \leq L \quad (B.17)$$

with the cylinder centerline on the x-axis, and the cylinder having a length L. Here, if $f(P_1) = 0$, P_1 is on the cylinder, if $f(P_1) < 0$, P_1 is outside the cylinder, and if $f(P_1) > 0$, P_1 is inside the cylinder. The representation of a disk in the y-z plane becomes:

$$f(x,y,z) = r^2 - y^2 - z^2 \quad (B.18)$$

and

$$x = M \quad (B.19)$$

where the disk of radius r is located at M on the x-axis.

Now all that remains is to rotate the velocity vector and the location of the particle from the central coordinate system to that of the valve, or that of a point on the surface of the cylinder. Angell and Griffith [5] separate the rotation of coordinates into three independent tasks. If the particle velocity vector, V, in the three dimensions is represented as:

$$V \equiv (V_x, V_y, V_z) \quad (B.20)$$

then the matrix transformation for rotation by an angle Ω

about the x-axis becomes:

$$\begin{bmatrix} \cos \Omega & \sin \Omega & 0 \\ -\sin \Omega & \cos \Omega & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (\text{B.21})$$

where Ω is positive in the counter clockwise direction and the axes are based on the right-hand rule. The same matrix transformation for rotation about the y-axis becomes:

$$\begin{bmatrix} \cos \Omega & 0 & \sin \Omega \\ 0 & 1 & 0 \\ \sin \Omega & 0 & \cos \Omega \end{bmatrix} \quad (\text{B.22})$$

and for rotation about the z-axis, it becomes:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \Omega & \sin \Omega \\ 0 & -\sin \Omega & \cos \Omega \end{bmatrix} \quad (\text{B.23})$$

Using this method, the order in which the coordinate rotations are performed becomes important. In other words, rotation of a vector first by an angle Ω about the x-axis, second by an angle Ω about the y-axis, and third by an angle Ω about the z-axis may produce a different result than rotating the same vector by first Ω about the y-axis, then Ω about the x-axis, and finally Ω about the z-axis.

second by Ω_z about the z-axis, and third by Ω_x about the x-axis.

The multiplication of the array representing the particle velocity vector with the array representing the rotation is performed according to the standard conventions of array multiplications. Vector V in equation (B.20) represented in array format is:

$$V \equiv \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} \quad (B.24)$$

and a general three element by three element array A may be defined as follows:

$$A \equiv \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad (B.25)$$

Multiplying the vector V and the array A will give the following results:

$$V \times A \equiv \begin{bmatrix} a_{11} * V_x + a_{12} * V_y + a_{13} * V_z \\ a_{21} * V_x + a_{22} * V_y + a_{23} * V_z \\ a_{31} * V_x + a_{32} * V_y + a_{33} * V_z \end{bmatrix} \quad (B.26)$$

Thus, a vector generated on the surface of the butterfly valve using its local coordinate system, or on the surface of the cylindrical portion of the valve using its local coordinate system, may be transformed back into the valve central coordinate system. With the velocity vector in the central coordinate system, the program may proceed to determine where the next boundary will be crossed.

APPENDIX C - MONTE CARLO PROGRAM LISTING

The following is the listing for the Monte Carlo simulation program used to calculate the results presented here:

```

C                                     1.D1
C      IMPLICIT NONE
C      CHARACTER*80 LINE, OLD_LINE, INPUT, OUTPUT, GAS_NAME,
C      &TITLE
C      CHARACTER*8  STAT
C      CHARACTER*11 ACC
C      CHARACTER*1  ANS
C      INTEGER      I, J
C      REAL*4       L_AFT, SEED
C      LOGICAL      EXISTS

C                                     1.C1
C      REAL*4       R_INLET, X0, Y0, Z0, RHO, PHI
C      LOGICAL      F_WRI_2
C      COMMON /U1_1/ R_INLET, X0, Y0, Z0, RHO, PHI, F_WRI_2

C                                     1.C2
C      INTEGER      N_TOTAL, N_OUT, N_IN, N_ABS(10),
C      >N_SURF, N_ABS(10)
C      COMMON /U1_2/ N_TOTAL, N_OUT, N_IN, N_ABS, N_SURF,
C      >N_ABS(10)

C                                     1.C3
C      REAL*4       V(4)
C      COMMON /U1_3/ V

C                                     1.C4
C      REAL*4       T(10), L_TOTAL, L_BEF, VALVE_ANG,
C      >R_OUTLET, R_VALVE
C      COMMON /U1_4/ T      , L_TOTAL, L_BEF, VALVE_ANG,
C      >R_OUTLET, R_VALVE

C                                     1.C5
C      INTEGER      I_BOUNCE, J_BOUNCE, LOOPCT
C      LOGICAL      F_PLOT
C      COMMON /U1_5/ I_BOUNCE, J_BOUNCE, LOOPCT, F_PLOT

```

```

C                                     1.C6
C      INTEGER      E_ACCURACY, GAMMA_ACCURACY, P_ACCURACY
C      LOGICAL      F_STOP
C      COMMON /U1_6/ E_ACCURACY, GAMMA_ACCURACY, P_ACCURACY

```

```

      PROGRAM U1

```

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

C
C      Program to calculate the conductance of a valve using
C      the Monte Carlo method of statistical analysis.

```

```

C
C      For more information look in the file with same name,
C      with '.C' extension

```

```

C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

      INCLUDE '1.D1'
      INCLUDE '1.C1'
      INCLUDE '1.C2'
      INCLUDE '1.C3'
      INCLUDE '1.C4'
      INCLUDE '1.C5'
      INCLUDE '1.C6'
      INCLUDE '1.DT1'
      INCLUDE '1.P1'

```

```

      REAL*4      BETA(10), VALVE_ANG_FROM, VALVE_ANG_TO,
>               VALVE_ANG_STEP, L_DELT, L_MAX
      COMMON      BETA
      INTEGER      N_MAX1, IVLV, IVLVF, IVLVT, IVLVS, I_TLF,
>               ITLT, ITLD, I_L, N_MAX2, N_MAX3
      LOGICAL      F_WRI_6

```

```

C *** INITIALIZE VARIABLES

```

```

      N_TOTAL = 0      ! Running total of particles so far
      N_IN    = 0      ! Number of Particles exiting the
                        ! valve from the INLET
      N_OUT   = 0      ! Number of Particles exiting the
                        ! valve from the OUTLET
      N_SURF  = 4      ! Number of surfaces being simulated
                        ! (including the I/O)
      DO 3 I = 1, 10
      N_BOUNCE(I)=0      ! Number of particles bounced off
                        ! of surface I
3      N_ABS(I)= 0      ! Number of particles absorbed by
                        ! each simulated surface
      DO 8 I = 1, 3
8      V(I)    = 0      ! Particle Velocity Vector in
                        ! Absolute Coordinate System
      V(4)    = 1      ! Magnitude of the particle Velocity
                        ! Vector

```

```

ACC      = 'SEQUENTIAL'      ! Output file access type
STAT     = 'NEW'              ! Output file status
F_STOP   = .FALSE.
E_ACCURACY = 0.0001
P_ACCURACY = 0.0001
GAMMA_ACCURACY = 0.0001

C *** GET INPUT FILE NAME

35      FORMAT(A)
1       WRITE(*,2)
2       FORMAT(/,1X,'Enter the INPUT file name > ')
C       READ(*,*) INPUT
        INPUT='1.INP'
        INQUIRE(FILE=INPUT,EXIST=EXISTS)
        IF(.NOT.EXISTS) THEN
4         WRITE(*,5) CHARNB(INPUT)
5         FORMAT(1X,'The INPUT file ',A,' does not exist')
        GO TO 1
        END IF
        OPEN(1,FILE=INPUT,STATUS='OLD')

C *** GET OUTPUT FILE NAME
6       WRITE(*,7)
7       FORMAT(/,1X,'Enter the OUTPUT PLOT file name > ')
C       READ(*,*) OUTPUT
        OUTPUT='1.OUT'
        INQUIRE(FILE=OUTPUT,EXIST=EXISTS)
        IF(EXISTS) THEN
C         DO 8 I = 80, 1, -1
C8        IF(OUTPUT(I:I).NE.' ') GO TO 9
C         I = NBLANK(OUTPUT)
9         WRITE(*,10) CHARNB(OUTPUT)
10        FORMAT(1X,'The OUTPUT PLOT file ',A,' already',
>              ' exist, '//
>              5X,'( O )      1.   Over-write'//
>              5X,'( A )      2.   Append'//
>              5X,'(<CR> )    3.   New File   [Default]'//
>              2X,'>> ')
C        READ(*,*) ANS
        ANS = 'O'
        IF(ANS.EQ.'O'.OR.ANS.EQ.'o'.OR.ANS.EQ.'1') THEN
            STAT = 'UNKNOWN'
        ELSE IF(ANS.EQ.'A'.OR.ANS.EQ.'a'.OR.ANS.EQ.'2') THEN
            ACC = 'APPEND'
        ELSE
            GO TO 6
        END IF
        END IF
        OPEN(2,FILE=OUTPUT,STATUS=STAT,ACCESS=ACC)
        OPEN(8,FILE='1.DAT',STATUS='UNKNOWN')
        CLOSE(8,STATUS='KEEP')

```

```

C *** BEGIN READING INPUT DATA

  OLD_LINE = LINE
  I_READ = I_READ + 1
  READ(1,*,ERR=11,END=12) LINE      ! READ PROBLEM TITLE
  TITLE = LINE
  WRITE(2,35) TITLE
  OLD_LINE = LINE
  I_READ = I_READ + 1
  READ(1,*,ERR=11,END=12) LINE      ! READ GAS NAME
  GAS_NAME = LINE
  WRITE(2,17) CHARNB(GAS_NAME)
17  FORMAT(1X,'The gas being analyzed > ',A)
  OLD_LINE = LINE
  I_READ = I_READ + 1
C    READ(1,*,ERR=11,END=12) LINE    ! READ INLET, OUTLET,
                                     !      & VALVE RADII
  READ(1,*,ERR=11,END=12) L_BEF, L_AFT, L_DELT, L_MAX
                                     ! READ LENGTH BEF & AFT VALVE LOCAT
  WRITE(OLD_LINE,*) L_BEF, L_AFT, L_DELT
  L_TOTAL = L_BEF + L_AFT
  WRITE(2,18) L_BEF, L_AFT, L_TOTAL, L_DELT, L_MAX
18  FORMAT(1X,'Length before Valve > ',G16.8/
>    1X,'Length after Valve > ',G16.8/
>    1X,'Total valve length > ',G16.8/
>    1X,'Valve length increment > ',G16.8/
>    1X,'Maximum valve length > ',G16.8)
  I_READ = I_READ + 1
C    READ(1,*,ERR=11,END=12) LINE    ! READ INLET, OUTLET,
                                     !      & VALVE RADII
C *** READ INLET, OUTLET, & VALVE RADII
  READ(1,*,ERR=11,END=12) R_INLET, R_OUTLET, R_VALVE
  WRITE(OLD_LINE,*) R_INLET, R_OUTLET, R_VALVE
  WRITE(2,19) R_INLET, R_OUTLET, R_VALVE
19  FORMAT(1X,'Inlet Radius > ',G16.8/
>    1X,'Outlet Radius > ',G16.8/
>    1X,'Valve Radius > ',G16.8)
C    READ(LINE,ERR=11) R_INLET, R_OUTLET, R_VALVE
  I_READ = I_READ + 1
C    READ(1,*,ERR=11,END=12) LINE ! READ VALVE ANGLE (DEG)
C    OLD_LINE = LINE
C    READ(LINE,*,ERR=11) VALVE_ANG_FROM, VALVE_ANG_TO,
C    > VALVE_ANG_STEP
  READ(1,*,ERR=11) VALVE_ANG_FROM, VALVE_ANG_TO,
> VALVE_ANG_STEP
  WRITE(2,20) VALVE_ANG_FROM, VALVE_ANG_TO,
> VALVE_ANG_STEP
20  FORMAT(1X,'Valve angle from > ',G16.8,' Deg.'/
>    1X,'Valve angle to > ',G16.8,' Deg.'/
>    1X,'Valve angle step > ',G16.8,' Deg.')

```

