APPENDIX B
VCR ENGINE MODIFICATION

VCR Engine Modifications

The design target for this phase of the project was to develop a swirl ratio of 2.66:1 for the Variable Compression Ratio (VCR) cylinder head. The following paragraphs give the chronological development process, beginning with background information.

The VCR cylinder head was flow-tested on the SwRI Flow Bench. A schematic of the Flow Bench is shown in Figure B-1. The cylinder head was tested for performance characteristics such as flow coefficient, swirl ratio, and pressure loss. We define these parameters in the ensuing discussion and describe below the SwRI Flow Bench and the methods of analyzing the data. The output from the data reduction program is shown in Appendix B. We used an impulse swirl meter. The impulse swirl meter to determine swirl ratio. The impulse swirl meter is preferred over a paddle, or vane meter because the latter tends to under predict the swirl level by as much as 30%. The pressure difference over all ports was maintained at 20 inches (508 mm) of water to ensure that the flow was fully turbulent, and hence, yield the equality between the steady-state flow bench and an actual operating engine.

Initially, a baseline test was performed of the un-modified head to provide a reference point for future development. Sensitivity of swirl ratio and pressure loss were evaluated for changes in compression ratio and engine speed. tests 1-4 consisted of a compression ratio of 16:1 and 22:1, each at an engine speed of 900 and 1800 rpm. A summary of these results is shown in Table B-1. Both swirl ratio and pressure loss proved to be insensitive to compression ratio. For the two engine speeds, the swirl ratio changed less than 2%. Pressure loss across the port changed with engine speed.

Table B-1. Compression Ratio and Engine Speed Sensitivity Results

Engine Speed, (rpm)	Compression Ratio Pressure Loss (kPa)	Swirl Ratio
900	16 +0.228	2.48
1800	16 +0.224	9.41
900	22 +0.228	2.49
1800	22 +0.241	9.48

The initial direction of development was to create a helical port out of the existing port because helical ports have the ability to generate high levels of swirl most efficiently. Tests 5–14 created the helical port by means of strategically placing modeling clay within the existing port to determine the correct port geometry. This procedure was an iterative process, relying on test results and intake port design experience.

After nine iterations in creating a helical port, we performed a so-called rotational test to determine the location of the directed swirl component and the percent helical/directed flow. A rotational test consists of moving the cylinder about the intake valve in 15 increments while maintaining the design distance between the centers. In this manner, the location of the largest value of non-dimensional swirl can be found. Non-dimensional swirl (N_r) is a measure of the level of swirl. The results of this test are shown in Figure B-2.

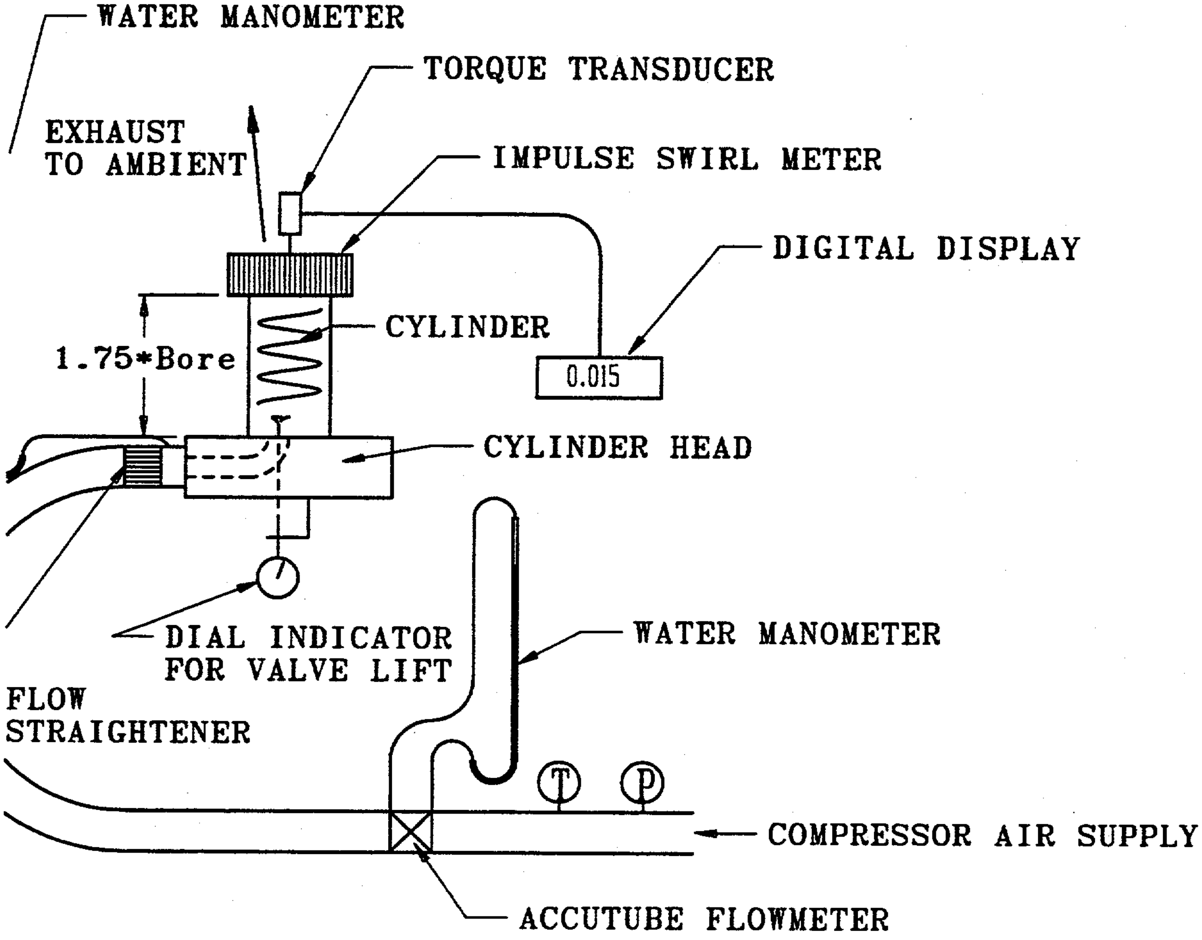


Figure B-1. SwRI flow bench schematic

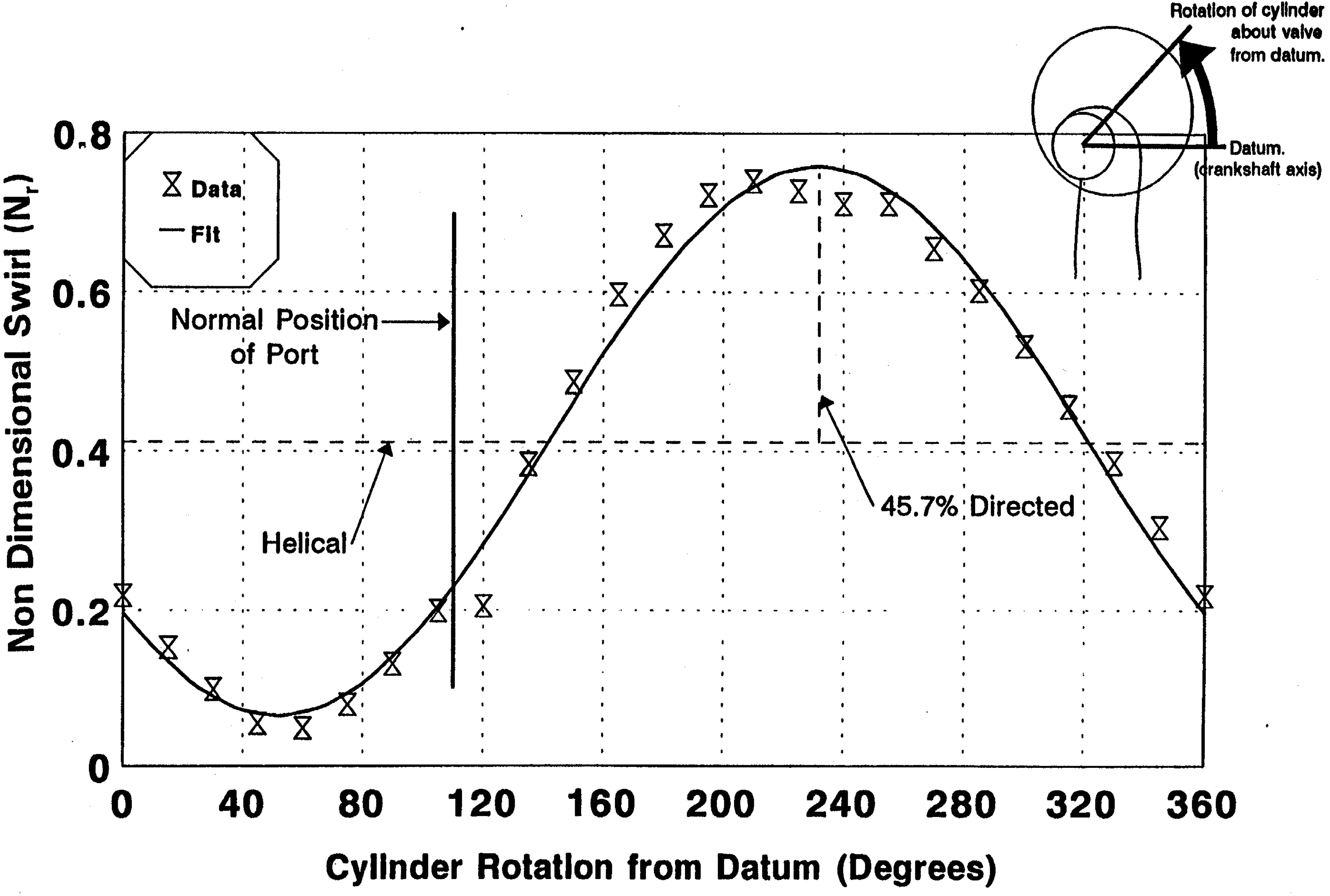


Figure B-2. SwRI rotational test - Labeco VCR - Mod.; #9 - Lift = 8.3 mm

The helical port of the swirl ratio is a horizontal line at Nr = 0.41. The directed component is the sinusoidal curve in which the maximum directed portion is given as Nr = p.35 at 225° cylinder rotation from datum. The normal position of the port is shown at 110 cylinder rotation from the datum. For the optimum design, the location of the maximum non-dimensional swirl (helical plus directed) should be coincident with the normal position of the port. In this case the location of the maximum non-dimensional swirl was 115 out-of-phase with the normal position of the port. The locations of the velocity vectors are illustrated in a top view of the cylinder in Figure B-3. The desired position of the velocity vector is shown tangential to the normal position of 110 counter-clock-wise from the datum. The actual velocity vector is shown pointing towards the center of the cylinder.

From the location of the velocity vector, the value of swirl ratio and the value of pressure drop across the port, we determined that the helical port solution to this problem is ineffective as tried. In Figure B-4, the velocity vector was oriented 115 from where it should be. Due to the spatial constraints of the VCR cylinder head, the necessary geometry cannot be created to allow the proper orientation of the velocity vector. Because swirl ratio is directly related to the velocity vector, the value of the swirl ratio cannot be dramatically increased without the re-orientation of the velocity vector. The maximum swirl ratio attained during clay modifications was 1.68:1 with a pressure drop of 6.85 (kPa). Table B-2 gives a summary of the baseline, target, and best clay modification. The pressure loss of the clay modification was 2.75 times higher than that of the baseline, and the swirl ration was 36% away from the target. We decided that the helical port solution to this problem was ineffective and that another approach should be taken.