```

VALVE_ANG = VALVE_ANG * PI / 180.
I_READ = I_READ + 1
READ(1,*,ERR=11,END=12) LINE      ! READ RANDOM NUMBER
                                   ! GENERATOR SEED

OLD_LINE = LINE
READ(LINE,*,ERR=11) SEED
WRITE(2,21) SEED
21  FORMAT(1X,'Rnd Num Generator SEED > ',G16.8)
SEED = RANDS(SEED)
READ(1,*) J, (BETA(I), I=1,J)  ! READ STICKIN COEFFS
READ(1,*) N_MAX1, N_MAX2      ! MAXIMUM LOOP COUNT
READ(1,*) F_PLOT              ! PLOT FLAG: .TRUE. = PLOT
READ(1,*) F_WRI_2             ! DIAG. OUTPUT FLAG TO UNIT 2
READ(1,*) F_WRI_6             ! DIAG. OUTPUT FLAG TO SCREEN

IF(F_PLOT) OPEN(3,FILE='1.ACD',STATUS='OLD',
> ACCESS='APPEND')

CLOSE(1,STATUS='KEEP')

IVLVF = VALVE_ANG_FROM
IVLVT = VALVE_ANG_TO
IVLVS = VALVE_ANG_STEP

I_TLF = L_TOTAL
ITLT  = L_MAX
ITLD  = (L_DELT * 2.)
IF(ITLD.EQ.0) ITLD = 1

DO 998 I_L = I_TLF, ITLT, ITLD

WRITE(*,*) 'LBEF, LAFT, LTOT = ', L_BEf, L_AFT,
> L_TOTAL
WRITE(*,*) 'VALVE ANGLE = ',IVLV , IVLVF, IVLVT, IVLVS

IF(IVLVS.EQ.0) IVLVS = 1

DO 999 IVLV = IVLVF, IVLVT, IVLVS

VALVE_ANG = IVLV
VALVE_ANG = VALVE_ANG * PI / 180.

WRITE(*,*) 'VALVE ANGLE = ',VALVE_ANG*180./PI

C *** MONTE CARLO ANALYSIS LOOP

WRITE(2,22)
22  FORMAT(80('*')/6X,'RHO',12X,'PHI',12X,'X0',14X,'Y0',
> 11X,'Z0'/5X,'THETA',11X,'PSI',3X,'Vx, Vy, Vz, |V|')

I_BOUNCE = 0
N_MAX3 = N_MAX2

```

```

DO 15 LOOPCT = 1, N_MAX1
  J_BOUNCE = -1
  IF(F_WRI_2) WRITE(2,16) LOOPCT
16  FORMAT(/80('*')/1X,'Iteration count (LOOPCT) = ',I7)
    CALL U2(LLOOPCT,F_PLOT)      ! INITIALIZE NEW
                                ! PARTICLE LOCATION
    N_TOTAL = N_TOTAL + 1
    CALL U3(V,F_WRI_2) ! INITIALIZE NEW PARTICLE V.V.
    IF(V(1).LT.0) THEN ! PARTICLE BACKSCATTERED,
                        ! GENERATE NEW ONE
      N_IN = N_IN + 1
      N_ABS(1) = N_ABS(1) + 1
      N_BOUNCE(1) = N_BOUNCE(1) + 1
      WRITE(2,*) 'BACKSCATTERED, LOOPCT = ', LOOPCT
      GO TO 15
    END IF
24  CALL U4()      ! DETERMINE POINTS OF INTERSECTION
                  ! BETWEEN V.V. & PLANES
    J_BOUNCE = J_BOUNCE + 1
    CALL U5(J,F_WRI_6) ! SELECT INTERSECTED SURFACE
                      ! & POINT OF INTERSECTION
    GO TO (23,24,15) J ! 23 --> CROSSD INLET/OUTLET
! 24 --> CROSSD CYL/VLV
23  CALL U6()      ! TAKE CARE OF OUTPUT
    IF(F_STOP) GO TO 25

    IF(N_TOTAL.EQ.N_MAX3) THEN
      N_MAX3 = N_MAX3 + N_MAX2
      CALL U7(VALVE_ANG,PI,L_TOTAL) ! WRITE OUTPUT
    END IF

15  CONTINUE
25  CALL U7(VALVE_ANG,PI,L_TOTAL) ! CLEAN UP AND END

    GO TO 9999

9999 CONTINUE

C *** INITIALIZE VARIABLES

    N_TOTAL = 0      ! Running total of particles so far
    N_IN     = 0      ! Number of Particles exiting the
                    ! valve from the INLET
    N_OUT    = 0      ! Number of Particles exiting the
                    ! valve from the OUTLET
    N_SURF   = 4      ! Number of surfaces being simulated
                    ! (including the I/O)
    DO 333 I = 1, 10
      N_BOUNCE(I)=0    ! Number of particles bounced off
                    ! of surface I
333  N_ABS(I)=0        ! Number of particles absorbed by
                    ! each simulated surface

```

```

      DO 888 I = 1, 3
888   V(I) = 0      ! Particle Velocity Vector in
                   ! Absolute Coordinate System
      V(4) = 1 ! Magnitude of the particle Velocity Vector
      F_STOP = .FALSE.
      E_ACCURACY = 0.0001
      P_ACCURACY = 0.0001
      GAMMA_ACCURACY = 0.0001
999   CONTINUE

      L_BEF = L_BEF + L_DELT
      L_AFT = L_AFT + L_DELT
      L_TOTAL = L_BEF + L_AFT

998   CONTINUE
      GO TO 9998

11    WRITE(*,13) I_READ, OLD_LINE
13    FORMAT(1X,'***** ERROR *****'//
>         1X,'INPUT file read error on line ',I7/
>         1X,'Last line read was :'/A80//)
      GO TO 9998

12    WRITE(*,14) I_READ, OLD_LINE
14    FORMAT(1X,'***** UEOF *****'//
>         ' Unexpected End Of File reached in INPUT file'
>         'on line ',I7/1X,'Last line read was :'/A80//)
      GO TO 9998

9998  CLOSE(2,STATUS='KEEP')
      WRITE(*,*) '[FORTRAN STOP - U1]'
      STOP
      END

      SUBROUTINE U2(LOOPCT,F_PLOT)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C   Subroutine to calculate the starting position (vector)
C   of the particle to be followed. {Po=(xo,yo,zo)}
C
C   For more information look in the file with same name,
C   with '.C' extension
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      IMPLICIT NONE
      INTEGER LOOPCT
      LOGICAL F_PLOT, F_WRI_2
      CALL RAND_POS(LOOPCT,F_PLOT)
      RETURN
      END

```

```

      SUBROUTINE U3(V,F_WRI_2)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      Subroutine to calculate the unit velocity vector of
C      the emerging particle. {D=(xd,yd,zd), |D|=1}
C
C      For more information look in the file with same name,
C      with '.C' extension
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IMPLICIT NONE
      REAL*4    V(4)
      LOGICAL   F_WRI_2
      CALL RAND_V_V(V,F_WRI_2)
      RETURN
      END

      SUBROUTINE U4()
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      Subroutine to calculate the the points of intersection
C      between the molecule trajectory and the surfaces.
C
C      For more information look in the file with same name,
C      with '.C' extension
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      IMPLICIT NONE
      INTEGER I
      INCLUDE '1.C1'
      INCLUDE '1.C2'
      INCLUDE '1.C4'
      INCLUDE '1.P1'
C *** INITIALIZE THE LENGTH VECTOR, T AS -1.
      DO 1 I = 1, N_SURF
1      T(I) = -1.
C *** CHECK FOR THE POSITION OF V.V. INTERSECT WITH THE C
      SURFACES
      IF(F_WRI_2) WRITE(2,*) 'INLET'
      CALL CHECK_PLANE(T(1),0.,R_INLET,0.) ! INLET CROSSING
      IF(F_WRI_2) WRITE(2,*) 'OUTLET'
      CALL CHECK_PLANE(T(2),L_TOTAL,R_OUTLET,0.)
C  OUTLET CROSSING
      IF(F_WRI_2) WRITE(2,*) 'VALVE'
      CALL CHECK_PLANE(T(3),L_BEF,R_VALVE,VALVE_ANG)
C  VALVE CROSSING
      IF(F_WRI_2) WRITE(2,*) 'CYLINDER'
      CALL CHECK_CYL(T(4)) ! CYL CROSSING
      RETURN
      END

```

```

      SUBROUTINE U5(J,F_WRI_6)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      Subroutine to calculate the surface at which the
C      particle has arrived and the coordinates of the point
C      of impact.
C      For more information look in the file with same name,
C      with '.C' extension
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IMPLICIT NONE
      REAL*4    T_STAR, BETA(10)
      INTEGER    L_STAR, I, J
      LOGICAL    F_WRI_6
      INCLUDE '1.C1'
      INCLUDE '1.C2'
      INCLUDE '1.C3'
      INCLUDE '1.C4'
      INCLUDE '1.C5'
      COMMON     BETA
      T_STAR = 99999.
      L_STAR = 0
      J = 3
      IF(F_WRI_2) WRITE(2,*) 'SUB U5'
      DO 1 I = 1, N_SURF
          IF(F_WRI_2) WRITE(2,*) 'T(',I,')=',T(I)
          IF(T(I).LT.0.OR.T(I).GT.T_STAR) GO TO 1
          T_STAR = T(I)
          L_STAR = I
1      CONTINUE
      IF(F_WRI_6) WRITE(*,*) 'T_STAR = ', T_STAR, ' L_STAR='
>      , L_STAR, 'LOOPCT = ', LOOPCT
      IF(F_WRI_2) WRITE(2,*) 'T_STAR = ',T_STAR, ' L_STAR='
>      , L_STAR
      IF(L_STAR.EQ.0) THEN
          WRITE(*,*) '*** NO PLANE CROSSED! ***'
          T_STAR = 2.
          IF(F_WRI_2) WRITE(2,*) (V(I),I=1,4)
          X0 = X0 + T_STAR* V(1)
          Y0 = Y0 + T_STAR* V(2)
          Z0 = Z0 + T_STAR* V(3)
          T_STAR = 99999.
          IF(F_PLOT) CALL PLOT_P(15,16)
      ELSE IF(L_STAR.EQ.1) THEN
          ! INLET
          N_ABS(1) = N_ABS(1) + 1
          N_BOUNCE(1) = N_BOUNCE(1) + 1
          N_IN = N_IN + 1
          J = 1
          X0 = X0 + T_STAR* V(1)
          Y0 = Y0 + T_STAR* V(2)
          Z0 = Z0 + T_STAR* V(3)
          IF(F_PLOT) CALL PLOT_P(13,14)
      ELSE IF(L_STAR.EQ.2) THEN
          ! OUTLET

```

```

      N_ABS(2) = N_ABS(2) + 1
      N_BOUNCE(2) = N_BOUNCE(2) + 1
      N_OUT = N_OUT + 1
      J = 1
      X0 = X0 + T_STAR* V(1)
      Y0 = Y0 + T_STAR* V(2)
      Z0 = Z0 + T_STAR* V(3)
      IF(F_PLOT) CALL PLOT_P(8,9)
      ELSE IF(L_STAR.EQ.3) THEN                                ! VALVE
        N_BOUNCE(3) = N_BOUNCE(3) + 1
        CALL BOUNCE_VALVE(T_STAR,BETA(3),J)
      ELSE IF(L_STAR.EQ.4) THEN                                ! CYLINDER
        N_BOUNCE(4) = N_BOUNCE(4) + 1
        CALL BOUNCE_CYL(T(4),BETA(4),J)
      END IF
      RETURN
      END

```

```

      SUBROUTINE U6()
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      C
      C      Subroutine to check for the accuracy and decide
      C      whether or not to continue
      C      For more information look in the file with same name,
      C      with '.C' extension
      C
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IMPLICIT NONE
      REAL*4 P, E, GAMMA(10), RN_TOTAL, PO, EO, GAMMAO(10)
      INTEGER I
      INCLUDE '1.C1'
      INCLUDE '1.C2'
      INCLUDE '1.C6'
      C *** CALCULATE THE NEW CONDUCTANCE, BACKSCATTER, AND
      C CAPTURE COEFFICIENTS:
      RN_TOTAL = N_TOTAL
      P = FLOAT(N_OUT) / RN_TOTAL      ! CONDUCTANCE
      E = FLOAT(N_IN ) / RN_TOTAL      ! BACKSCATTER
      DO 1 I = 1, N_SURF
      1  GAMMA(I) = FLOAT(N_ABS(I)) / RN_TOTAL ! CAPTURE
      IF(ABS(P-PO).GT.P_ACCURACY.OR.ABS(E-EO).GT.E_ACCURACY)
      >                                     GO TO 5
      DO 2 I = 1, N_SURF
      2  IF(ABS(GAMMA(I)-GAMMAO(I)).GT.GAMMA_ACCURACY) GOTO 5
      F_STOP = .TRUE.
      5  PO = P
      EO = E
      DO 4 I = 1, N_SURF
      4  GAMMAO(I) = GAMMA(I)
      SAVE
      RETURN
      END

```

```

      SUBROUTINE U7 (VALVE_ANG,PI,L_TOTAL)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      Subroutine to clean-up and finish.
C
C      For more information look in the file with same name,
C      with '.C' extension
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      INCLUDE '1.D1'
      INCLUDE '1.C1'
      INCLUDE '1.C2'
      REAL*4 P, E, GAMMA(10), RN_TOTAL, BOUNCE(10),
>      VALVE_ANG, PI, L_TOTAL

C *** CALCULATE THE CONDUCTANCE, BACKSCATTER, AND CAPTURE
C COEFFICIENTS:

      IF (N_TOTAL.GT.0) THEN
        RN_TOTAL = N_TOTAL
        P = FLOAT(N_OUT) / RN_TOTAL ! CONDUCTANCE
        E = FLOAT(N_IN) / RN_TOTAL ! BACKSCATTER

        OPEN(8,FILE='1.DAT',STATUS='OLD',ACCESS='APPEND')
        WRITE(8,*) P, VALVE_ANG*180./PI, L_TOTAL, N_TOTAL
        CLOSE(8,STATUS='KEEP')

        DO 1 I = 1, N_SURF
          GAMMA(I) = FLOAT(N_ABS(I)) / RN_TOTAL ! CAPTURE
          BOUNCE(I) = FLOAT(N_BOUNCE(I)) / RN_TOTAL

C BOUNCE
          WRITE(2,2) I, GAMMA(I), I, BOUNCE(I)
1          WRITE(*,2) I, GAMMA(I), I, BOUNCE(I)
2          FORMAT(1X,'Capture Coeff (Γ) for surf ',I1,' = '
>            ,G16.8/1X,'Bounce Coefficient for surf ',
>            I1,' = ',G16.8/)
          WRITE(2,3) N_TOTAL, P, E
          WRITE(*,3) N_TOTAL, P, E
3          FORMAT(//1X,'Number of particles modeled = ',I7/
>            1X,'Conductance Coefficient (P) = ',G16.8/
>            1X,'Backscatter Coefficient (E) = ',G16.8/)

        ELSE

          WRITE(*,*) ' TOTAL NUMBER OF SIMULATED PARTICLES=',
>            N_TOTAL
        END IF
C      WRITE(*,*) '^G^G^G'
      RETURN
      END

```

```

      REAL*4 FUNCTION DOT3(X1,Y1,Z1,X2,Y2,Z2)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      Real*4 function subroutine performs scalar (dot)
C      product of two vectors
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

      IMPLICIT NONE
      REAL*4 X1, Y1, Z1, X2, Y2, Z2
      DOT3 = X1*X2 + Y1*Y2 + Z1*Z2
      RETURN
      END

```

```

      SUBROUTINE CHECK_PLANE(T,L,R,OMEGA)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      Subroutine to check for the crossing of the valve at
C      L, R, Theta and calculate the distance to this point
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

      IMPLICIT NONE
      REAL*4      N_DOT_D, N_DOT_B, OMEGA, N1, N2, N3, DOT3,
>      L, R, T
      INCLUDE '1.C1'
      INCLUDE '1.C3'

      N1 = + COS(OMEGA)
      N2 = - SIN(OMEGA)
      N3 = 0
      T = 0
      N_DOT_D = DOT3(N1,N2,N3,V(1),V(2),V(3))
      IF(N_DOT_D.EQ.0) T = T-100
      N_DOT_B = DOT3(N1,N2,N3,X0,Y0,Z0)

      IF(N_DOT_B.EQ.L) THEN
        T = T-10
        GO TO 1
      END IF

      T = ( L - N_DOT_B ) / N_DOT_D
      N1 = X0 + T * V(1) - L
      N2 = Y0 + T * V(2)
      N3 = Z0 + T * V(3)
      IF(N1*N1+N2*N2+N3*N3.GT.R*R) T = -1000
1  IF(F_WRI_2) WRITE(2,*) 'PLANE, T= ', T, ' N_DOT_D= ',
>      N_DOT_D, ' N_DOT_B= ', N_DOT_B

      RETURN
      END

```

```

      SUBROUTINE CHECK_CYL(T)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      Subroutine to check for the crossing of the cylinder
C       $Y^2 + Z^2 = R^2$ , and calculate the distance to this point
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      IMPLICIT NONE

      INCLUDE '1.C1'
      INCLUDE '1.C3'

      REAL*4      T, R, A, B, C

      R = R_INLET
      T = V(2)*V(2) + V(3)*V(3)

      IF(T.EQ.0.) THEN
          T = -100.

      ELSE
          A = (Z0*V(2)-Y0*V(3))
          A = R*R * T - A*A

          IF(A.LT.0) THEN

              T = -200.

          ELSE

              A = SQRT( A )
              B = Y0*V(2) + Z0*V(3)
              C = ( -B - A ) / T
              T = ( -B + A ) / T
              IF(F_WRI_2) WRITE(2,*) 'T = ',T,' C = ',C
              T = AMAX1(T,C)

              IF(T.LT.0) T = -400.

              IF(F_WRI_2) WRITE(2,*) 'CYL, T= ',T,' A = ',A,
>              'B= ',B,' C= ',C

          END IF

      END IF

      RETURN
      END

```

```

      SUBROUTINE BOUNCE_VALVE(T1, BETA, J)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      Subroutine to determine the reflection / absorption
C      of the particle by the surface.
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IMPLICIT NONE
      INCLUDE '1.C1'
      INCLUDE '1.C2'
      INCLUDE '1.C3'
      INCLUDE '1.C4'
      INCLUDE '1.C5'
      REAL*4 X1, Y1, Z1, X2, Y2, Z2, V2(4), BETA, T1, C, S
      INTEGER J
C *** check for particle being cold-pumped by (stuck to) the
C      surface
      IF(BETA.GT.0.AND.BETA.GE.RND()) THEN
          N_ABS(3) = N_ABS(3) + 1
          J = 1
      ELSE
          J = 2
          C = COS(VALUE_ANG)
          S = SIN(VALUE_ANG)
C *** Calculate the location where the particle impacts on
C      the surface
          X1 = X0 + T1 * V(1)
          Y1 = Y0 + T1 * V(2)
          Z1 = Z0 + T1 * V(3)
C *** Move P0 from primary coordinate sys. to the Valve
C      Coordinate sys
          X2 = (X0-L_BEF)*C - Z0*S
          Y2 = Y0
          Z2 = (X0-L_BEF)*S + Z0*C
C *** Make point of impact the new P0
          X0 = X1
          Y0 = Y1
          Z0 = Z1
          IF(F_WRI_2) WRITE(2,*) X0, Y0, Z0, 'VLV COORD'
C *** Calculate a new trajectory for the particle
          CALL U3(V2,F_WRI_2)
C *** Sign of the x velocity component in the valve coord
C      sys should be the same as the sign of X2
          V2(1) = SIGN(V2(1),X2)
C          IF(SIGN(V2(1)).NE.SIGN(X2)) V2(1) = -V2(1)
C *** Rotate the new V.V. back to the primary axis
          V(1) = V2(1)*C + V2(3)*S
          V(2) = V2(2)
          V(3) = -V2(1)*S + V2(3)*C
          IF(F_PLOT) CALL PLOT_P(11,12)
      END IF
      RETURN
      END

```