Table B-2. Best Clay Modification

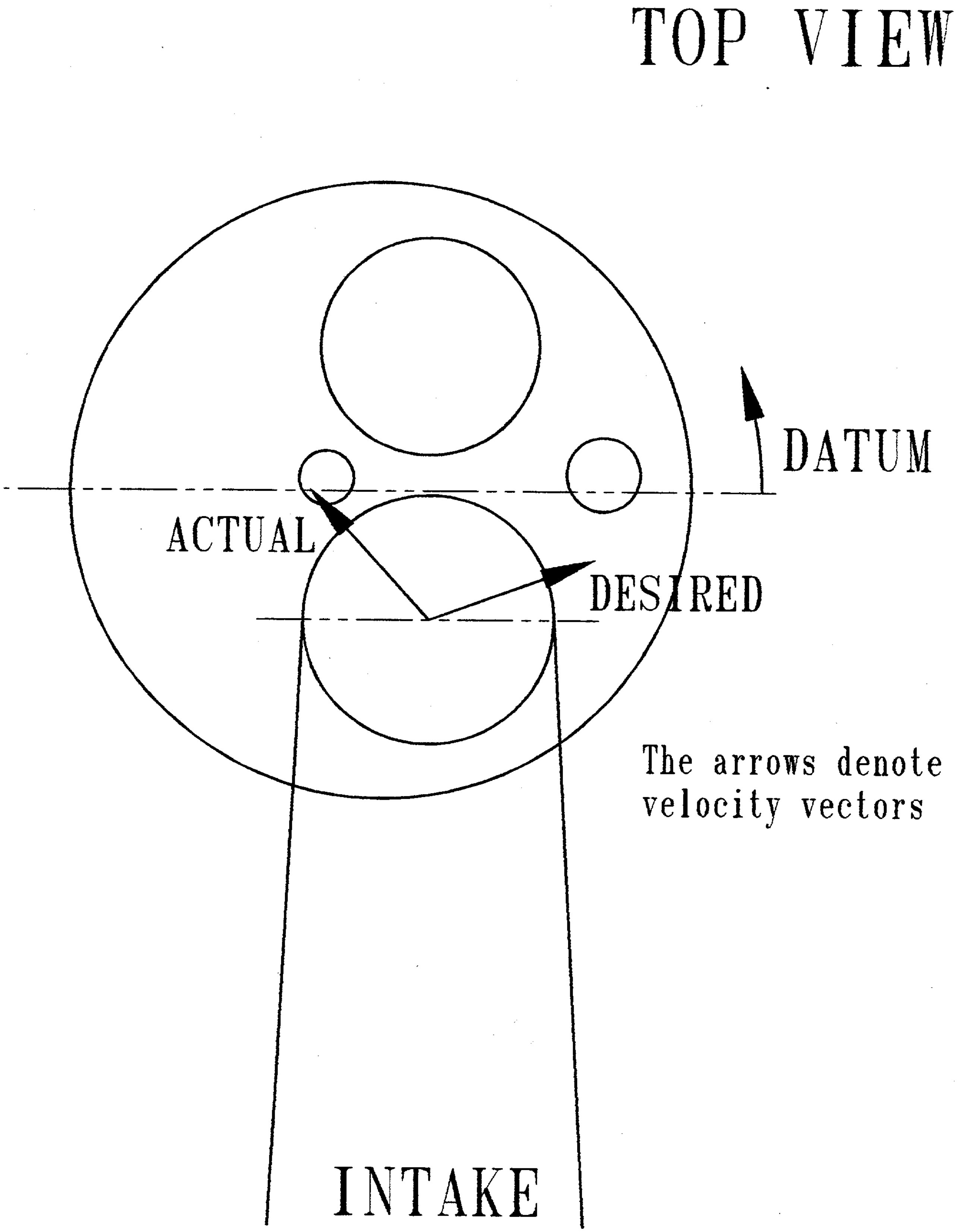
	Baseline	Target	Best Clay
Swirl Ratio	-0.23:1	2.66:1	1.69:1
Pressure Loss (kPa)	2.49	—	6.85

The second direction of development was to employ a shrouded valve. A shrouded valve directs a large portion of the air flow through an unrestricted section of the valve. Thus, the velocity vector can be forced in a desired direction. A masked valve was manufactured in which the unrestricted section measured 150. To determine the proper orientation, we performed a standard test (test #16) inn which the shrouded valve was rotated until the torque readout maximized at each valve lift position. From these results, we selected a valve position in which higher valve lifts were weighted more due to higher mass flow rates. The standard test was repeated (test #17) at a fixed valve position, and the results are shown in Table B-3. The pressure loss was 3.96 kPa and was only 1.6 times higher than the baseline pressure loss. The swirl ration was 16.5% away from the target swirl ratio. The orientation of the masked valve is shown in B-6.

Table B-2. Shrouded Valved Results

	Baseline	Target	Shrouded Valve
Swirl Ratio	-0.23:1	2.66:1	3.10:1
Pressure Loss (kPa)	2.49	—	3.96

We used two important non-dimensional parameters — non-dimensional swirl and non-dimensional flow coefficient — to compare the masked valve to the baseline. Non-dimensional swirl (Nr) is shown versus non-dimensional valve lift in Figure B-5. The nearly horizontal trend indicates that the baseline configuration does not produce swirl. The masked valve exhibits traits of a helical/directed combination.



The arrows denote velocity vectors

Figure B-3. Top view of cylinder - datum

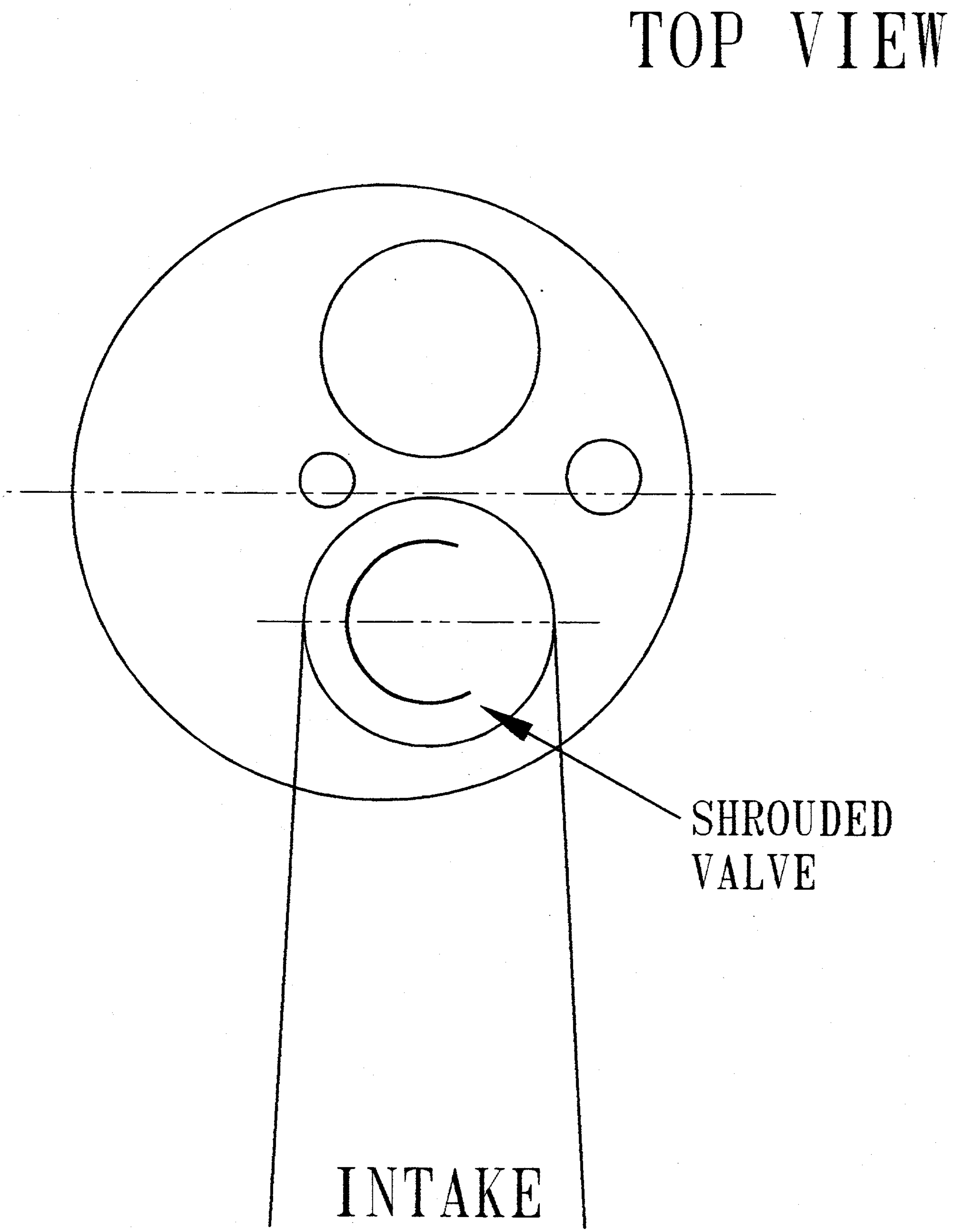


Figure B-4. Top view shrouded valve

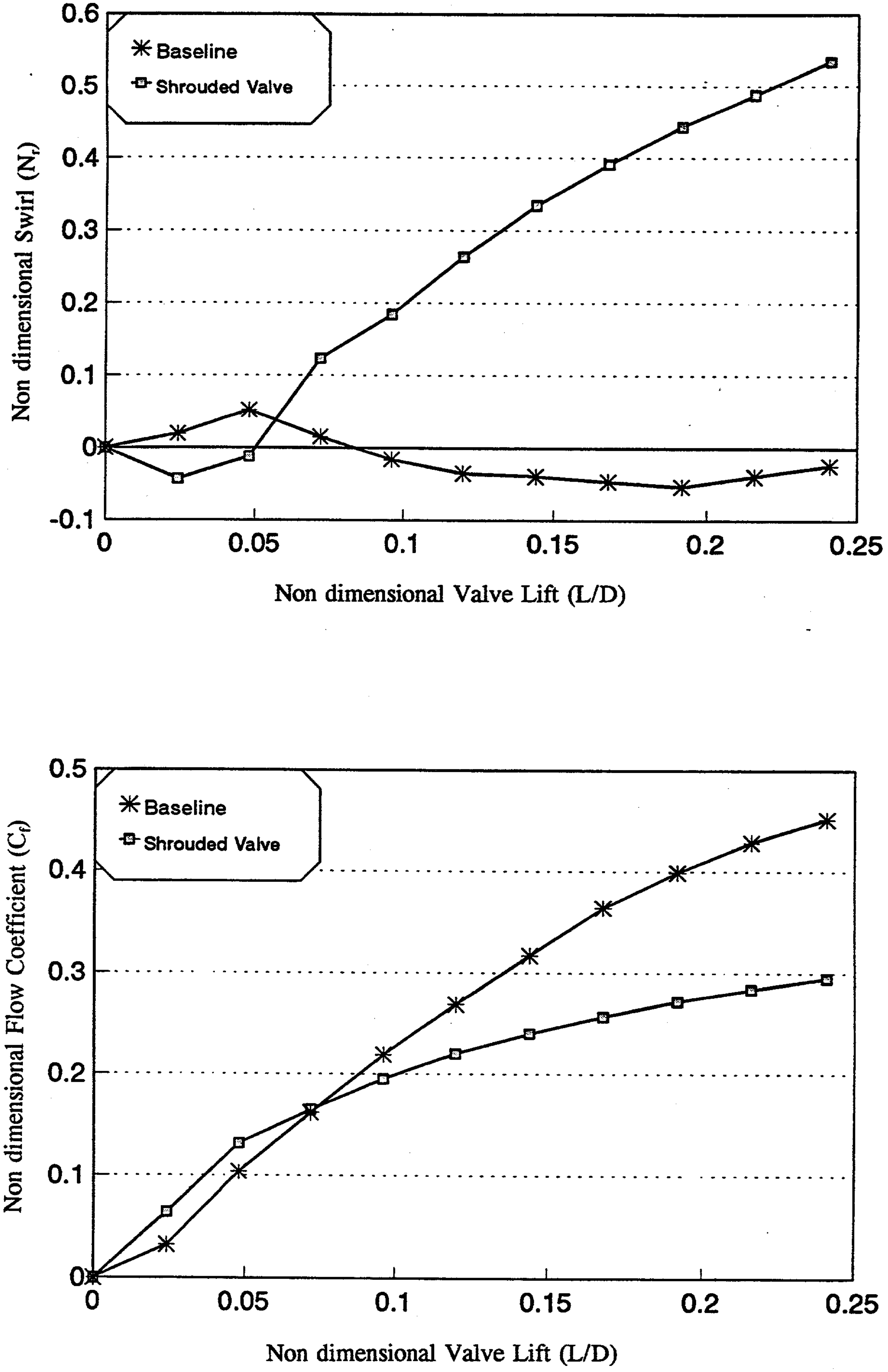


Figure B-5. SwRI flow bench standard test results Labeco VCR - 900 rpm - CR 16.10:1

Swirl is created at lower lifts and steadily increases. The non-dimensional flow coefficient (C_f) is defined as the actual flow divided by the ideal flow. Therefore, the larger C_f, the less restriction offered. The non-dimensional flow coefficient versus L/D is shown in Figure B-6. The baseline configuration is revealed to have a higher C_f than the masked valve. This was expected, because the masked valve obstructed the flow area and increased pressure loss.