```

      SUBROUTINE BOUNCE_CYL(T,BETA, J)
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      C      Subroutine to determine the reflection / absorption
      C      of the particle by the surface.
      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IMPLICIT NONE
      INCLUDE '1.C1'
      INCLUDE '1.C2'
      INCLUDE '1.C3'
      INCLUDE '1.C5'
      REAL*4      V2(4), BETA, T, C, S, ALPHA
      INTEGER      J
      C *** check for particle being cold-pumped by (stuck to) the
      C      surface
      IF(BETA.GT.0.AND.BETA.GE.RND()) THEN
          N_ABS(4) = N_ABS(4) + 1
          J = 1
      ELSE
          J = 2
      C *** Calculate the location where the particle impacts on
      C      the surface &
      C *** Make point of impact the new P0
          X0 = X0 + T * V(1)
          Y0 = Y0 + T * V(2)
          Z0 = Z0 + T * V(3)
          IF(F_WRI_2) WRITE(2,*) X0, Y0, Z0, 'CYL COORD'
      C *** Calculate angle of rotation & its sine and cosine
      C      about X-axis (Y"-axis):
          ALPHA = ATAN2(Z0,Y0)
      C *** Calculate a new trajectory for the particle
          CALL U3(V2,F_WRI_2)
          IF(F_WRI_2) WRITE(2,*) 'CYL V"x = ', V2(1),
      >      ' V"y = ', V2(2), ' V"z = ', V2(3), '  $\alpha$  = ',ALPHA
      C *** Rotate -90 degrees about the Z-axis:
      C      = V2(1)
      V2(1) = V2(2)
      V2(2) = -C
      IF(F_WRI_2) WRITE(2,*) 'CYL V`x = ', V2(1),
      >      ' V`y = ', V2(2), ' V`z = ', V2(3)
      C = COS(-ALPHA)
      S = SIN(-ALPHA)
      C *** Rotate the new V.V. by the angle (+ALPHA) about the
      C      X"-axis:
          V(1) = V2(1)
          V(2) = V2(2)*C + V2(3)*S
          V(3) = -V2(2)*S + V2(3)*C
          IF(F_WRI_2) WRITE(2,*) 'CYL Vx = ', V(1),
      >      ' Vy = ', V(2), ' Vz = ', V(3)
          IF(F_PLOT) CALL PLOT_P(6,7)
      END IF
      RETURN
      END

```

```

      SUBROUTINE RAND_POS(LOOPCT,F_PLOT)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      Subroutine to calculate the random starting position
C      (vector) of the particle to be followed.
C      {Po=(xo,yo,zo)}
C
C      For more information look in the file with same name,
C      with '.C' extension
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IMPLICIT NONE
      INCLUDE '1.C1'
      INCLUDE '1.P1'
      INTEGER LOOPCT
      REAL SAM1,SAM2,SAM3
      LOGICAL F_PLOT
      RHO = R_INLET * SQRT( RND() )      ! RND() = ZETA
      PHI = 2. * PI * RND()              ! RND() = ETA
      XO = 0.
      YO = RHO * SIN( PHI )
      ZO = RHO * COS( PHI )
      IF(F_WRI_2) WRITE(2,*) RHO, PHI, XO, YO, ZO
      IF(F_PLOT)
1    > WRITE(3,1) XO*10000., YO*10000., ZO*10000., LOOPCT
      FORMAT('EndPoint X ',G16.8,' Y ',G16.8,' Z ',G16.8,
> ' Name L',I4.4)
      RETURN
      END

```

```

      SUBROUTINE RAND_V_V(V,F_WRI_2)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      Subroutine to calculate the random unit velocity
C      vector of the emerging particle. {D=(xd,yd,zd), |D|=1}
C      For more information look in the file with same name,
C      with '.C' extension
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IMPLICIT NONE
      REAL*4 DUMMY, V(4), PSI, THETA
      INTEGER I
      LOGICAL F_WRI_2
      INCLUDE '1.DT1'
      INCLUDE '1.P1'
      THETA = ASIN( SQRT( RND() ) )      ! RND() = TAU
      PSI = PI2 * RND()                  ! RND() = NU
      DUMMY = SIN( THETA )
      V( 1 ) = COS( THETA )              ! xd
      V( 2 ) = SIN( PSI ) * DUMMY        ! yd
      V( 3 ) = COS( PSI ) * DUMMY        ! zd
      V(4) = SQRT(V(1)*V(1)+V(2)*V(2)+V(3)*V(3)) ! Should
                                           ! equal 1. & IS!
      IF(F_WRI_2) WRITE(2,*) THETA, PSI, (V(I),I=1,4)
      RETURN
      END

```

```

      SUBROUTINE PLOT_P(I_COLOR1,I_COLOR2)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C      Subroutine to generate plot output for the particle.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      IMPLICIT NONE

      INCLUDE '1.C1'
      INCLUDE '1.C5'
      INTEGER I_COLOR1, I_COLOR2

      I_BOUNCE = I_BOUNCE + 1
      WRITE(3,3) X0*10000., 10000.*Y0, 10000.*Z0, I_BOUNCE
3      FORMAT('EndPoint X ',G16.8,' Y ',G16.8,' Z ',G16.8,
>      ' Name I',I4.4)
      IF(J_BOUNCE.EQ.0) THEN
          WRITE(3,1) LOOPCT, I_BOUNCE, I_COLOR1
1      FORMAT('Line From L',I4.4,' To I',I4.4,' Color ',I2)
      ELSE
          WRITE(3,2) I_BOUNCE - 1, I_BOUNCE, I_COLOR2
2      FORMAT('Line From I',I4.4,' To I',I4.4,' Color ',I2)
      END IF
      RETURN
      END

```

APPENDIX D - MONTE CARLO PROGRAM SAMPLE INPUT

The following is the listing for a sample input to the Monte Carlo simulation program used to calculate the results presented here:

Valve Conductance

NITROGEN

```
1.,1.,0.,2. ! L_BEF,L_AFT,L_DELT IS ADDED TO EACH 'TIL L_MAX
1., 1.,1.    ! RADII: INLET, OUTLET, VLV
-45.,-45., 10. ! VLV_ANG: FROM, TO, STEP
0.           ! SEED
4, 0., 0., 0., 0. ! STICKING COEFF: #, SURF 1, 2, 3, 4
10.,100000.    ! # OF PARTICLES TO SIMULATE, STEP
.TRUE.        ! PLOT FLAG
.FALSE.       ! UNIT 2 FLAG
.FALSE.       ! SCREEN FLAG
```

APPENDIX E - MONTE CARLO PROGRAM SAMPLE OUTPUT

The following is the listing for the output from the Monte Carlo simulation program used to calculate the results presented here, given the input in Appendix D:

0.100000	-45.0000	2.00000	10
----------	----------	---------	----

APPENDIX F - SOLID MODELING PROGRAM LISTING

The following is the listing for the program which generates the valve geometry input data for use by the Acrospin three-dimensional dynamic modeling program (Reference 4):

```

PROGRAM CYLINDER
  CHARACTER POINT*46/'EndPoint X -32768  Y -32768  Z
    &-32768  Name  P'/, RECORD*50, LINE*34/'Line From
&P9999 To  P9999  Color'/', A*1,BLANK*50,
    &J*6/'      '/,C_ANS*2/'  '/, V_ANS*2/'  '/
    INTEGER IX, LINES, IY/0/, IZ/0/, ISCALE/1/, I,
    &JSCALE/1/
    REAL*4 U_LIMIT/32767./, ANGLE, DELTA_THETA, THETA/0./,
    &TWO_PI/6.283185308/, R, LEN
    LOGICAL CFLAG_C/.FALSE./, CFLAG_V/.FALSE./
    BLANK = '
    &'
    OPEN(1,FILE='CYLINDER.ACD',STATUS='UNKNOWN')
    WRITE(1,*) '-- This is the output of the program'
    &'Cylinder.for,'
    WRITE(1,*) '--   written by S. Edwards'
    WRITE(*,1)
1  FORMAT(1H+,' PLEASE ENTER THE CYLINDER RADIUS > ')
    READ(*,*) R
    IF( R .GT. U_LIMIT ) THEN
        ISCALE = R / U_LIMIT
        ISCALE = ISCALE + 1
        R = R / REAL( ISCALE )
    ELSE IF( R .LE. 10000. ) THEN
        JSCALE = 10000. / R
        R = R * JSCALE
    END IF
    WRITE(*,2)
2  FORMAT(1H+,' PLEASE ENTER THE CYLINDER LENGTH > ')
    READ(*,*) LEN
    WRITE(1,*) '-- Cylinder length = ',LEN,' Radius = ',R
    IF( ISCALE .GT. 1 ) LEN = LEN / REAL( ISCALE )
    IF( LEN .GT. U_LIMIT ) THEN
        ISCALE = LEN / U_LIMIT
        ISCALE = ISCALE + 1
        LEN = LEN / REAL( ISCALE )
        R = R / REAL( ISCALE )

```

```

ELSE IF( JSCALE .GT. 1 ) THEN
400   XI = LEN * JSCALE
      IF( XI .GT. U_LIMIT ) THEN
        JSCALE = JSCALE / 10
        R = R * .1
        GO TO 400
      ELSE
        LEN = XI
      END IF
    END IF
  WRITE(*,31)
31   FORMAT(" IF YOU WANT THE CYLINDER TO BE A CERTAIN"
    &" COLOR, ENTER THE COLOR'S NUMBER, ELSE"//1H+" ENTER"
    &" AN ALPHA CHARACTER [A/4,5..]>")
    READ(*,'(A2)') C_ANS
    A = C_ANS(1:1)
    IF(A.EQ.'0'.OR.A.EQ.'1'.OR.A.EQ.'2'.OR.A.EQ.'3'.OR.
    & A.EQ.'4'.OR.A.EQ.'5'.OR.A.EQ.'6') THEN
      CFLAG_C = .TRUE.
    ELSE IF(A.EQ.'7'.OR.A.EQ.'8'.OR.A.EQ.'9') THEN
      CFLAG_C = .TRUE.
    END IF
    WRITE(*,3)
3   FORMAT(1H+,' PLEASE ENTER THE NUMBER OF LINES DESIRED'
    &,' >')
    READ(*,*) LINES
    WRITE(*,30)
30   FORMAT(1H+,' PLEASE ENTER THE VALVE ANGLE WITH THE ',
    &'X-AXIS ( DEG ) > ')
    READ(*,*) ANGLE
    WRITE(*,32)
32   FORMAT(" IF YOU WANT THE VALVE TO BE A CERTAIN COLOR, '
    &' ENTER THAT COLOR'S NUMBER, ELSE"//1H+" ENTER AN ',
    &'ALPHA CHARACTER [A/4,5,...]>")
    READ(*,'(A2)') V_ANS
    A = V_ANS(1:1)
    IF(A.EQ.'0'.OR.A.EQ.'1'.OR.A.EQ.'2'.OR.A.EQ.'3'
    & .OR.A.EQ.'4'.OR.A.EQ.'5'.OR.A.EQ.'6') THEN
      CFLAG_V = .TRUE.
    ELSE IF(A.EQ.'7'.OR.A.EQ.'8'.OR.A.EQ.'9') THEN
      CFLAG_V = .TRUE.
    END IF
    ANGLE = ANGLE * 1.745329252E-02
    DELTA_THETA = TWO_PI / REAL( LINES )
    LINES = LINES * 2
C --- GENERATE THE POINTS DATA FOR THE CYLINDER
    IX = R
    WRITE(1,*) 'Set Layer 1'
    WRITE(1,*) 'EndpointList Z Y X Name'
66   FORMAT(3(I6,2X),'P',I4.4)
    DO 100 I = 1, LINES, 2
      WRITE(1,66) IX,IY,IZ,I

```