It is often desirable to compare the swirl ratio and pressure loss of various cylinder heads. To do this, the cylinder heads must be evaluated on an equal basis. SwRI has accumulated a data base of swirl ratios and pressure losses and has determined the "state-of-the-art" for both 4-valve and 2-valve engines. For our particular engine, and 11.2 m/s piston speed equates to 3527 rpm. The baseline and masked valve configurations are shown in Figure B-6.

We selected the 210 masked valve to complete the design phase of the project. Even though the swirl ratio target was 2.66:1, we considered the masked swirl ratio of 3:10:1 satisfactory. Further, small increases of the swirl ratio from the one obtained would be costly and time consuming and were not pursued.

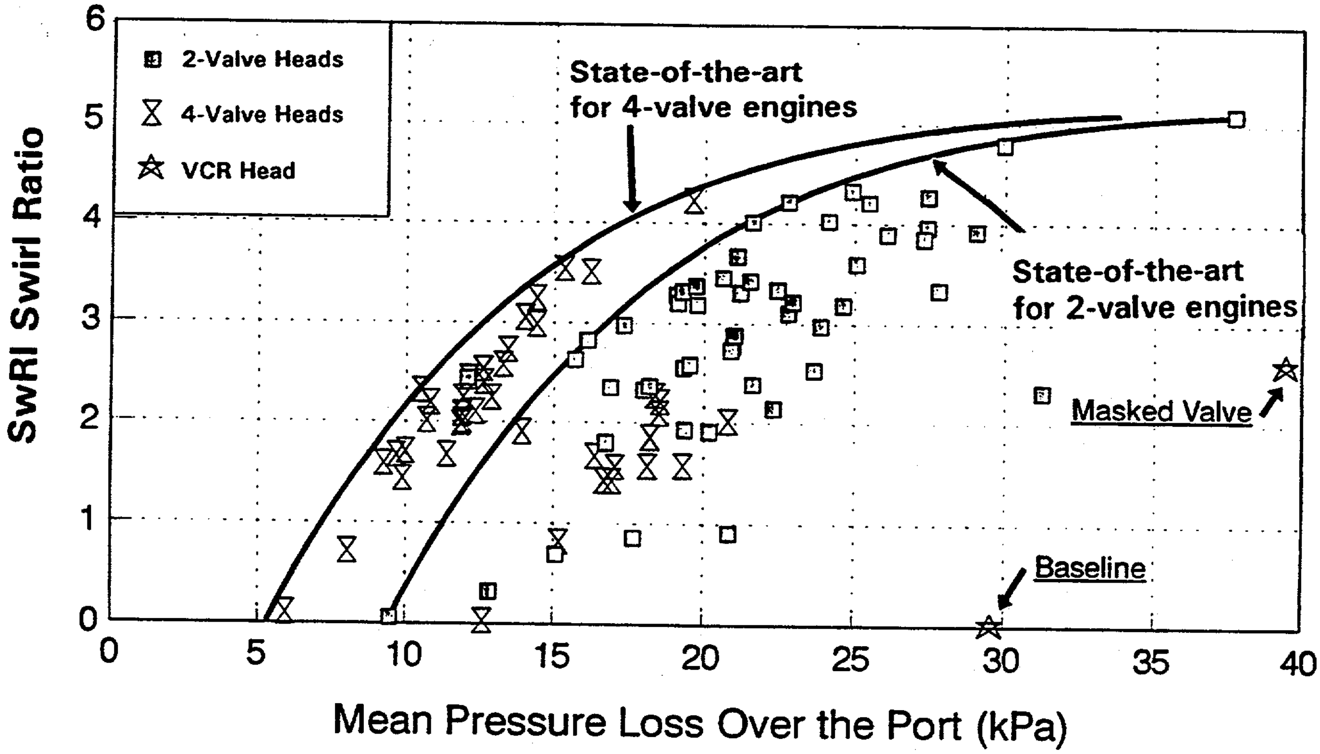


Figure B-6. SwRI swirl ratio comparison of different intake ports at the same mean piston speed of 11.2 m/s

FLOW BENCH and DATA REDUCTION TECHNIQUES

The flow bench is a time-tested steady-state air rig used to test the flow performance of the ports in a cylinder head. The techniques and analysis are appropriate for either spark-ignited (SI) or compression-ignited (CI) engines. A diagram of the SwRI Flow Bench is shown in Figure B-1.

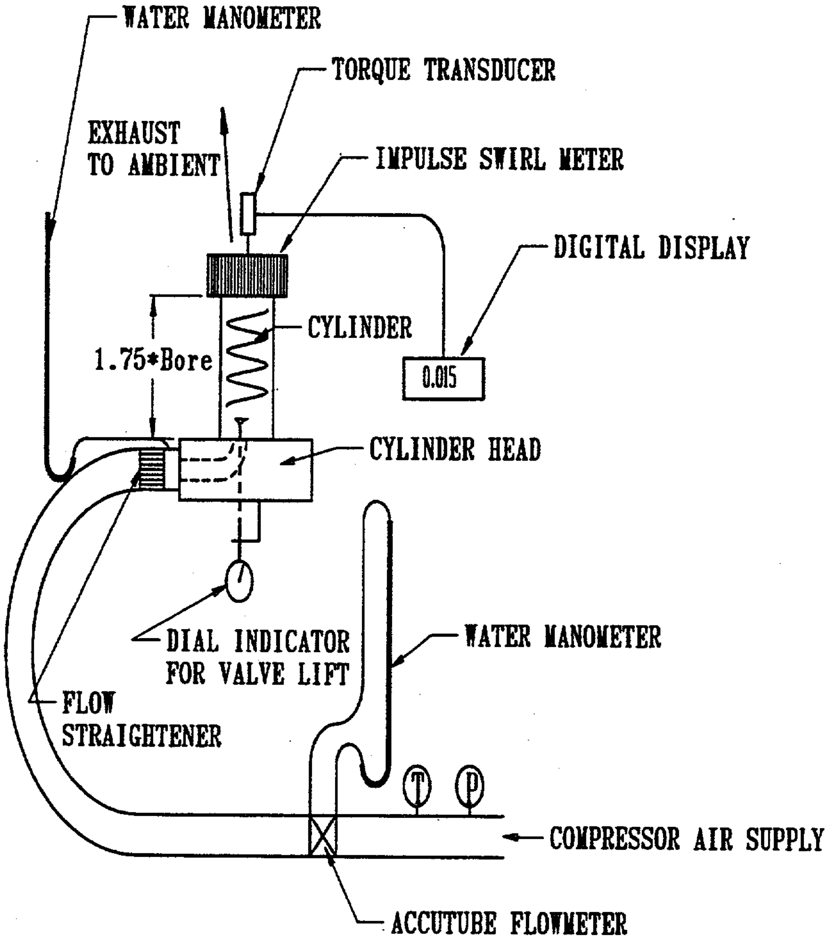


Figure B-1. SwRI Flow Bench Schematic

Flow benches have been used extensively in the past to determine flow capacity, usually in (CFM) cubic feet per minute. Since the 1970's, the ability to estimate in-cylinder air motion is the main strength of the flow bench. Swirl and tumble are the two components of the overall in-cylinder air motion that the flow bench can predict. The concepts of swirl and tumble are illustrated in Figures B-7 and B-8, respectively.

The generation of swirl and/or tumble is dependent upon many things, including port orientation, chamber masking, number of valves, and piston crown, among others. It is also beneficial to analyze the flow bench data in terms of non-dimensional parameters so as to allow comparisons independent of size. A discussion of non-dimensional parameters will be given below.

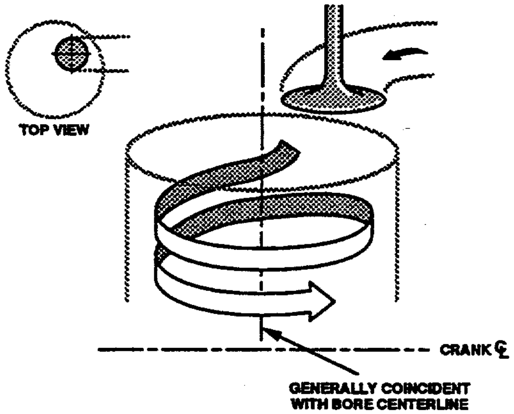


Figure B-7. Swirl Motion

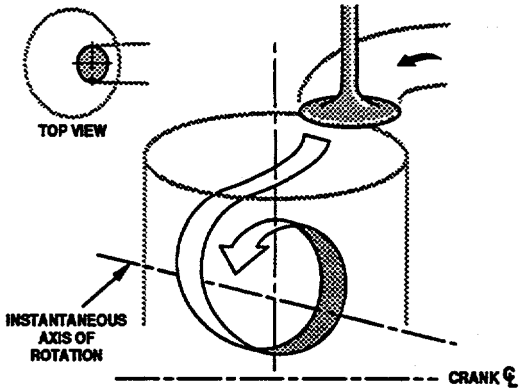


Figure B-8. Tumble Motion

The Purpose of Using Non-Dimensional Parameters

The non-dimensional parameters used to describe flow, swirl and tumble conditions at each valve lift are:

Flow Coefficient

$$C_F = \frac{Q}{n \cdot A \cdot V_o}$$

Non-Dimensional Swirl

$$N_R = \frac{8 \cdot G}{M \cdot B \cdot V_o}$$

Coefficient of Performance

$$C_p = \sqrt{\left[\frac{B \cdot N_R}{4 \cdot D \cdot n}\right]^2 + \left[\frac{D \cdot C_F}{4 \cdot L}\right]^2}$$

Angle of Outflow

$$Theta = Tan^{-1} \left[\frac{B \cdot L \cdot N_R}{n \cdot D^2 \cdot C_F}\right]$$

Non-Dimensional Valve Lift = L/D

where: α	is crank angle degrees	
	A	is valve seat area (m^2)
	A	= $\frac{\pi \cdot D^2}{4}$
	B	is the bore (m)
	D	is the inner valve seat diameter (m)
	G	is the torque measured on the swirl meter (N.m)
	I	is the moment of inertia ($kg \cdot m^2$)
	L	is the valve lift (m)

M	is the total mass flow through the port (kg/sec)
n	is the number of valves open, usually one or two
Q	is the total volume flow (m^3/sec)
r	is the pressure ratio over the port (p_{o2}/p_{o1})
R	is the gas constant for air (287.1 J/kg. °K)
S	is the stroke (m)
T	is the air temperature at the port (°K)
γ	is the ratio of specific heats for air (C_p/C_v)
V_o	is the velocity head upstream of the port (m/sec)

$$V_o = \sqrt{\frac{2 \cdot \gamma R \cdot T}{\gamma - 1}\left[1 - \frac{(1)}{(r)}^{\frac{\gamma-1}{\gamma}}\right]}$$

The port properties are described in non-dimensional terms as these do not vary with Reynolds number; that is, the non-dimensional terms are unchanged when the pressure drop over the port varies. This is because the flow is in the fully turbulent regime, so it exhibits Reynolds number similarity. This feature is important as it means that the port has the same flow properties in the engine as on the flow bench. This permits an emptying and filling engine model to predict terminal swirl from the non-dimensional flow properties on the flow bench.

The independence of the non-dimensional port properties to pressure drop also means that it does not really matter at what pressure differential the port is tested provided the flow is in the fully turbulent region. For engines under 150 mm bore diameter, this is usually above 350 mm water pressure differential.

The independence of non-dimensional parameters with pressure differential over the port also allows the emptying and filling model to predict conditions in an engine from the measurements made on the flow bench even though the flow bench measurements were made at a different pressure differential. The accurate extrapolation of flow bench measurements to running engine conditions allows the meaningful prediction of swirl in the engine.

The significance of the non-dimensional parameters that have already been defined will now be discussed:

Flow Coefficient

$$C_F = \frac{Q}{n \cdot A \cdot V_o} = \frac{\text{Actual Flow}}{\text{Ideal Flow}}$$

This is analogous to a flow coefficient based in the valve seat area. For two intake valves (n=2) then C_F represents the average flow coefficient for both ports.

Non-Dimensional Swirl or Tumble

$$N_R = \frac{8 \cdot G}{M \cdot B \cdot V_o}$$

$$N_R = \frac{\omega \cdot B}{V_o} = \frac{2 \times \mathit{Swirl\ Velocity\ at\ Cylinder\ Wall}}{V_o}$$

This is a measure of the level of swirl (or tumble), where ω is the equivalent swirl velocity in radians/sec. The non-dimensional swirl is independent of the number of intake valves, as it is calculated from global measurements, which by themselves, are not a function of the number of intake valves open.

Coefficient of Performance

$$C_p = \sqrt{\left[\frac{B \cdot N_R}{4 \cdot D \cdot n}\right]^2 + \left[\frac{D \cdot C_f}{4 \cdot L}\right]^2}$$

$$C_p = \sqrt{\frac{V_T^2 + V_R^2}{V_o^2}}$$

Coefficient of Performance $= V/V_o$

Coefficient of Performance is the relative velocity vector at the valve seat in a plane perpendicular to the valve stem axis divided by the maximum possible velocity upstream of the port. It is the weighted sum of the radial (or flow) component (V_R) and the tangential (or swirl) component (V_T). Coefficient of Performance is a useful parameter as it indicates the efficiency of the port in its ability to generate flow and swirl.

Angle of Outflow

$$\mathit{Theta} = \mathit{Tan}^{-1} \left[\frac{B \cdot L \cdot N_R}{n \cdot D^2 \cdot C_F}\right]$$

$$\mathit{Theta} = \mathit{Tan}^{-1} \left(\frac{V_T}{V_R}\right)$$

Theta is the angle subtended by these two components, V_T and V_R and indicates the proportion of velocity given to swirl or the flow. Theta increases with higher swirl.

Discussion of the Various Swirl Models

All of the swirl models predict swirl ratio. This is defined as:

$$\text{Swirl Ratio } (R_s) = \frac{\text{Swirl Speed at the End of Induction}}{\text{Engine Speed}}$$

As the flows in the engine are fully turbulent, swirl ratio does not change very much with engine speed.

The swirl models predict the solid-body terminal swirl by integrating the angular momentum flux at each crank position during induction. Dividing this value by the induced charge mass then gives terminal swirl speed.

SwRI Method

This method used the same equations as used by other, more sophisticated emptying and filling programs. It integrates between TDC and inlet valve closing and assumes an initial pressure in the port and in the cylinder of 1 bar, and assumes there is no heat transfer. Although this method requires compression ratio as input, it calculates volumetric efficiency, while the other methods stipulate 100 percent volumetric efficiency. This method also accounts for compressible flow.

$$\text{Terminal Swirl } (\omega) = \frac{1}{I_{final}} \int_{tdc}^{ivc} \bar{I} \cdot \omega \cdot dt$$

where: $\bar{I} \cdot \omega$ is the angular momentum flux (kg·m^2/sec^2)

I_{final} is the moment of inertia of the induced charge at intake valve closing (kg·m^2)

Ricardo Method

This method assumes a constant pressure drop over the port during induction. This pressure drop is calculated from the mean flow coefficient during intake valve opening. The momentum flux at any crank angle is then determined from this pressure drop and the valve lift at that crank angle. This method assumed 100 percent volumetric efficiency and incompressible flow.

$$\text{Swirl Ratio} = \frac{B \cdot S \cdot \int_{ivc}^{ivo} C_F \cdot N_R \cdot d\alpha}{n \cdot D^2 \left[\int_{ivc}^{ivo} C_F \cdot d\alpha \right]^2}$$

AVL Method

This method assumes that the flow rate equals the rate of piston displacement. It therefore integrates only between top and bottom dead centers (TDC to BDC), and assumes 100% volumetric efficiency.

SwRI Impulse Swirl Meter

The swirl meter is shown in Figure B-9 below. This is the impulse type that has the advantage over vane or paddle wheel swirl meters in that it measures the torque reaction from the arrested swirl. This equals momentum flux that is used directly by the swirl prediction model. A paddle wheel meter has the disadvantage in that flow profiles in the flow bench cylinder must be assumed, and that these assumptions can cause significant errors in the swirl predictions.

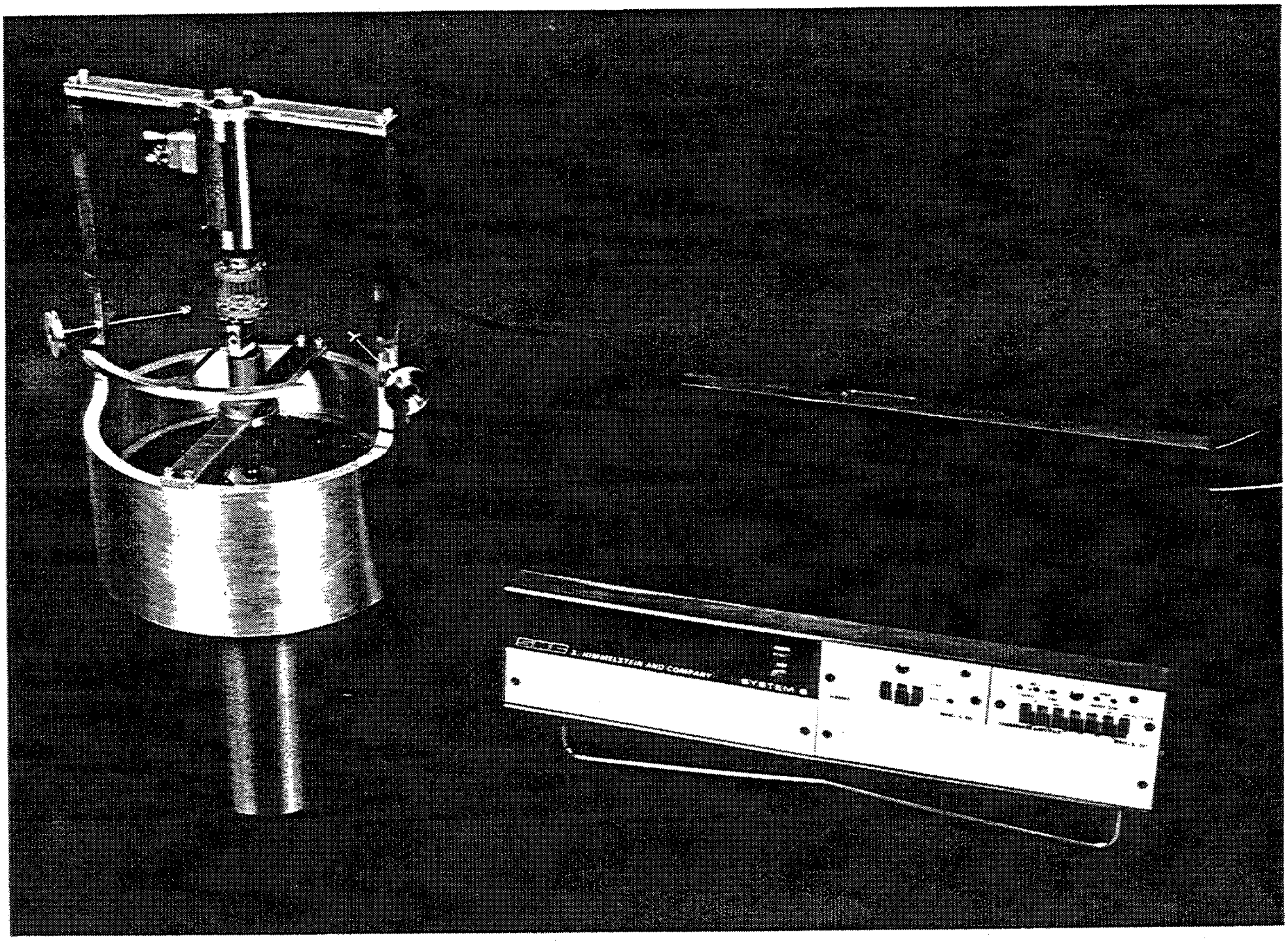


Figure B-9. Impulse type swirl meter on SwRI flow bench

It can be seen that for swirl, the cylinder head is tested in the upside down position on the SwRI flow bench. This allows simple repositioning of the flow bench cylinder. The swirl meter is positioned 1.75 bore lengths downstream of the head for swirl measurements. The flow bench is calibrated monthly with a standard calibration cylinder head, and the impulse swirl meter is calibrated monthly with a static deadweight procedure.

SwRI Rotational Test

A more detailed characterization of the swirl motion can be gained with the use of the SwRI Rotational Test. The measured swirl is comprised of a *directed* (or radial) and a *helical* (or tangential) component. These two components add vectorially to produce the measured swirl. This test determines the percentage of the directed and helical components of the swirl and also the orientation of the maximum directed component. This test allows the designer to ensure that the directed component is effectively utilized.

The Rotational Test consists of rotating the center of the cylinder about the center of the intake valve maintaining the normally design separation distance between the two centers. This test is conducted at a fixed valve lift; normally at maximum intake valve lift. Figure B-10 shows the principle of the Rotational Test. This test can be conducted on individual ports for a four-valve head and also on heads with an integral combustion chamber.

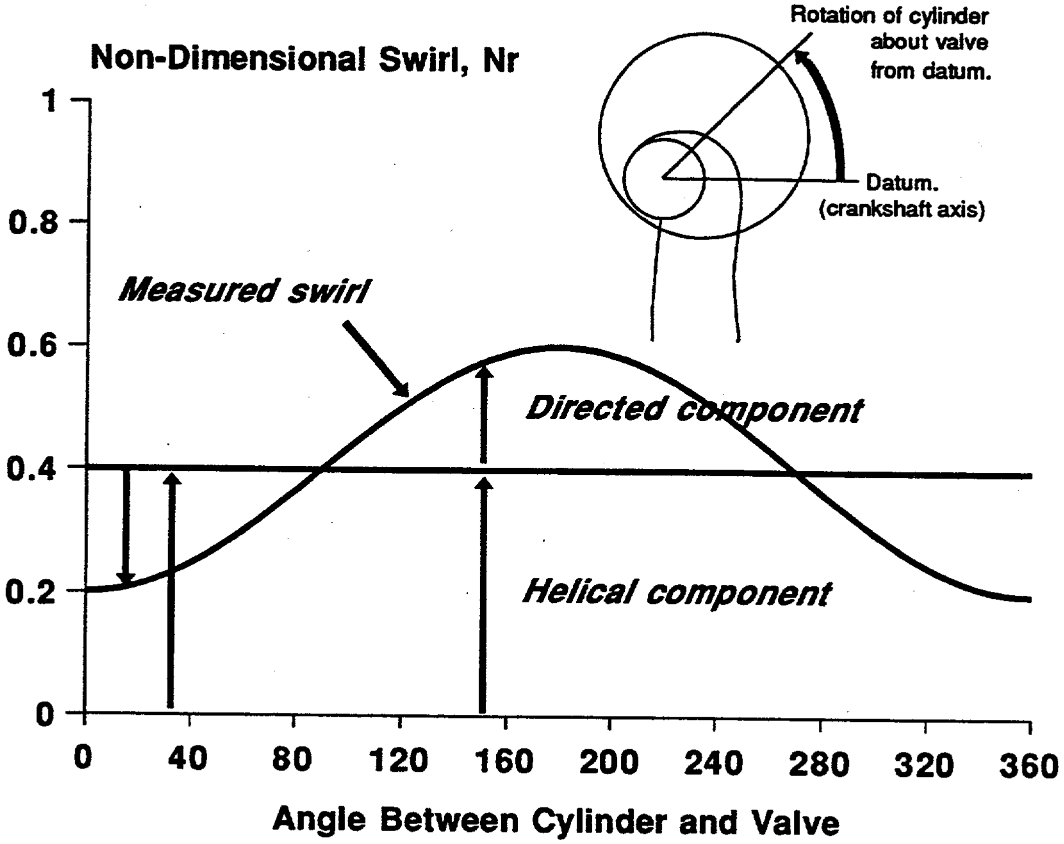


Figure B-10. Description of rotational test result

Effect of Manifold on Flow and Swirl

Tests are also conducted with and without the intake manifold to assess the contribution of the manifold to the overall calculated mean pressure loss, and to assess its effect on cylinder-to-cylinder air distribution.