```

        WRITE(1,66) IX,IY,LEN,I+1
        THETA = THETA + DELTA_THETA
        IX = R * COS( THETA )
        IY = R * SIN( THETA )
100    CONTINUE
C --- GENERATE THE POINTS FOR THE VALVE
        LEN = LEN / 2.
        IX = R
        IY = 0
        IZ = LEN
        THETA = 0.
        DELTA_THETA = DELTA_THETA * 2.
        WRITE(1,*) '-- Beginning the Valve Points'
        WRITE(1,*) 'Set Layer 2'
        WRITE(1,*) 'EndpointList Z Y X Name'
        DO 110 I = LINES+1, LINES*3/2, 2
            IX = R * COS( THETA )
            IY = R * SIN( THETA ) * SIN( ANGLE )
            IZ = LEN - R * SIN( THETA ) * COS( ANGLE )
            THETA = THETA + DELTA_THETA
            WRITE(1,66) IX,IY,IZ,I
            WRITE(1,66) -IX,IY,IZ,I+1
110    CONTINUE
C --- GENERATE AXIS
        WRITE(1,*) '-- THE AXIS POINTS'
        WRITE(1,*) 'Set Layer 3'
        WRITE(1,*) 'EndpointList Z Y X Name'
        I = LINES * 3/2 + 1
        IX = 0
        IY = 0
        IZ = 0
        WRITE(1,66) IX,IY,IZ,I
        WRITE(1,66) R + JSCALE/5,IY,IZ,I+1
        WRITE(1,66) IX,R+JSCALE/5,IZ,I+2
        WRITE(1,66) IX,IY,LEN*2,I+3
        WRITE(1,66) -R,IY,IZ,I+4
        WRITE(1,66) -R-JSCALE/5,IY,IZ,I+5
        WRITE(1,66) IX,-R,IZ,I+6
        WRITE(1,66) IX,-R-JSCALE/5,IZ,I+7
        WRITE(1,66) IX,IY,-JSCALE/5,I+8
C --- GENERATE THE LONGITUDINAL LINES FOR THE CYLINDER
        WRITE(1,*) '-- DRAW LINES - End Circles and ',
        &'Cylindrical Body'
        WRITE(1,*) 'Set Layer 1 Color ',C_ANS
        WRITE(1,*) 'LineList From To'
        II = 0
        DO 200 I = 1, LINES, 2
            II = II + 1
200    WRITE(1,67) I, I+1
67    FORMAT(2('P',I4.4,3X))
C --- GENERATE THE CIRCUMFERENTIAL LINES FOR THE CYLINDER
        WRITE(1,*) '-- GENERATE CYLINDER CIRCULAR ENDS'

```

```

DO 300 I = 1, LINES-2
300  WRITE(1,67) I, I+2
C --- CLEAN-UP AND FINISH-UP THE CIRCUMFRENTIAL LINES FOR
C      THE CYLINDER
      WRITE(1,67) LINES-1, 1
      WRITE(1,67) LINES, 2
C --- GENERATE THE LONGITUDINAL LINES FOR THE VALVE
      WRITE(1,*) '-- BEGINNING LONGITUDINAL LINES FOR VALVE'
      WRITE(1,*) 'Set Layer 2 Color ',V_ANS
      WRITE(1,*) 'LineList From To'
      II = 0
      DO 210 I = LINES+1, LINES*3/2, 2
210  WRITE(1,67) I,I+1
C --- GENERATE THE CIRCUMFRENTIAL LINES FOR THE VALVE
      WRITE(1,*) '-- CIRCUMFRENTIAL LINES FOR THE VALVE'
      WRITE(1,*) 'Set Layer 2 Color ',V_ANS
      WRITE(1,*) 'LineList From To'
      DO 310 I = LINES+1, LINES*3/2 - 2
310  WRITE(1,67) I,I+2
C --- CLEAN-UP AND FINISH-UP THE CIRCUMFRENTIAL LINES FOR
C      THE VALVE
      WRITE(1,67) LINES*3/2 - 1, LINES + 1
      WRITE(1,67) LINES*3/2, LINES + 2
C --- GENERATE THE LINES FOR THE 3 AXIS
      WRITE(1,*) '-- THE LINES FOR THE AXIS'
      WRITE(1,*) 'Set Layer 3'
      WRITE(1,*) 'LineList From To Color '
      I = LINES * 3/2 + 1
      II = 1
      WRITE(1,68) I,I+1,II
68  FORMAT(2('P',I4.4,3X),I2)
      II = 2
      WRITE(1,68) I,I+2,II
      II = 3
      WRITE(1,68) I,I+3,II
C --- NEGATIVE DIRECTIONS
      II = 1
      WRITE(1,68) I+4,I+5,II
      II = 2
      WRITE(1,68) I+6,I+7,II
      II = 3
      WRITE(1,68) I,I+8,II
C --- END OF FILE
      WRITE(1,*) '-- Begin Bouncing Particles'
      WRITE(1,*) 'Set Layer 4'
      CLOSE(1,STATUS='KEEP')
      STOP
4  FORMAT(A50)
5  FORMAT(I6)
6  FORMAT(I4.4)
7  FORMAT(I6.6)
END

```

APPENDIX G - SOLID MODELING PROGRAM SAMPLE INPUT

The following is the listing for a sample input to the program which generates the valve geometry input data for use by the Acrospin three-dimensional dynamic modeling program (Reference 4). This input file requests a valve at 45° angle located in the middle of a pipe of the same diameter. The pipe length is equal to its diameter.

D:\F77L3> CYL

PLEASE ENTER THE CYLINDER RADIUS > 1

PLEASE ENTER THE CYLINDER LENGTH > 2

IF YOU WANT THE CYLINDER TO BE A CERTAIN COLOR, ENTER THE COLOR'S NUMBER, ELSE

ENTER AN ALPHA CHARACTER [A/4,5..]>1

PLEASE ENTER THE NUMBER OF LINES DESIRED > 300

PLEASE ENTER THE VALVE ANGLE WITH THE X-AXIS (DEG) > 45

IF YOU WANT THE VALVE TO BE A CERTAIN COLOR, ENTER THAT COLOR'S NUMBER, ELSE

ENTER AN ALPHA CHARACTER [A/4,5,...]>2

APPENDIX H - SOLID MODELING PROGRAM SAMPLE OUTPUT

The following is the listing for the resultant output of the program which generates the valve geometry input data for use by Acrospin three-dimensional dynamic modeling program (Reference 4). This output was generated by inputting the data in Appendix G to the program.