Cylinder-to-Cylinder Variability Tests

In addition to the variability of the air quantity supplied to each cylinder due to the manifolding the individual cylinders or heads are tested to quantify the amount of swirl, tumble, and flow variation from cylinder-to-cylinder due to casting and/or machining defects. Flow bench results quantify the effect of any core shifts or machining errors and molds of the ports help visualize the direction and extent of any anomaly. SwRI has port design techniques that make the performance of the port insensitive to any of these defects.

Tumble Testing

As shown in Figure B-8, tumble motion is defined as rotation about an axis perpendicular to the cylinder centerline. Tumble is also thought of as an end-over-end cascading motion or a that of a vortex. Tumble motion has been shown to break down into small scale turbulence near TDC helping flame propagation rates in SI engines.

The SwRI approach to measuring tumble on the flow bench is illustrated in Figure B-11. The SwRI convention for measuring tumble is shown in Figure B-12.

Combined Swirl Ratio

Rarely is in-cylinder air motion just comprised of swirl or just tumble through the entire intake and compression strokes. The effect of squish motion, which plays an important role near TDC, has not been considered either. However, in an attempt to better predict total in-cylinder swirl SwRI vectorially summarizes the individual angular momentums of the swirl and tumble orthoganol components and calls this Combined Swirl. Figure B-13 illustrates the concept of combined swirl. The combined swirl ratio has resulted in better engine/flow bench correlations than traditional swirl alone.

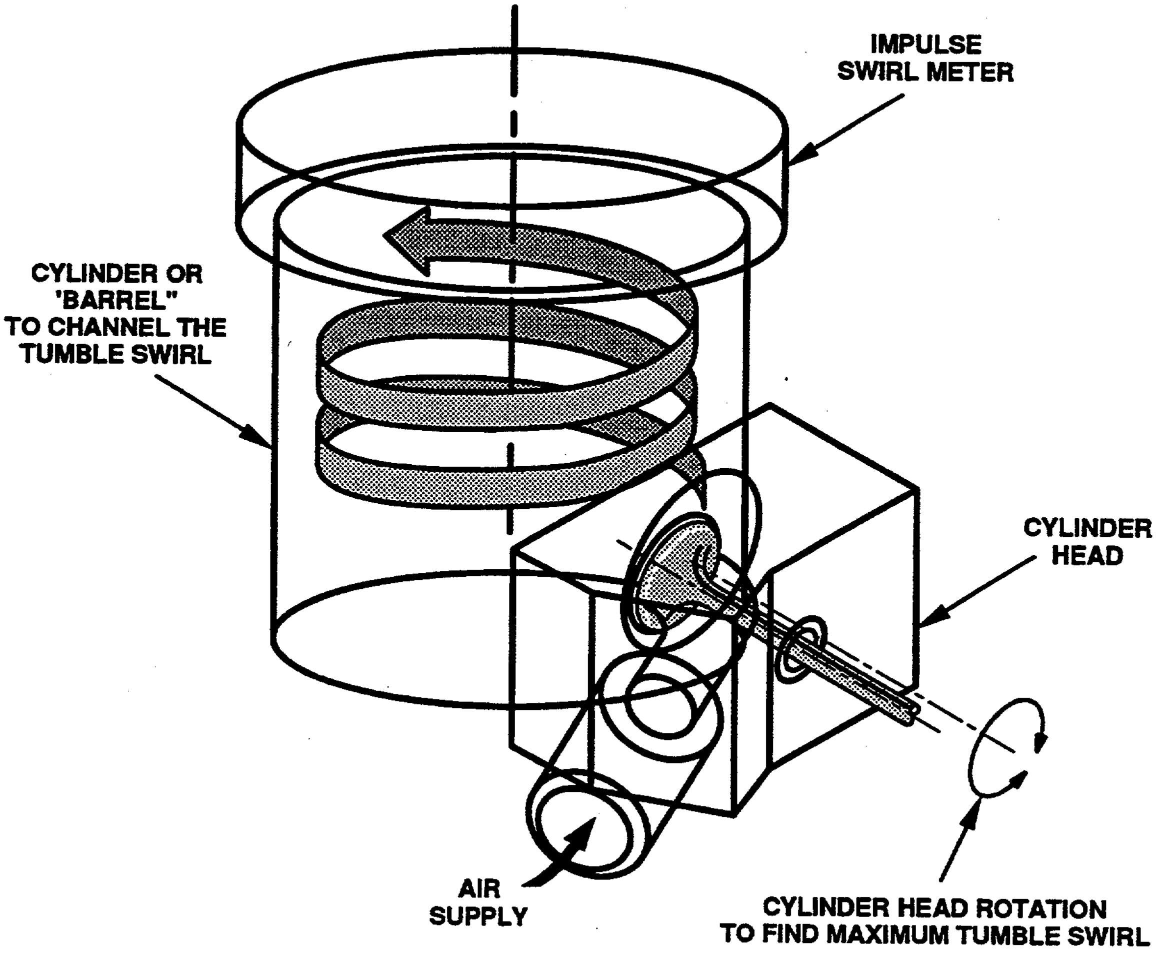


Figure B-11. Measurement of Tumble

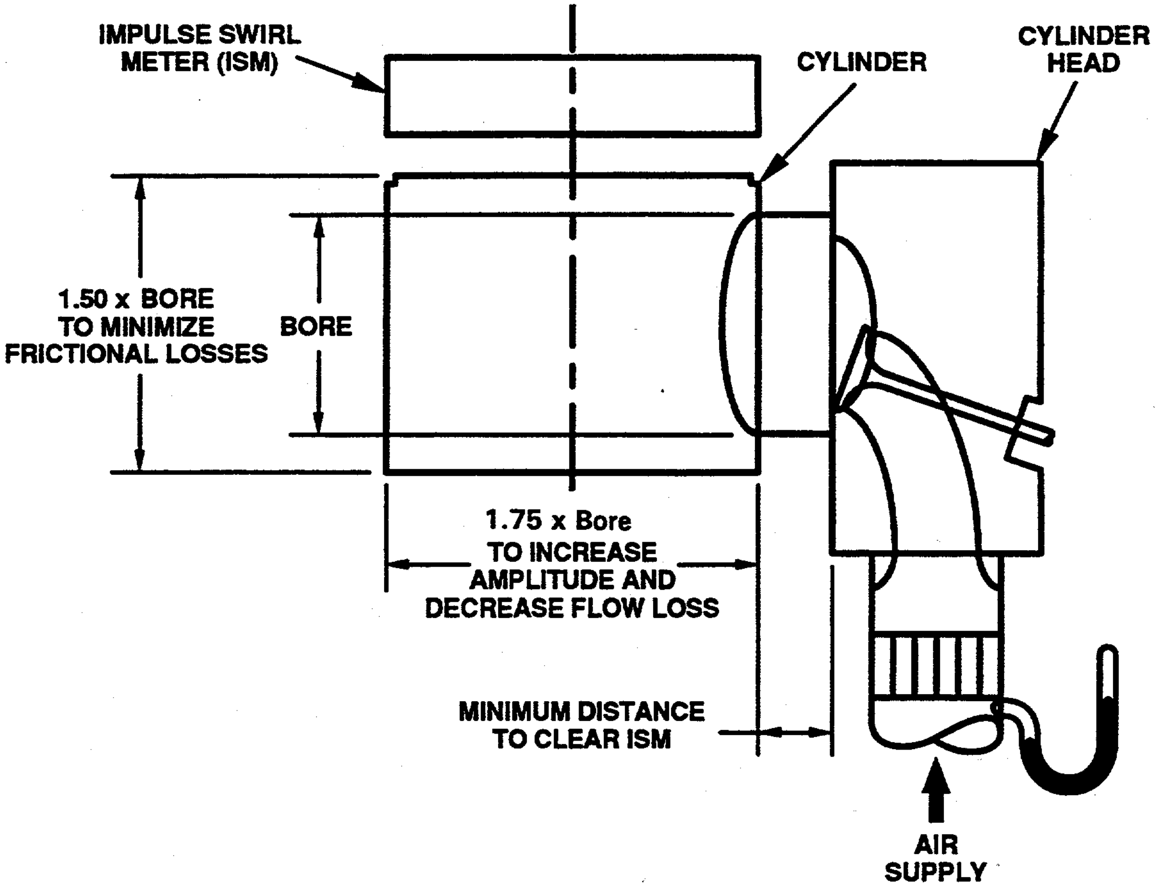


Figure B-12. Tumble Convention

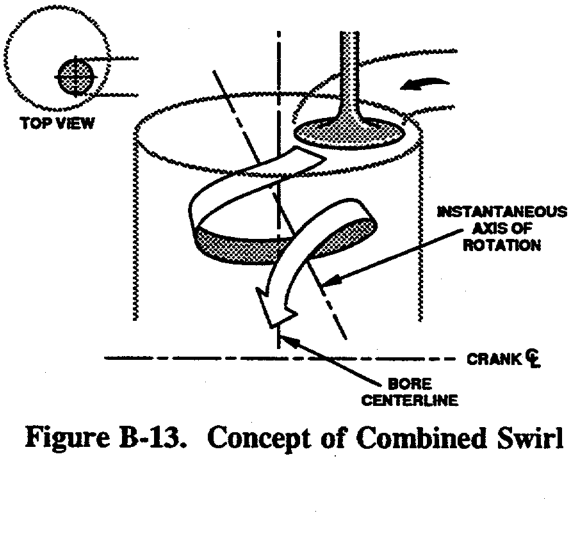


Figure B-13. Concept of Combined Swirl

ANALYSIS OF SwRI FLOW BENCH RESULTS

Test Number 1   Date: 16 FEB 92

VCR Head: SwRI Project 03-4764-280. Standard Test.

Bore	96.52(mm)	Inner Valve Seat	41.58(mm)	Valve Opens	-30.00 deg	Compression Ratio	16.00:1
Stroke	95.25(mm)	Maximum Valve Lift	8.38(mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62(mm)	Number Of Valves	1	Engine Speed	900. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	900	3527	900	3527	900	3527
Swirl Ratio	-.228	-.249	-.208	-.208	-.226	-.226
Mean Flow Coefficient			.199	.199	.214	.214
Gulp Factor	.182	.621	.226	.885	.209	.820
Mean Pressure Loss (kPa)	2.48	29.56	1.71	26.28	3.06	47.07
Port Effectiveness (%)			25.49	25.49	23.13	23.13
Volumetric Efficiency (%)	1.028	.866				
Maximum Mach Number	.621	.865				

Max Flow Coeff = .411

Valve Lift (mm)	Valve Lift / Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0040	.0049	.032	.10	.019	.334	1.9	.997	.984
2.00	.048	508.00	.0129	.0157	.104	.90	.052	.542	3.2	.854	.843
3.00	.072	508.00	.0202	.0245	.162	.40	.015	.562	.9	.156	.154
4.00	.096	508.00	.0273	.0330	.219	-.60	-.016	.569	-1.0	-.128	-.127
5.00	.120	508.00	.0337	.0406	.269	-1.60	-.035	.560	-2.1	-.226	-.223
6.00	.144	508.00	.0397	.0479	.317	-2.10	-.039	.550	-2.4	-.213	-.210
7.00	.168	508.00	.0456	.0550	.364	-2.80	-.046	.540	-2.8	-.216	-.213
8.00	.192	508.00	.0501	.0603	.399	-3.60	-.053	.519	-3.4	-.230	-.227
9.00	.216	508.00	.0540	.0650	.429	-2.80	-.039	.496	-2.6	-.154	-.152
10.00	.241	508.00	.0569	.0684	.452	-1.80	-.024	.470	-1.7	-.089	-.088

ANALYSIS OF SwRI FLOW BENCH RESULTS

Test Number 2   Date: 16 FEB 92

VCR Head: SwRI Project 03-4764-280. Standard Test.

Bore	96.52(mm)	Inner Valve Seat	41.58(mm)	Valve Opens	-30.00 deg	Compression Ratio	16.00:1
Stroke	95.25(mm)	Maximum Valve Lift	8.38(mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62(mm)	Number Of Valves	1	Engine Speed	1800. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	1800	3527	1800	3527	1800	3527
Swirl Ratio	-.244	-.249	-.208	-.208	-.226	-.226
Mean Flow Coefficient			.199	.199	.214	.214
Gulp Factor	.348	.621	.452	.885	.419	.820
Mean Pressure Loss (kPa)	9.41	29.56	6.84	26.28	12.26	47.07
Port Effectiveness (%)			25.49	25.49	23.13	23.13
Volumetric Efficiency (%)	.989	.866				
Maximum Mach Number	.591	.865				

Max Flow Coeff = .411

Valve Lift (mm)	Valve Lift / Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0040	.0049	.032	.10	.019	.334	1.9	.997	.984
2.00	.048	508.00	.0129	.0157	.104	.90	.052	.542	3.2	.854	.843
3.00	.072	508.00	.0202	.0245	.162	.40	.015	.562	.9	.156	.154
4.00	.096	508.00	.0273	.0330	.219	-.60	-.016	.569	-1.0	-.128	-.127
5.00	.120	508.00	.0337	.0406	.269	-1.60	-.035	.560	-2.1	-.226	-.223
6.00	.144	508.00	.0397	.0479	.317	-2.10	-.039	.550	-2.4	-.213	-.210
7.00	.168	508.00	.0456	.0550	.364	-2.80	-.046	.540	-2.8	-.216	-.213
8.00	.192	508.00	.0501	.0603	.399	-3.60	-.053	.519	-3.4	-.230	-.227
9.00	.216	508.00	.0540	.0650	.429	-2.80	-.039	.496	-2.6	-.154	-.152
10.00	.241	508.00	.0569	.0684	.452	-1.80	-.024	.470	-1.7	-.089	-.088

ANALYSIS OF SwRI FLOW BENCH RESULTS

Test Number 3   Date: 16 FEB 92

VCR Head: SwRI Project 03-4764-280. Standard Test.

Bore	96.52(mm)	Inner Valve Seat	41.58(mm)	Valve Opens	-30.00 deg	Compression Ratio	22.00:1
Stroke	95.25(mm)	Maximum Valve Lift	8.38(mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62(mm)	Number Of Valves	1	Engine Speed	900. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	900	3527	900	3527	900	3527
Swirl Ratio	-.228	-.248	-.208	-.208	-.226	-.226
Mean Flow Coefficient			.199	.199	.214	.214
Gulp Factor	.183	.631	.226	.885	.209	.820
Mean Pressure Loss (kPa)	2.49	30.14	1.71	26.28	3.06	47.07
Port Effectiveness (%)			25.49	25.49	23.13	23.13
Volumetric Efficiency (%)	1.029	.867				
Maximum Mach Number	.627	.884				

Max Flow Coeff = .411

Valve Lift (mm)	Valve Lift ------------- Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0040	.0049	.032	.10	.019	.334	1.9	.997	.984
2.00	.048	508.00	.0129	.0157	.104	.90	.052	.542	3.2	.854	.843
3.00	.072	508.00	.0202	.0245	.162	.40	.015	.562	.9	.156	.154
4.00	.096	508.00	.0273	.0330	.219	-.60	-.016	.569	-1.0	-.128	-.127
5.00	.120	508.00	.0337	.0406	.269	-1.60	-.035	.560	-2.1	-.226	-.223
6.00	.144	508.00	.0397	.0479	.317	-2.10	-.039	.550	-2.4	-.213	-.210
7.00	.168	508.00	.0456	.0550	.364	-2.80	-.046	.540	-2.8	-.216	-.213
8.00	.192	508.00	.0501	.0603	.399	-3.60	-.053	.519	-3.4	-.230	-.227
9.00	.216	508.00	.0540	.0650	.429	-2.80	-.039	.496	-2.6	-.154	-.152
10.00	.241	508.00	.0569	.0684	.452	-1.80	-.024	.470	-1.7	-.089	-.088

ANALYSIS OF SwRI FLOW BENCH RESULTS

Test Number 4   Date: 16 FEB 92

VCR Head: SwRI Project 03-4764-280. Standard Test.

Bore	96.52(mm)	Inner Valve Seat	41.58(mm)	Valve Opens	-30.00 deg	Compression Ratio	22.00:1
Stroke	95.25(mm)	Maximum Valve Lift	8.38(mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62(mm)	Number Of Valves	1	Engine Speed	1800. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	1800	3527	1800	3527	1800	3527
Swirl Ratio	-.241	-.248	-.208	-.208	-.226	-.226
Mean Flow Coefficient			.199	.199	.214	.214
Gulp Factor	.354	.631	.452	.885	.419	.820
Mean Pressure Loss (kPa)	9.48	30.14	6.84	26.28	12.26	47.07
Port Effectiveness (%)			25.49	25.49	23.13	23.13
Volumetric Efficiency (%)	.989	.867				
Maximum Mach Number	.596	.884				

Max Flow Coeff = .411

Valve Lift (mm)	Valve Lift ------------- Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0040	.0049	.032	.10	.019	.334	1.9	.997	.984
2.00	.048	508.00	.0129	.0157	.104	.90	.052	.542	3.2	.854	.843
3.00	.072	508.00	.0202	.0245	.162	.40	.015	.562	.9	.156	.154
4.00	.096	508.00	.0273	.0330	.219	-.60	-.016	.569	-1.0	-.128	-.127
5.00	.120	508.00	.0337	.0406	.269	-1.60	-.035	.560	-2.1	-.226	-.223
6.00	.144	508.00	.0397	.0479	.317	-2.10	-.039	.550	-2.4	-.213	-.210
7.00	.168	508.00	.0456	.0550	.364	-2.80	-.046	.540	-2.8	-.216	-.213
8.00	.192	508.00	.0501	.0603	.399	-3.60	-.053	.519	-3.4	-.230	-.227
9.00	.216	508.00	.0540	.0650	.429	-2.80	-.039	.496	-2.6	-.154	-.152
10.00	.241	508.00	.0569	.0684	.452	-1.80	-.024	.470	-1.7	-.089	-.088

ANALYSIS OF SwRI FLOW BENCH RESULTS

Test Number 5 Date: 16 FEB 92

VCR Head: SwRI Project 03-4764-280. Standard Test.

Bore	96.52 (mm)	Inner Valve Seat	41.58 (mm)	Valve Opens	-30.00 deg	Compression Ratio	16.00:1
Stroke	95.25 (mm)	Maximum Valve Lift	8.38 (mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62 (mm)	Number Of Valves	1	Engine Speed	900. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	900	3527	900	3527	900	3527
Swirl Ratio	-.255	-.272	-.267	-.267	-.250	-.250
Mean Flow Coefficient			.193	.193	.031	.031
Gulp Factor	.188	.624	.233	.913	1.438	5.637
Mean Pressure Loss (kPa)	2.58	29.88	1.82	27.92	144.74	******
Port Effectiveness (%)			23.99	23.99	.49	.49
Volumetric Efficiency (%)	1.056	.865				
Maximum Mach Number	.662	.873				

Max Flow Coeff = .410

Valve Lift (mm)	Valve Lift / Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0028	.0034	.023	.10	.026	.237	3.7	1.994	1.968
2.00	.048	508.00	.0127	.0153	.102	.50	.030	.528	1.9	.498	.492
3.00	.072	508.00	.0200	.0242	.161	.20	.007	.556	.4	.080	.079
4.00	.096	508.00	.0272	.0328	.218	-.80	-.022	.566	-1.3	-.173	-.171
5.00	.120	508.00	.0337	.0406	.269	-1.80	-.040	.560	-2.4	-.254	-.251
6.00	.144	508.00	.0399	.0480	.318	-2.50	-.047	.551	-2.8	-.252	-.249
7.00	.168	508.00	.0454	.0546	.361	-3.00	-.049	.537	-3.0	-.234	-.231
8.00	.192	508.00	.0501	.0602	.398	-3.60	-.054	.518	-3.4	-.231	-.228
9.00	.216	508.00	.0539	.0648	.428	-2.80	-.039	.495	-2.6	-.155	-.153
10.00	.241	508.00	.0569	.0684	.452	-1.70	-.022	.470	-1.6	-.084	-.083

ANALYSIS OF SwRI FLOW BENCH RESULTS

Test Number 6 Date: 19 MAR 92

VCR Head: Mod 1 - Clayed Intake Port.

Bore	96.52 (mm)	Inner Valve Seat	41.58 (mm)	Valve Opens	-30.00 deg	Compression Ratio	16.00:1
Stroke	95.25 (mm)	Maximum Valve Lift	8.38 (mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62 (mm)	Number Of Valves	1	Engine Speed	900. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	900	3527	900	3527	900	3527
Swirl Ratio	-.248	-.199	-.193	-.193	-.259	-.259
Mean Flow Coefficient			.195	.195	.235	.235
Gulp Factor	.180	.632	.230	.900	.191	.749
Mean Pressure Loss (kPa)	2.53	30.37	1.77	27.16	2.55	39.22
Port Effectiveness (%)			24.66	24.66	27.76	27.76
Volumetric Efficiency (%)	1.012	.854				
Maximum Mach Number	.595	.846				

Max Flow Coeff = .383

Valve Lift (mm)	Valve Lift / Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0056	.0069	.045	-.94	-.125	.478	-8.7	-4.705	-4.643
2.00	.048	508.00	.0147	.0178	.118	-1.82	-.092	.616	-5.0	-1.342	-1.325
3.00	.072	508.00	.0218	.0262	.174	-2.50	-.086	.606	-4.7	-.844	-.832
4.00	.096	508.00	.0280	.0336	.223	-4.15	-.111	.584	-6.3	-.852	-.841
5.00	.120	508.00	.0337	.0403	.268	-5.22	-.116	.562	-6.9	-.742	-.732
6.00	.144	508.00	.0386	.0462	.307	-3.86	-.075	.534	-4.7	-.417	-.412
7.00	.168	508.00	.0430	.0515	.342	-.65	-.011	.508	-.7	-.057	-.056
8.00	.192	508.00	.0469	.0560	.372	.86	.014	.483	.9	.063	.062
9.00	.216	508.00	.0503	.0601	.399	1.05	.016	.461	1.1	.067	.066
10.00	.241	508.00	.0529	.0632	.419	1.54	.022	.436	1.7	.089	.088

ANALYSIS OF SwRI FLOW BENCH RESULTS
Test Number 7 Date: 19 MAR 92

VCR Head: Mod 2 - 180 deg Masking (Clayed IP)

Bore	96.52(mm)	Inner Valve Seat	41.58(mm)	Valve Opens	-30.00 deg	Compression Ratio	16.00:1
Stroke	95.25(mm)	Maximum Valve Lift	8.38(mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62(mm)	Number Of Valves	1	Engine Speed	900. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	900	3527	900	3527	900	3527
Swirl Ratio	.639	.634	.583	.583	.626	.626
Mean Flow Coefficient			.194	.194	.232	.232
Gulp Factor	.181	.639	.231	.905	.193	.757
Mean Pressure Loss (kPa)	2.59	30.91	1.79	27.44	2.61	40.09
Port Effectiveness (%)			24.41	24.41	27.18	27.18
Volumetric Efficiency (%)	1.002	.847				
Maximum Mach Number	.579	.849				