```
-- This is the output of the program Cylinder.for,
-- written by S. Edwards
-- Cylinder length =      2.00000      Radius =      10000.0
Set Layer 1
```

EndpointList	Z	Y	X	Name				
10000	0	0	P0001	9573	2890	20000	P0030	
10000	0	20000	P0002	9510	3090	0	P0031	
9997	209	0	P0003	9510	3090	20000	P0032	
9997	209	20000	P0004	9443	3288	0	P0033	
9991	418	0	P0005	9443	3288	20000	P0034	
9991	418	20000	P0006	9372	3485	0	P0035	
9980	627	0	P0007	9372	3485	20000	P0036	
9980	627	20000	P0008	9297	3681	0	P0037	
9964	836	0	P0009	9297	3681	20000	P0038	
9964	836	20000	P0010	9218	3875	0	P0039	
9945	1045	0	P0011	9218	3875	20000	P0040	
9945	1045	20000	P0012	9135	4067	0	P0041	
9921	1253	0	P0013	9135	4067	20000	P0042	
9921	1253	20000	P0014	9048	4257	0	P0043	
9892	1460	0	P0015	9048	4257	20000	P0044	
9892	1460	20000	P0016	8957	4446	0	P0045	
9859	1667	0	P0017	8957	4446	20000	P0046	
9859	1667	20000	P0018	8862	4632	0	P0047	
9822	1873	0	P0019	8862	4632	20000	P0048	
9822	1873	20000	P0020	8763	4817	0	P0049	
9781	2079	0	P0021	8763	4817	20000	P0050	
9781	2079	20000	P0022	8660	4999	0	P0051	
9735	2283	0	P0023	8660	4999	20000	P0052	
9735	2283	20000	P0024	8553	5180	0	P0053	
9685	2486	0	P0025	8553	5180	20000	P0054	
9685	2486	20000	P0026	8443	5358	0	P0055	
9631	2689	0	P0027	8443	5358	20000	P0056	
9631	2689	20000	P0028	8329	5533	0	P0057	
9573	2890	0	P0029	8329	5533	20000	P0058	

8211	5707	0	P0059	4067	9135	0	P0111
8211	5707	20000	P0060	4067	9135	20000	P0112
8090	5877	0	P0061	3875	9218	0	P0113
8090	5877	20000	P0062	3875	9218	20000	P0114
7965	6045	0	P0063	3681	9297	0	P0115
7965	6045	20000	P0064	3681	9297	20000	P0116
7836	6211	0	P0065	3485	9372	0	P0117
7836	6211	20000	P0066	3485	9372	20000	P0118
7705	6374	0	P0067	3288	9443	0	P0119
7705	6374	20000	P0068	3288	9443	20000	P0120
7569	6534	0	P0069	3090	9510	0	P0121
7569	6534	20000	P0070	3090	9510	20000	P0122
7431	6691	0	P0071	2890	9573	0	P0123
7431	6691	20000	P0072	2890	9573	20000	P0124
7289	6845	0	P0073	2689	9631	0	P0125
7289	6845	20000	P0074	2689	9631	20000	P0126
7144	6996	0	P0075	2486	9685	0	P0127
7144	6996	20000	P0076	2486	9685	20000	P0128
6996	7144	0	P0077	2283	9735	0	P0129
6996	7144	20000	P0078	2283	9735	20000	P0130
6845	7289	0	P0079	2079	9781	0	P0131
6845	7289	20000	P0080	2079	9781	20000	P0132
6691	7431	0	P0081	1873	9822	0	P0133
6691	7431	20000	P0082	1873	9822	20000	P0134
6534	7569	0	P0083	1667	9859	0	P0135
6534	7569	20000	P0084	1667	9859	20000	P0136
6374	7705	0	P0085	1460	9892	0	P0137
6374	7705	20000	P0086	1460	9892	20000	P0138
6211	7836	0	P0087	1253	9921	0	P0139
6211	7836	20000	P0088	1253	9921	20000	P0140
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6045	7965	20000	P0090	1045	9945	20000	P0142
5877	8090	0	P0091	836	9964	0	P0143
5877	8090	20000	P0092	836	9964	20000	P0144
5707	8211	0	P0093	627	9980	0	P0145
5707	8211	20000	P0094	627	9980	20000	P0146
5533	8329	0	P0095	418	9991	0	P0147
5533	8329	20000	P0096	418	9991	20000	P0148
5358	8443	0	P0097	209	9997	0	P0149
5358	8443	20000	P0098	209	9997	20000	P0150
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5180	8553	20000	P0100	0	9999	20000	P0152
5000	8660	0	P0101	-209	9997	0	P0153
5000	8660	20000	P0102	-209	9997	20000	P0154
4817	8763	0	P0103	-418	9991	0	P0155
4817	8763	20000	P0104	-418	9991	20000	P0156
4632	8862	0	P0105	-627	9980	0	P0157
4632	8862	20000	P0106	-627	9980	20000	P0158
4446	8957	0	P0107	-836	9964	0	P0159
4446	8957	20000	P0108	-836	9964	20000	P0160
4257	9048	0	P0109	-1045	9945	0	P0161
4257	9048	20000	P0110	-1045	9945	20000	P0162

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-9964	-836	0	P0309	-8090	-5877	0	P0361
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-9945	-1045	20000	P0312	-7965	-6045	20000	P0364
-9921	-1253	0	P0313	-7836	-6211	0	P0365
-9921	-1253	20000	P0314	-7836	-6211	20000	P0366
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-7289	-6845	20000	P0374	-2689	-9631	20000	P0426
-7144	-6996	0	P0375	-2486	-9685	0	P0427
-7144	-6996	20000	P0376	-2486	-9685	20000	P0428
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-6996	-7144	20000	P0378	-2283	-9735	20000	P0430
-6845	-7289	0	P0379	-2079	-9781	0	P0431
-6845	-7289	20000	P0380	-2079	-9781	20000	P0432
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-6691	-7431	20000	P0382	-1873	-9822	20000	P0434
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-6374	-7705	0	P0385	-1460	-9892	0	P0437
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-6211	-7836	0	P0387	-1253	-9921	0	P0439
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-6046	-7965	0	P0389	-1045	-9945	0	P0441
-6046	-7965	20000	P0390	-1045	-9945	20000	P0442
-5877	-8090	0	P0391	-836	-9964	0	P0443
-5877	-8090	20000	P0392	-836	-9964	20000	P0444
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-5358	-8443	0	P0397	-209	-9997	0	P0449
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-5000	-8660	0	P0401	209	-9997	0	P0453
-5000	-8660	20000	P0402	209	-9997	20000	P0454
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-4817	-8763	20000	P0404	418	-9991	20000	P0456
-4632	-8862	0	P0405	627	-9980	0	P0457
-4632	-8862	20000	P0406	627	-9980	20000	P0458
-4446	-8957	0	P0407	836	-9964	0	P0459
-4446	-8957	20000	P0408	836	-9964	20000	P0460
-4257	-9048	0	P0409	1045	-9945	0	P0461
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-4067	-9135	0	P0411	1253	-9921	0	P0463
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-3681	-9297	0	P0415	1667	-9859	0	P0467
-3681	-9297	20000	P0416	1667	-9859	20000	P0468
-3485	-9372	0	P0417	1873	-9822	0	P0469
-3485	-9372	20000	P0418	1873	-9822	20000	P0470
-3288	-9443	0	P0419	2079	-9781	0	P0471
-3288	-9443	20000	P0420	2079	-9781	20000	P0472
-3090	-9510	0	P0421	2283	-9735	0	P0473
-3090	-9510	20000	P0422	2283	-9735	20000	P0474

2486	-9685	0	P0475	7144	-6996	0	P0527
2486	-9685	20000	P0476	7144	-6996	20000	P0528
2689	-9631	0	P0477	7289	-6845	0	P0529
2689	-9631	20000	P0478	7289	-6845	20000	P0530
2890	-9573	0	P0479	7431	-6691	0	P0531
2890	-9573	20000	P0480	7431	-6691	20000	P0532
3090	-9510	0	P0481	7570	-6534	0	P0533
3090	-9510	20000	P0482	7570	-6534	20000	P0534
3288	-9443	0	P0483	7705	-6374	0	P0535
3288	-9443	20000	P0484	7705	-6374	20000	P0536
3485	-9372	0	P0485	7836	-6211	0	P0537
3485	-9372	20000	P0486	7836	-6211	20000	P0538
3681	-9297	0	P0487	7965	-6045	0	P0539
3681	-9297	20000	P0488	7965	-6045	20000	P0540
3875	-9218	0	P0489	8090	-5877	0	P0541
3875	-9218	20000	P0490	8090	-5877	20000	P0542
4067	-9135	0	P0491	8211	-5707	0	P0543
4067	-9135	20000	P0492	8211	-5707	20000	P0544
4257	-9048	0	P0493	8329	-5533	0	P0545
4257	-9048	20000	P0494	8329	-5533	20000	P0546
4446	-8957	0	P0495	8443	-5358	0	P0547
4446	-8957	20000	P0496	8443	-5358	20000	P0548
4633	-8862	0	P0497	8553	-5180	0	P0549
4633	-8862	20000	P0498	8553	-5180	20000	P0550
4817	-8763	0	P0499	8660	-4999	0	P0551
4817	-8763	20000	P0500	8660	-4999	20000	P0552
5000	-8660	0	P0501	8763	-4817	0	P0553
5000	-8660	20000	P0502	8763	-4817	20000	P0554
5180	-8553	0	P0503	8862	-4632	0	P0555
5180	-8553	20000	P0504	8862	-4632	20000	P0556
5358	-8443	0	P0505	8957	-4446	0	P0557
5358	-8443	20000	P0506	8957	-4446	20000	P0558
5533	-8329	0	P0507	9048	-4257	0	P0559
5533	-8329	20000	P0508	9048	-4257	20000	P0560
5707	-8211	0	P0509	9135	-4067	0	P0561
5707	-8211	20000	P0510	9135	-4067	20000	P0562
5877	-8090	0	P0511	9218	-3875	0	P0563
5877	-8090	20000	P0512	9218	-3875	20000	P0564
6046	-7965	0	P0513	9297	-3681	0	P0565
6046	-7965	20000	P0514	9297	-3681	20000	P0566
6211	-7836	0	P0515	9372	-3485	0	P0567
6211	-7836	20000	P0516	9372	-3485	20000	P0568
6374	-7705	0	P0517	9443	-3288	0	P0569
6374	-7705	20000	P0518	9443	-3288	20000	P0570
6534	-7569	0	P0519	9510	-3090	0	P0571
6534	-7569	20000	P0520	9510	-3090	20000	P0572
6691	-7431	0	P0521	9573	-2890	0	P0573
6691	-7431	20000	P0522	9573	-2890	20000	P0574
6845	-7289	0	P0523	9631	-2689	0	P0575
6845	-7289	20000	P0524	9631	-2689	20000	P0576
6996	-7144	0	P0525	9685	-2486	0	P0577
6996	-7144	20000	P0526	9685	-2486	20000	P0578

9735	-2283	0	P0579	-8553	3663	6336	P0628
9735	-2283	20000	P0580	8329	3913	6086	P0629
9781	-2079	0	P0581	-8329	3913	6086	P0630
9781	-2079	20000	P0582	8090	4156	5843	P0631
9822	-1873	0	P0583	-8090	4156	5843	P0632
9822	-1873	20000	P0584	7836	4392	5607	P0633
9859	-1667	0	P0585	-7836	4392	5607	P0634
9859	-1667	20000	P0586	7569	4620	5379	P0635
9892	-1460	0	P0587	-7569	4620	5379	P0636
9892	-1460	20000	P0588	7289	4840	5159	P0637
9921	-1253	0	P0589	-7289	4840	5159	P0638
9921	-1253	20000	P0590	6996	5052	4947	P0639
9945	-1045	0	P0591	-6996	5052	4947	P0640
9945	-1045	20000	P0592	6691	5254	4745	P0641
9964	-836	0	P0593	-6691	5254	4745	P0642
9964	-836	20000	P0594	6374	5448	4551	P0643
9980	-627	0	P0595	-6374	5448	4551	P0644
9980	-627	20000	P0596	6045	5632	4367	P0645
9991	-418	0	P0597	-6045	5632	4367	P0646
9991	-418	20000	P0598	5707	5806	4193	P0647
9997	-209	0	P0599	-5707	5806	4193	P0648
9997	-209	20000	P0600	5358	5970	4029	P0649
-- Beginning the Valve Points				-5358	5970	4029	P0650
Set Layer 2				5000	6123	3876	P0651
EndpointList Z Y X Name				-5000	6123	3876	P0652
10000	0	10000	P0601	4632	6266	3733	P0653
-10000	0	10000	P0602	-4632	6266	3733	P0654
9991	296	9703	P0603	4257	6398	3601	P0655
-9991	296	9703	P0604	-4257	6398	3601	P0656
9964	591	9408	P0605	3875	6518	3481	P0657
-9964	591	9408	P0606	-3875	6518	3481	P0658
9921	886	9113	P0607	3485	6627	3372	P0659
-9921	886	9113	P0608	-3485	6627	3372	P0660
9859	1179	8820	P0609	3090	6724	3275	P0661
-9859	1179	8820	P0610	-3090	6724	3275	P0662
9781	1470	8529	P0611	2689	6810	3189	P0663
-9781	1470	8529	P0612	-2689	6810	3189	P0664
9685	1758	8241	P0613	2283	6884	3115	P0665
-9685	1758	8241	P0614	-2283	6884	3115	P0666
9573	2043	7956	P0615	1873	6945	3054	P0667
-9573	2043	7956	P0616	-1873	6945	3054	P0668
9443	2325	7674	P0617	1460	6995	3004	P0669
-9443	2325	7674	P0618	-1460	6995	3004	P0670
9297	2603	7396	P0619	1045	7032	2967	P0671
-9297	2603	7396	P0620	-1045	7032	2967	P0672
9135	2876	7123	P0621	627	7057	2942	P0673
-9135	2876	7123	P0622	-627	7057	2942	P0674
8957	3144	6855	P0623	209	7069	2930	P0675
-8957	3144	6855	P0624	-209	7069	2930	P0676
8763	3406	6593	P0625	-209	7069	2930	P0677
-8763	3406	6593	P0626	209	7069	2930	P0678
8553	3663	6336	P0627	-627	7057	2942	P0679

627	7057	2942	P0680	9135	2876	7123	P0732
-1045	7032	2967	P0681	-9297	2603	7396	P0733
1045	7032	2967	P0682	9297	2603	7396	P0734
-1460	6995	3004	P0683	-9443	2325	7674	P0735
1460	6995	3004	P0684	9443	2325	7674	P0736
-1873	6945	3054	P0685	-9573	2043	7956	P0737
1873	6945	3054	P0686	9573	2043	7956	P0738