Max Flow Coeff = .370

Valve Lift (mm)	Valve Lift / Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0063	.0077	.051	-.85	-.100	.531	-6.3	-3.377	-3.332
2.00	.048	508.00	.0150	.0181	.120	-.46	-.023	.625	-1.2	-.326	-.322
3.00	.072	508.00	.0216	.0260	.173	-.56	-.019	.599	-1.1	-.191	-.188
4.00	.096	508.00	.0277	.0332	.221	-.17	-.005	.575	-.3	-.035	-.035
5.00	.120	508.00	.0335	.0400	.266	1.93	.043	.554	2.6	.278	.275
6.00	.144	508.00	.0383	.0456	.304	5.24	.103	.530	6.5	.579	.571
7.00	.168	508.00	.0425	.0505	.337	8.06	.142	.507	9.4	.726	.716
8.00	.192	508.00	.0458	.0543	.362	7.67	.126	.476	8.8	.596	.588
9.00	.216	508.00	.0484	.0574	.383	11.38	.176	.454	13.0	.790	.780
10.00	.241	508.00	.0507	.0602	.401	14.30	.211	.434	16.4	.904	.892

ANALYSIS OF SwRI FLOW BENCH RESULTS
Test Number 8 Date: 19 MAR 92

VCR Head: Mod 3 - 230 deg Masking (Clayed IP)

Bore	96.52(mm)	Inner Valve Seat	41.58(mm)	Valve Opens	-30.00 deg	Compression Ratio	16.00:1
Stroke	95.25(mm)	Maximum Valve Lift	8.38(mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62(mm)	Number Of Valves	1	Engine Speed	900. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	900	3527	900	3527	900	3527
Swirl Ratio	.012	.034	.039	.039	-.004	-.004
Mean Flow Coefficient			.182	.182	.218	.218
Gulp Factor	.194	.669	.247	.968	.206	.806
Mean Pressure Loss (kPa)	2.92	33.27	2.05	31.45	2.96	45.46
Port Effectiveness (%)			21.30	21.30	23.95	23.95
Volumetric Efficiency (%)	1.009	.818				
Maximum Mach Number	.593	.872				

Max Flow Coeff = .338

Valve Lift (mm)	Valve Lift / Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0049	.0060	.039	-.85	-.129	.416	-10.4	-5.628	-5.554
2.00	.048	508.00	.0136	.0164	.109	-1.43	-.079	.568	-4.6	-1.239	-1.223
3.00	.072	508.00	.0212	.0256	.170	-2.50	-.088	.591	-5.0	-.889	-.877
4.00	.096	508.00	.0273	.0327	.218	-2.30	-.063	.567	-3.7	-.499	-.492
5.00	.120	508.00	.0321	.0384	.256	-1.72	-.040	.532	-2.5	-.270	-.266
6.00	.144	508.00	.0365	.0436	.290	-.56	-.011	.503	-.8	-.067	-.066
7.00	.168	508.00	.0401	.0477	.318	.56	.011	.472	.7	.057	.056
8.00	.192	508.00	.0427	.0507	.338	2.51	.044	.440	3.3	.224	.221
9.00	.216	508.00	.0431	.0512	.341	7.28	.127	.401	10.6	.638	.630
10.00	.241	508.00	.0448	.0531	.354	8.94	.150	.378	13.3	.725	.716

ANALYSIS OF SwRI FLOW BENCH RESULTS
Test Number 9 Date: 19 MAR 92

VCR Head: Mod 4 - Helical Port Attempt 1 (Clayed IP)

Bore	96.52(mm)	Inner Valve Seat	41.58(mm)	Valve Opens	-30.00 deg	Compression Ratio	16.00:1
Stroke	95.25(mm)	Maximum Valve Lift	8.38(mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62(mm)	Number Of Valves	1	Engine Speed	900. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	900	3527	900	3527	900	3527
Swirl Ratio	.513	.460	.426	.426	.510	.510
Mean Flow Coefficient			.173	.173	.206	.206
Gulp Factor	.201	.698	.259	1.016	.217	.852
Mean Pressure Loss (kPa)	3.27	35.55	2.25	34.61	3.30	50.77
Port Effectiveness (%)			19.35	19.35	21.45	21.45
Volumetric Efficiency (%)	.996	.787				
Maximum Mach Number	.571	.899				

Max Flow Coeff = .304

Valve Lift (mm)	Valve Lift / Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0062	.0078	.051	.08	.009	.528	.6	.311	.307
2.00	.048	508.00	.0145	.0180	.118	.39	.020	.614	1.1	.287	.283
3.00	.072	508.00	.0211	.0262	.171	1.05	.037	.594	2.1	.368	.363
4.00	.096	508.00	.0267	.0330	.216	1.44	.040	.563	2.4	.315	.311
5.00	.120	508.00	.0306	.0377	.247	2.61	.063	.516	4.1	.437	.431
6.00	.144	508.00	.0341	.0421	.276	3.00	.065	.479	4.5	.403	.398
7.00	.168	508.00	.0359	.0443	.290	3.00	.062	.433	4.7	.364	.359
8.00	.192	508.00	.0376	.0462	.303	3.97	.078	.397	6.6	.442	.436
9.00	.216	508.00	.0379	.0466	.306	5.82	.113	.359	10.6	.637	.628
10.00	.241	508.00	.0381	.0469	.307	6.51	.126	.328	12.9	.703	.694

ANALYSIS OF SwRI FLOW BENCH RESULTS
Test Number 10 Date: 19 MAR 92

VCR Head: Mod 5 - Helical Port Attemp 2 (Clayed IP).

SwRI Project 03-4764-280. Labeco Variable Compression Ratio Engine.

Bore	96.52(mm)	Inner Valve Seat	41.58(mm)	Valve Opens	-30.00 deg	Compression Ratio	16.00:1
Stroke	95.25(mm)	Maximum Valve Lift	8.38(mm)	Valve Closes	230.00 deg	Engine Speed with 11.2 m/sec Mean Piston Speed	3527 rpm
Connecting Rod	166.62(mm)	Number Of Valves	1	Engine Speed	900. rpm		

SwRI Method = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method = Flow Equals Rate of Piston Displacement

	SwRI		Ricardo		AVL	
RPM	900	3527	900	3527	900	3527
Swirl Ratio	.410	.357	.353	.353	.407	.407
Mean Flow Coefficient			.159	.159	.190	.190
Gulp Factor	.217	.747	.282	1.104	.236	.924
Mean Pressure Loss (kPa)	3.84	38.74	2.66	40.91	3.89	59.79
Port Effectiveness (%)			16.37	16.37	18.21	18.21
Volumetric Efficiency (%)	.998	.741				
Maximum Mach Number	.578	.949				

Max Flow Coeff = .274

Valve Lift (mm)	Valve Lift / Seat Diameter	Differential Pressure (mm water)	Volume Flow (m**3/s)	Mass Flow (kg/s)	Flow Coeff (Cf)	Torque (N.mm)	N-D Swirl (Nr)	Coeff of Performance (Cp)	Theta (deg)	Momentum Ratio (Vr)	AVL Swirl Number (nd/n)
1.00	.024	508.00	.0063	.0077	.051	-.26	-.031	.528	-2.0	-1.053	-1.039
2.00	.048	508.00	.0146	.0180	.118	.20	.010	.613	.5	.147	.145
3.00	.072	508.00	.0206	.0254	.167	.86	.031	.578	1.8	.316	.312
4.00	.096	508.00	.0253	.0311	.204	1.05	.031	.531	1.9	.259	.255
5.00	.120	508.00	.0288	.0353	.232	1.73	.045	.484	3.1	.329	.324
6.00	.144	508.00	.0317	.0388	.256	2.32	.054	.444	4.1	.363	.359
7.00	.168	508.00	.0333	.0408	.268	2.03	.045	.399	3.8	.288	.284
8.00	.192	508.00	.0337	.0412	.271	2.61	.057	.354	5.4	.363	.358
9.00	.216	508.00	.0345	.0421	.278	2.51	.054	.322	5.6	.333	.329
10.00	.241	508.00	.0350	.0427	.281	2.42	.051	.294	5.8	.312	.308

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                           ANALYSIS OF SwRI FLOW BENCH RESULTS
                          Test Number 11        Date: 23 MAR 92

VCR Head: Mod 6 - Helical attempt 3:sharp wall edges, more ramp.

   SwRI Project 03-4764-280.  Labeco Variable Compression Ratio Engine

Bore                 96.52(mm)     Inner Valve Seat      41.58(mm)     Valve Opens        -30.00 deg     Compression Ratio  16.00:1
Stroke               95.25(mm)     Maximum Valve Lift     8.38(mm)     Valve Closes       230.00 deg     Engine Speed with
Connecting Rod      166.62(mm)     Number Of Valves       1            Engine Speed        900.  rpm     11.2 m/sec Mean
                                                                                                         Piston Speed       3527 rpm

SwRI Method    = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method     = Flow Equals Rate of Piston Displacement

                                 SwRI          Ricardo          AVL
RPM                           900   3527     900   3527      900   3527
Swirl Ratio                 1.596  1.208   1.280  1.280    1.606  1.606
Mean Flow Coefficient                       .129   .129     .152   .152
Gulp Factor                  .266   .864    .348  1.363     .294  1.154
Mean Pressure Loss (kPa)     5.91  46.66    4.06  62.31     6.06  93.13
Port Effectiveness (%)                     10.75  10.75    11.72  11.72
Volumetric Efficiency (%)    .997   .618
Maximum Mach Number          .585  1.000

Max Flow Coeff =  .209

Valve    Valve Lift     Differential   Volume    Mass      Flow     Torque    N-D    Coeff of      Theta    Momentum    AVL Swirl
Lift    ------------      Pressure      Flow     Flow      Coeff             Swirl  Performance              Ratio      Number
(mm)    Seat Diameter   (mm water)   (m**3/s)  (kg/s)     (Cf)     (N.mm)    (Nr)      (Cp)        (deg)     (Vr)       (nd/n)
 1.00       .024          508.00       .0063    .0077      .051      .76     .090      .531          5.6     3.031       2.991
 2.00       .048          508.00       .0143    .0176      .116     1.34     .070      .603          3.8     1.031       1.017
 3.00       .072          508.00       .0192    .0237      .156     2.80     .108      .543          6.6     1.189       1.174
 4.00       .096          508.00       .0223    .0274      .180     4.07     .135      .475          9.5     1.288       1.271
 5.00       .120          508.00       .0247    .0302      .199     5.14     .154      .424         12.2     1.330       1.313
 6.00       .144          508.00       .0253    .0310      .204     5.34     .156      .365         14.4     1.312       1.295
 7.00       .168          508.00       .0257    .0314      .207     5.34     .154      .320         16.3     1.281       1.264
 8.00       .192          508.00       .0258    .0315      .208     5.43     .156      .285         18.5     1.289       1.272
 9.00       .216          508.00       .0261    .0319      .210     5.53     .157      .260         20.6     1.281       1.264
10.00       .241          508.00       .0261    .0319      .210     5.53     .157      .237         22.6     1.281       1.264
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                           ANALYSIS OF SwRI FLOW BENCH RESULTS
                          Test Number 12        Date: 23 MAR 92

Mod 7 - Helical attempt 4:filled in around valve stem, higher & steeper.

SwRI Project 03-4764-280.  Labeco Variable Compression Ratio Engine.