-2283	6884	3115	P0687	-9685	1758	8241	P0739
2283	6884	3115	P0688	9685	1758	8241	P0740
-2689	6810	3189	P0689	-9781	1470	8529	P0741
2689	6810	3189	P0690	9781	1470	8529	P0742
-3090	6724	3275	P0691	-9859	1179	8820	P0743
3090	6724	3275	P0692	9859	1179	8820	P0744
-3485	6627	3372	P0693	-9921	886	9113	P0745
3485	6627	3372	P0694	9921	886	9113	P0746
-3875	6518	3481	P0695	-9964	591	9408	P0747
3875	6518	3481	P0696	9964	591	9408	P0748
-4257	6398	3601	P0697	-9991	296	9703	P0749
4257	6398	3601	P0698	9991	296	9703	P0750
-4632	6266	3733	P0699	-9999	0	10000	P0751
4632	6266	3733	P0700	9999	0	10000	P0752
-4999	6123	3876	P0701	-9991	-296	10296	P0753
4999	6123	3876	P0702	9991	-296	10296	P0754
-5358	5970	4029	P0703	-9964	-591	10591	P0755
5358	5970	4029	P0704	9964	-591	10591	P0756
-5707	5806	4193	P0705	-9921	-886	10886	P0757
5707	5806	4193	P0706	9921	-886	10886	P0758
-6045	5632	4367	P0707	-9859	-1179	11179	P0759
6045	5632	4367	P0708	9859	-1179	11179	P0760
-6374	5448	4551	P0709	-9781	-1470	11470	P0761
6374	5448	4551	P0710	9781	-1470	11470	P0762
-6691	5254	4745	P0711	-9685	-1758	11758	P0763
6691	5254	4745	P0712	9685	-1758	11758	P0764
-6996	5052	4947	P0713	-9573	-2043	12043	P0765
6996	5052	4947	P0714	9573	-2043	12043	P0766
-7289	4840	5159	P0715	-9443	-2325	12325	P0767
7289	4840	5159	P0716	9443	-2325	12325	P0768
-7569	4620	5379	P0717	-9297	-2603	12603	P0769
7569	4620	5379	P0718	9297	-2603	12603	P0770
-7836	4392	5607	P0719	-9135	-2876	12876	P0771
7836	4392	5607	P0720	9135	-2876	12876	P0772
-8090	4156	5843	P0721	-8957	-3144	13144	P0773
8090	4156	5843	P0722	8957	-3144	13144	P0774
-8329	3913	6086	P0723	-8763	-3406	13406	P0775
8329	3913	6086	P0724	8763	-3406	13406	P0776
-8553	3662	6337	P0725	-8553	-3663	13663	P0777
8553	3662	6337	P0726	8553	-3663	13663	P0778
-8763	3406	6593	P0727	-8329	-3913	13913	P0779
8763	3406	6593	P0728	8329	-3913	13913	P0780
-8957	3144	6855	P0729	-8090	-4156	14156	P0781
8957	3144	6855	P0730	8090	-4156	14156	P0782
-9135	2876	7123	P0731	-7836	-4392	14392	P0783

7836	-4392	14392	P0784	-1873	-6945	16945	P0836
-7569	-4620	14620	P0785	2283	-6884	16884	P0837
7569	-4620	14620	P0786	-2283	-6884	16884	P0838
-7289	-4840	14840	P0787	2689	-6810	16810	P0839
7289	-4840	14840	P0788	-2689	-6810	16810	P0840
-6996	-5052	15052	P0789	3090	-6724	16724	P0841
6996	-5052	15052	P0790	-3090	-6724	16724	P0842
-6691	-5254	15254	P0791	3485	-6627	16627	P0843
6691	-5254	15254	P0792	-3485	-6627	16627	P0844
-6374	-5448	15448	P0793	3875	-6518	16518	P0845
6374	-5448	15448	P0794	-3875	-6518	16518	P0846
-6045	-5632	15632	P0795	4257	-6398	16398	P0847
6045	-5632	15632	P0796	-4257	-6398	16398	P0848
-5707	-5806	15806	P0797	4632	-6266	16266	P0849
5707	-5806	15806	P0798	-4632	-6266	16266	P0850
-5358	-5970	15970	P0799	4999	-6123	16123	P0851
5358	-5970	15970	P0800	-4999	-6123	16123	P0852
-4999	-6123	16123	P0801	5358	-5970	15970	P0853
4999	-6123	16123	P0802	-5358	-5970	15970	P0854
-4632	-6266	16266	P0803	5707	-5806	15806	P0855
4632	-6266	16266	P0804	-5707	-5806	15806	P0856
-4257	-6398	16398	P0805	6045	-5632	15632	P0857
4257	-6398	16398	P0806	-6045	-5632	15632	P0858
-3875	-6518	16518	P0807	6374	-5448	15448	P0859
3875	-6518	16518	P0808	-6374	-5448	15448	P0860
-3485	-6627	16627	P0809	6691	-5254	15254	P0861
3485	-6627	16627	P0810	-6691	-5254	15254	P0862
-3090	-6724	16724	P0811	6996	-5052	15052	P0863
3090	-6724	16724	P0812	-6996	-5052	15052	P0864
-2689	-6810	16810	P0813	7289	-4840	14840	P0865
2689	-6810	16810	P0814	-7289	-4840	14840	P0866
-2283	-6884	16884	P0815	7569	-4620	14620	P0867
2283	-6884	16884	P0816	-7569	-4620	14620	P0868
-1873	-6945	16945	P0817	7836	-4392	14392	P0869
1873	-6945	16945	P0818	-7836	-4392	14392	P0870
-1460	-6995	16995	P0819	8090	-4156	14156	P0871
1460	-6995	16995	P0820	-8090	-4156	14156	P0872
-1045	-7032	17032	P0821	8329	-3913	13913	P0873
1045	-7032	17032	P0822	-8329	-3913	13913	P0874
-627	-7057	17057	P0823	8553	-3663	13663	P0875
627	-7057	17057	P0824	-8553	-3663	13663	P0876
-209	-7069	17069	P0825	8763	-3406	13406	P0877
209	-7069	17069	P0826	-8763	-3406	13406	P0878
209	-7069	17069	P0827	8957	-3144	13144	P0879
-209	-7069	17069	P0828	-8957	-3144	13144	P0880
627	-7057	17057	P0829	9135	-2876	12876	P0881
-627	-7057	17057	P0830	-9135	-2876	12876	P0882
1045	-7032	17032	P0831	9297	-2603	12603	P0883
-1045	-7032	17032	P0832	-9297	-2603	12603	P0884
1460	-6995	16995	P0833	9443	-2325	12325	P0885
-1460	-6995	16995	P0834	-9443	-2325	12325	P0886
1873	-6945	16945	P0835	9573	-2043	12043	P0887

-9573	-2043	12043	P0888
9685	-1758	11758	P0889
-9685	-1758	11758	P0890
-9781	-1470	11470	P0891
-9781	-1470	11470	P0892
9859	-1179	11179	P0893
-9859	-1179	11179	P0894
9921	-886	10886	P0895
-9921	-886	10886	P0896
9964	-591	10591	P0897
-9964	-591	10591	P0898
9991	-296	10296	P0899
-9991	-296	10296	P0900

-- THE AXIS POINTS

Set Layer 3

EndpointList	Z	Y	X	Name
0	0		0	P0901
12000		0	0	P0902
0	12000		0	P0903
0	0		20000	P0904
-10000		0	0	P0905
-12000		0	0	P0906
0	-10000		0	P0907
0	-12000		0	P0908
0	0		-2000	P0909

-- DRAW LINES - End Circles and Cylindrical Body

Set Layer 1 Color 4

LineList From To

P0001	P0002	P0049	P0050
P0003	P0004	P0051	P0052
P0005	P0006	P0053	P0054
P0007	P0008	P0055	P0056
P0009	P0010	P0057	P0058
P0011	P0012	P0059	P0060
P0013	P0014	P0061	P0062
P0015	P0016	P0063	P0064
P0017	P0018	P0065	P0066
P0019	P0020	P0067	P0068
P0021	P0022	P0069	P0070
P0023	P0024	P0071	P0072
P0025	P0026	P0073	P0074
P0027	P0028	P0075	P0076
P0029	P0030	P0077	P0078
P0031	P0032	P0079	P0080
P0033	P0034	P0081	P0082
P0035	P0036	P0083	P0084
P0037	P0038	P0085	P0086
P0039	P0040	P0087	P0088
P0041	P0042	P0089	P0090
P0043	P0044	P0091	P0092
P0045	P0046	P0093	P0094
P0047	P0048	P0095	P0096

P0097	P0098
P0099	P0100
P0101	P0102
P0103	P0104
P0105	P0106
P0107	P0108
P0109	P0110
P0111	P0112
P0113	P0114
P0115	P0116
P0117	P0118
P0119	P0120
P0121	P0122
P0123	P0124
P0125	P0126
P0127	P0128
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P0197	P0198
P0199	P0200

P0201	P0202
P0203	P0204
P0205	P0206
P0207	P0208
P0209	P0210
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P0229	P0230
P0231	P0232
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P0235	P0236
P0237	P0238
P0239	P0240
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P0243	P0244
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P0287	P0288
P0289	P0290
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P0297	P0298
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P0595	P0596
P0597	P0598
P0599	P0600

-- GENERATE CYLINDER CIRCULAR ENDS

P0001	P0003	P0008	P0010
P0002	P0004	P0009	P0011
P0003	P0005	P0010	P0012
P0004	P0006	P0011	P0013
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P0007	P0009	P0014	P0016

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P0599	P0001
P0600	P0002

-- BEGINNING LONGITUDINAL LINES FOR VALVE

Set Layer 2 Color 5

LineList From To

P0601	P0602	P0699	P0700
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P0609	P0610	P0707	P0708
P0611	P0612	P0709	P0710
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P0617	P0618	P0715	P0716
P0619	P0620	P0717	P0718
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P0637	P0638	P0735	P0736
P0639	P0640	P0737	P0738
P0641	P0642	P0739	P0740
P0643	P0644	P0741	P0742
P0645	P0646	P0743	P0744
P0647	P0648	P0745	P0746
P0649	P0650	P0747	P0748
P0651	P0652	P0749	P0750
P0653	P0654	P0751	P0752
P0655	P0656	P0753	P0754
P0657	P0658	P0755	P0756
P0659	P0660	P0757	P0758
P0661	P0662	P0759	P0760
P0663	P0664	P0761	P0762
P0665	P0666	P0763	P0764
P0667	P0668	P0765	P0766
P0669	P0670	P0767	P0768
P0671	P0672	P0769	P0770
P0673	P0674	P0771	P0772
P0675	P0676	P0773	P0774
P0677	P0678	P0775	P0776
P0679	P0680	P0777	P0778
P0681	P0682	P0779	P0780
P0683	P0684	P0781	P0782
P0685	P0686	P0783	P0784
P0687	P0688	P0785	P0786
P0689	P0690	P0787	P0788
P0691	P0692	P0789	P0790
P0693	P0694	P0791	P0792
P0695	P0696	P0793	P0794
P0697	P0698	P0795	P0796

P0797	P0798
P0799	P0800
P0801	P0802
P0803	P0804
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P0807	P0808
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P0887	P0888
P0889	P0890
P0891	P0892
P0893	P0894
P0895	P0896
P0897	P0898
P0899	P0900

-- CIRCUMFRENTIAL LINES FOR THE VALVE

Set Layer 2 Color 5

LineList From To

P0601	P0603	P0650	P0652
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P0605	P0607	P0654	P0656
P0606	P0608	P0655	P0657
P0607	P0609	P0656	P0658
P0608	P0610	P0657	P0659
P0609	P0611	P0658	P0660
P0610	P0612	P0659	P0661
P0611	P0613	P0660	P0662
P0612	P0614	P0661	P0663
P0613	P0615	P0662	P0664
P0614	P0616	P0663	P0665
P0615	P0617	P0664	P0666
P0616	P0618	P0665	P0667
P0617	P0619	P0666	P0668
P0618	P0620	P0667	P0669
P0619	P0621	P0668	P0670
P0620	P0622	P0669	P0671
P0621	P0623	P0670	P0672
P0622	P0624	P0671	P0673
P0623	P0625	P0672	P0674
P0624	P0626	P0673	P0675
P0625	P0627	P0674	P0676
P0626	P0628	P0675	P0677
P0627	P0629	P0676	P0678
P0628	P0630	P0677	P0679
P0629	P0631	P0678	P0680
P0630	P0632	P0679	P0681
P0631	P0633	P0680	P0682
P0632	P0634	P0681	P0683
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P0635	P0637	P0684	P0686
P0636	P0638	P0685	P0687
P0637	P0639	P0686	P0688
P0638	P0640	P0687	P0689
P0639	P0641	P0688	P0690
P0640	P0642	P0689	P0691
P0641	P0643	P0690	P0692
P0642	P0644	P0691	P0693
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P0646	P0648	P0695	P0697
P0647	P0649	P0696	P0698
P0648	P0650	P0697	P0699
P0649	P0651	P0698	P0700

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P0700	P0702
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P0827	P0829
P0828	P0830
P0829	P0831
P0830	P0832
P0831	P0833
P0832	P0834
P0833	P0835
P0834	P0836
P0835	P0837
P0836	P0838
P0837	P0839
P0838	P0840
P0839	P0841
P0840	P0842
P0841	P0843
P0842	P0844
P0843	P0845
P0844	P0846
P0845	P0847
P0846	P0848
P0847	P0849
P0848	P0850
P0849	P0851
P0850	P0852
P0851	P0853
P0852	P0854
P0853	P0855
P0854	P0856

P0855 P0857
 P0856 P0858
 P0857 P0859
 P0858 P0860
 P0859 P0861
 P0860 P0862
 P0861 P0863
 P0862 P0864
 P0863 P0865
 P0864 P0866
 P0865 P0867
 P0866 P0868
 P0867 P0869
 P0868 P0870
 P0869 P0871
 P0870 P0872
 P0871 P0873
 P0872 P0874
 P0873 P0875
 P0874 P0876
 P0875 P0877
 P0876 P0878
 P0877 P0879
 P0878 P0880
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 P0880 P0882
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 P0883 P0885
 P0884 P0886
 P0885 P0887
 P0886 P0888
 P0887 P0889
 P0888 P0890
 P0889 P0891
 P0890 P0892
 P0891 P0893
 P0892 P0894
 P0893 P0895
 P0894 P0896
 P0895 P0897
 P0896 P0898
 P0897 P0899
 P0898 P0900
 P0899 P0601
 P0900 P0602

```

-- THE LINES FOR THE AXIS
Set Layer 3
LineList From To Color
P0901 P0902 1
P0901 P0903 2
P0901 P0904 3
P0905 P0906 1
P0907 P0908 2
P0901 P0909 3
-- Begin Bouncing Particles
Set Layer 4
  
```

APPENDIX I - MONTE CARLO PROGRAM SAMPLE GRAPHIC DATA OUTPUT

The following is a sample trajectory data output for ten particles generated by the Monte Carlo Program for input to the Acrospin three-dimensional dynamic graphic modeling program [7]:

EndPoint X	0.00000000	Y	0.62812290E-09	Z	5000.0000	Name	L0001
EndPoint X	4311.7710	Y	7059.6000	Z	7082.5180	Name	I0001
Line From L0001 To I0001	Color 6						
EndPoint X	2604.3050	Y	-9657.2340	Z	-2595.7330	Name	I0002
Line From I0001 To I0002	Color 7						
EndPoint X	789.49520	Y	4907.9980	Z	8712.7250	Name	I0003
Line From I0002 To I0003	Color 7						
EndPoint X	5136.2710	Y	2130.1070	Z	-9770.4990	Name	I0004
Line From I0003 To I0004	Color 7						
EndPoint X	0.18560880E-03	Y	-1950.9950	Z	-6623.6640	Name	I0005
Line From I0004 To I0005	Color 14						
EndPoint X	0.00000000	Y	-5750.3890	Z	1250.3350	Name	L0002
EndPoint X	2367.2990	Y	-9359.7670	Z	3520.6190	Name	I0006
Line From L0002 To I0006	Color 6						
EndPoint X	0.86972350E-04	Y	-6619.2300	Z	4934.4280	Name	I0007
Line From I0006 To I0007	Color 14						
EndPoint X	0.00000000	Y	1330.0930	Z	7147.1740	Name	L0003
EndPoint X	4046.0080	Y	-356.73900	Z	9993.6340	Name	I0008
Line From L0003 To I0008	Color 6						
EndPoint X	2972.6240	Y	-9999.5020	Z	99.889800	Name	I0009
Line From I0008 To I0009	Color 7						
EndPoint X	-0.17866850E-04	Y	-8057.4030	Z	394.83020	Name	I0010
Line From I0009 To I0010	Color 14						
EndPoint X	0.00000000	Y	-2766.1180	Z	8102.0560	Name	L0004

EndPoint X	3018.3060	Y	-3890.8460	Z	9212.0210	Name	I0011
Line From L0004	To I0011	Color	6				
EndPoint X	5283.7540	Y	-8029.1190	Z	5960.9780	Name	I0012
Line From I0011	To I0012	Color	7				
EndPoint X	0.17192040E-03	Y	-2750.4570	Z	2377.6730	Name	I0013
Line From I0012	To I0013	Color	14				
EndPoint X	0.00000000	Y	4264.7470	Z	1181.7160	Name	L0005
EndPoint X	2496.5940	Y	3215.2980	Z	-9468.9940	Name	I0014
Line From L0005	To I0014	Color	6				
EndPoint X	6449.1040	Y	-9643.9960	Z	2644.4940	Name	I0015
Line From I0014	To I0015	Color	7				
EndPoint X	20000.000	Y	-5365.3540	Z	-4545.8150	Name	I0016
Line From I0015	To I0016	Color	9				
EndPoint X	0.00000000	Y	2799.0490	Z	3638.8980	Name	L0006
EndPoint X	3830.1560	Y	9899.4470	Z	-1414.5470	Name	I0017
Line From L0006	To I0017	Color	6				
EndPoint X	5941.0360	Y	8201.1000	Z	-2203.4140	Name	I0018
Line From I0017	To I0018	Color	12				
EndPoint X	2355.2250	Y	8920.9730	Z	-4518.4360	Name	I0019
Line From I0018	To I0019	Color	7				
EndPoint X	0.98146290E-04	Y	7602.9070	Z	-3212.4620	Name	I0020
Line From I0019	To I0020	Color	14				
EndPoint X	0.00000000	Y	-4433.2270	Z	2729.0220	Name	L0007
EndPoint X	8362.0490	Y	5780.0880	Z	4282.3260	Name	I0021
Line From L0007	To I0021	Color	11				
EndPoint X	2692.0150	Y	-2176.2790	Z	-9760.3180	Name	I0022
Line From I0021	To I0022	Color	7				
EndPoint X	11571.870	Y	-2967.3180	Z	9549.6070	Name	I0023
Line From I0022	To I0023	Color	7				
EndPoint X	2683.0960	Y	9999.9480	Z	32.230550	Name	I0024
Line From I0023	To I0024	Color	7				
EndPoint X	0.64361910E-04	Y	7876.8190	Z	-785.37360	Name	I0025
Line From I0024	To I0025	Color	14				
EndPoint X	0.00000000	Y	-480.04530	Z	7030.4420	Name	L0008

EndPoint X	3934.7500	Y	496.55170	Z	-9987.6650	Name	I0026
Line From	L0008 To I0026	Color	6				
EndPoint X	4738.5040	Y	-9972.3620	Z	-742.96250	Name	I0027
Line From	I0026 To I0027	Color	7				
EndPoint X	-0.37787800E-04	Y	2906.4590	Z	-3472.8050	Name	I0028
Line From	I0027 To I0028	Color	14				
EndPoint X	0.00000000	Y	-3373.8650	Z	-4865.6250	Name	L0009
EndPoint X	17056.190	Y	-7280.7910	Z	6854.9310	Name	I0029
Line From	L0009 To I0029	Color	6				
EndPoint X	10877.940	Y	-9986.1800	Z	-525.56450	Name	I0030
Line From	I0029 To I0030	Color	7				
EndPoint X	12303.610	Y	-5858.6080	Z	8104.1160	Name	I0031
Line From	I0030 To I0031	Color	7				
EndPoint X	-0.82238500E-04	Y	-1885.9860	Z	320.80440	Name	I0032
Line From	I0031 To I0032	Color	14				
EndPoint X	0.00000000	Y	-1645.0810	Z	-7452.8540	Name	L0010
EndPoint X	1818.7090	Y	-2342.4010	Z	-9721.7880	Name	I0033
Line From	L0010 To I0033	Color	6				
EndPoint X	-0.88975550E-04	Y	-559.06830	Z	-9314.2870	Name	I0034
Line From	I0033 To I0034	Color	14				

APPENDIX J - LIST OF ACRONYMS

ESA - European Space Agency
MSFC - Marshall Space Flight Center
NASA - National Air & Space Administration
RSIC - Redstone Scientific Information Center
SL-J - Spacelab - Japan
SPAH-C - Spacelab Payload Accommodations Handbook-Volume C

VITA

Samuel Christopher Edwards was born in Tehran, Iran on January 14, 1963. He attended grammar school and high school in that city until August, 1978 when he came to the United States to continue his education. He graduated from Tullahoma High School in June 1979, and entered the University of Tennessee, Knoxville in the fall of 1979. In June of 1983 he received a Bachelor of Science degree in Mechanical Engineering. In the fall of 1983 he accepted a teaching assistantship at the University of Tennessee, Knoxville and began study toward a Master's degree in Mechanical Engineering.

In April 1986, after completing the required courses (but before completing his thesis) he accepted a position with Teledyne Brown Engineering Company in Huntsville, Alabama as an engineer. There he worked as a thermal and environmental / life support engineer supporting the NASA / ESA spacelab program. After the NASA Challenger Space Shuttle accident, he began working on the Solid Rocket Booster redesign effort. In May of 1988 he left Teledyne Brown to accept a position with Lockheed Missiles and Space

Company in Huntsville, Alabama where he worked on the thermal design of the Hubble Space Telescope Maintenance and Refurbishment Missions. He also analyzed the Long Duration Exposure Facility satellite for reentry aerothermal heating profile. He left Lockheed to begin working at Sverdrup Technology, Inc. in Huntsville, Alabama in October 1989. There he is responsible for the NASA Space Station Freedom carbon dioxide vacuum venting analysis.

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