Bore                 96.52(mm)     Inner Valve Seat      41.58(mm)     Valve Opens        -30.00 deg     Compression Ratio  16.00:1
Stroke               95.25(mm)     Maximum Valve Lift     8.38(mm)     Valve Closes       230.00 deg     Engine Speed with
Connecting Rod      166.62(mm)     Number Of Valves       1            Engine Speed        900.  rpm     11.2 m/sec Mean
                                                                                                         Piston Speed       3527 rpm

SwRI Method    = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method     = Flow Equals Rate of Piston Displacement

                                 SwRI          Ricardo          AVL
RPM                           900   3527     900   3527      900   3527
Swirl Ratio                 1.687  1.154   1.264  1.264    1.693  1.693
Mean Flow Coefficient                       .123   .123     .141   .141
Gulp Factor                  .287   .889    .363  1.425     .318  1.246
Mean Pressure Loss (kPa)     6.85  49.38    4.43  68.06     7.07 108.60
Port Effectiveness (%)                      9.84   9.84    10.05  10.05
Volumetric Efficiency (%)    .974   .583
Maximum Mach Number          .551  1.000

Max Flow Coeff =  .192

Valve    Valve Lift     Differential   Volume    Mass      Flow     Torque    N-D    Coeff of      Theta    Momentum    AVL Swirl
Lift    ------------      Pressure      Flow     Flow      Coeff             Swirl  Performance              Ratio      Number
(mm)    Seat Diameter   (mm water)   (m**3/s)  (kg/s)     (Cf)     (N.mm)    (Nr)      (Cp)        (deg)     (Vr)       (nd/n)
 1.00       .024          508.00       .0063    .0077      .051      .08     .009      .528           .6      .311        .307
 2.00       .048          508.00       .0132    .0161      .107      .66     .037      .554          2.2      .600        .592
 3.00       .072          508.00       .0185    .0225      .149     2.03     .082      .518          5.2      .939        .926
 4.00       .096          508.00       .0213    .0259      .171     3.19     .112      .450          8.3     1.116       1.102
 5.00       .120          508.00       .0228    .0276      .183     3.97     .130      .388         11.2     1.218       1.202
 6.00       .144          508.00       .0238    .0289      .191     4.46     .140      .341         13.7     1.252       1.235
 7.00       .168          508.00       .0239    .0288      .191     5.14     .161      .299         18.2     1.443       1.424
 8.00       .192          508.00       .0239    .0288      .191     5.24     .164      .266         20.9     1.470       1.451
 9.00       .216          508.00       .0240    .0290      .193     5.34     .166      .242         23.4     1.477       1.457
10.00       .241          508.00       .0240    .0290      .193     5.34     .166      .222         25.7     1.477       1.457
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                          ANALYSIS OF SwRI FLOW BENCH RESULTS
                        Test Number 13        Date: 23 MAR 92

Mod 8 - Helical attempt 5:lowered ramp's roof.

SwRI Project 03-4764-280.  Labeco Variable Compression Ratio Engine.

Bore               96.52(mm)    Inner Valve Seat     41.58(mm)    Valve Opens        -30.00 deg    Compression Ratio  16.00:1
Stroke             95.25(mm)    Maximum Valve Lift    8.38(mm)    Valve Closes       230.00 deg    Engine Speed with
Connecting Rod    166.62(mm)    Number Of Valves      1           Engine Speed       900.   rpm    11.2 m/sec Mean
                                                                                                   Piston Speed       3527 rpm

SwRI Method     = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method  = Flow Dependent Upon Valve Lift
AVL Method      = Flow Equals Rate of Piston Displacement

                                  SwRI          Ricardo          AVL
RPM                            900   3527     900   3527     900   3527
Swirl Ratio                  1.431   .863    .833   .833   1.431  1.431
Mean Flow Coefficient                        .116   .116    .142   .142
Gulp Factor                   .289   .892    .387  1.516    .316  1.239
Mean Pressure Loss (kPa)      6.77  49.34    5.02  77.09    6.99 107.43
Port Effectiveness (%)                       8.69   8.69   10.15  10.15
Volumetric Efficiency (%) 1.015      .569
Maximum Mach Number           .619  1.000

Max Flow Coeff =  .195

Valve    Valve Lift    Differential  Volume   Mass     Flow    Torque   N-D   Coeff of     Theta  Momentum  AVL Swirl
Lift    ------------     Pressure     Flow    Flow    Coeff            Swirl Performance            Ratio    Number
(mm)    Seat Diameter  (mm water)  (m**3/s) (kg/s)    (Cf)    (N.mm)   (Nr)     (Cp)       (deg)    (Vr)     (nd/n)
 1.00        .024         508.00     .0049   .0060    .039      .66    .101     .413         8.2    4.403     4.345
 2.00        .048         508.00     .0132   .0161    .107     -.65   -.037     .554        -2.2    -.591     -.583
 3.00        .072         508.00     .0181   .0220    .145     -.56   -.023     .504        -1.5    -.270     -.266
 4.00        .096         508.00     .0215   .0261    .173      .18    .006     .449          .4     .060      .059
 5.00        .120         508.00     .0230   .0278    .184     2.61    .085     .387         7.3     .788      .777
 6.00        .144         508.00     .0237   .0286    .190     4.17    .131     .338        13.0    1.186     1.171
 7.00        .168         508.00     .0242   .0292    .194     4.75    .147     .300        16.5    1.297     1.280
 8.00        .192         508.00     .0242   .0292    .194     5.14    .159     .268        20.1    1.403     1.385
 9.00        .216         508.00     .0244   .0294    .195     5.73    .175     .247        24.3    1.542     1.521
10.00        .241         508.00     .0244   .0294    .195     6.12    .187     .230        28.2    1.647     1.625
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                          ANALYSIS OF SwRI FLOW BENCH RESULTS
                        Test Number 14        Date: 24 MAR 92

Mod 9 - Helical attempt 6

SwRI Project 03-4764-280.  Labeco Variable Compression Ratio Engine.

Bore               96.52(mm)    Inner Valve Seat     41.58(mm)    Valve Opens        -30.00 deg    Compression Ratio  16.00:1
Stroke             95.25(mm)    Maximum Valve Lift    8.38(mm)    Valve Closes       230.00 deg    Engine Speed with
Connecting Rod    166.62(mm)    Number Of Valves      1           Engine Speed       900.   rpm    11.2 m/sec Mean
                                                                                                   Piston Speed       3527 rpm

SwRI Method     = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method  = Flow Dependent Upon Valve Lift
AVL Method      = Flow Equals Rate of Piston Displacement

                                  SwRI          Ricardo          AVL
RPM                            900   3527     900   3527     900   3527
Swirl Ratio                  1.456   .984   1.013  1.013   1.464  1.464
Mean Flow Coefficient                        .121   .121    .145   .145
Gulp Factor                   .280   .881    .372  1.458    .309  1.212
Mean Pressure Loss (kPa)      6.49  48.25    4.64  71.32    6.69 102.71
Port Effectiveness (%)                       9.39   9.39   10.62  10.62
Volumetric Efficiency (%) 1.009      .587
Maximum Mach Number           .609  1.000

Max Flow Coeff =  .197

Valve    Valve Lift    Differential  Volume   Mass     Flow    Torque   N-D   Coeff of     Theta  Momentum  AVL Swirl
Lift    ------------     Pressure     Flow    Flow    Coeff            Swirl Performance            Ratio    Number
(mm)    Seat Diameter  (mm water)  (m**3/s) (kg/s)    (Cf)    (N.mm)   (Nr)     (Cp)       (deg)    (Vr)     (nd/n)
 1.00        .024         508.00     .0056   .0069    .045      .86    .113     .477         7.9    4.273     4.217
 2.00        .048         508.00     .0141   .0171    .114      .47    .025     .590         1.4     .373      .368
 3.00        .072         508.00     .0190   .0229    .152     1.44    .057     .529         3.6     .638      .630
 4.00        .096         508.00     .0222   .0266    .177     2.12    .072     .463         5.2     .693      .684
 5.00        .120         508.00     .0238   .0285    .190     3.49    .110     .400         9.2     .992      .979
 6.00        .144         508.00     .0246   .0295    .197     4.17    .127     .348        12.2    1.107     1.092
 7.00        .168         508.00     .0247   .0295    .197     4.75    .145     .304        16.0    1.262     1.246
 8.00        .192         508.00     .0247   .0295    .197     4.85    .148     .269        18.5    1.288     1.271
 9.00        .216         508.00     .0248   .0296    .198     5.34    .161     .247        22.3    1.399     1.380
10.00        .241         508.00     .0249   .0296    .198     5.53    .167     .227        25.3    1.450     1.431
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SwRI Flow Bench Data Output from FLOWDATA.EXE
ROTATIONAL TEST RESULTS
TEST NO. 15

Output File: vcr12.out                      Run Date:  3/25/1992
Mod 9 - Rotational Test

  l/D    kg/sec    Cf      Nr      Vt      Vr       Cp       Theta
----------------------------------------------------------------------
 .1996   .0293   .1939   .2187   .1269   .2428   .2740    27.59
 .1996   .0294   .1952   .1515   .0879   .2445   .2598    19.79
 .1996   .0292   .1939   .0985   .0572   .2428   .2495    13.25
 .1996   .0290   .1925   .0538   .0312   .2411   .2432     7.38
 .1996   .0290   .1925   .0478   .0277   .2411   .2427     6.56
 .1996   .0287   .1912   .0786   .0456   .2395   .2438    10.78
 .1996   .0287   .1912   .1304   .0757   .2395   .2511    17.53
 .1996   .0289   .1925   .1990   .1155   .2411   .2674    25.59
 .1996   .0289   .1925   .2051   .1190   .2411   .2689    26.27
 .1996   .0291   .1939   .3839   .2228   .2428   .3295    42.53
 .1996   .0290   .1939   .4860   .2820   .2428   .3722    49.27
 .1996   .0290   .1939   .5971   .3465   .2428   .4231    54.98
 .1996   .0290   .1939   .6722   .3901   .2428   .4595    58.10
 .1996   .0290   .1939   .7233   .4197   .2428   .4849    59.95
 .1996   .0288   .1925   .7404   .4297   .2411   .4927    60.70
 .1996   .0288   .1925   .7283   .4227   .2411   .4866    60.29
 .1996   .0286   .1912   .7121   .4133   .2395   .4776    59.91
 .1996   .0286   .1912   .7121   .4133   .2395   .4776    59.91
 .1996   .0288   .1925   .6557   .3805   .2411   .4505    57.64
 .1996   .0286   .1912   .6025   .3496   .2395   .4238    55.59
 .1996   .0288   .1925   .5317   .3086   .2411   .3916    51.99
 .1996   .0286   .1912   .4563   .2648   .2395   .3570    47.87
 .1996   .0286   .1912   .3862   .2241   .2395   .3280    43.10
 .1996   .0290   .1939   .3058   .1774   .2428   .3007    36.16
 .1996   .0290   .1939   .2187   .1269   .2428   .2740    27.59
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                                            ANALYSIS OF SwRI FLOW BENCH RESULTS
                                          Test Number 16       Date: 16 FEB 92


VCR Head: SwRI 03-4764-280. Standard Test using valve w/shroud.

SwRI Project 03-4764-280.  Labeco Variable Compression Ratio Engine.

Bore                96.52(mm)     Inner Valve Seat      41.58(mm)     Valve Opens      -30.00 deg     Compression Ratio  16.00:1
Stroke              95.25(mm)     Maximum Valve Lift     8.38(mm)     Valve Closes     230.00 deg     Engine Speed with
Connecting Rod     166.62(mm)     Number Of Valves      1             Engine Speed      900.  rpm     11.2 m/sec Mean
                                                                                                      Piston Speed      3527 rpm

SwRI Method     = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method      = Flow Equals Rate of Piston Displacement

                               SwRI            Ricardo              AVL
RPM                         900   3527       900   3527       900   3527
Swirl Ratio               3.090  2.608     2.383  2.383     3.065  3.065
Mean Flow Coefficient                       .159   .159      .188   .188
Gulp Factor                .216   .753      .282  1.106      .239   .936
Mean Pressure Loss (kPa)   3.94  39.37      2.67  41.01      3.99  61.35
Port Effectiveness (%)                     16.35  16.35     18.00  18.00
Volumetric Efficiency (%)  .993   .737
Maximum Mach Number        .570   .965

Max Flow Coeff =  .277

Valve    Valve Lift    Differential   Volume   Mass     Flow    Torque   N-D    Coeff of     Theta    Momentum   AVL Swirl
Lift     -------------   Pressure      Flow    Flow     Coeff            Swirl Performance              Ratio    Number
(mm)     Seat Diameter (mm water)    (m**3/s) (kg/s)    (Cf)     (N.mm)  (Nr)        (Cp)     (deg)      (Vr)    (nd/n)
 1.00        .024          508.00     .0086    .0101      .068     .37     .033      .709        1.5      .820      .809
 2.00        .048          508.00     .0170    .0199      .134    1.05     .047      .699        2.2      .599      .591
 3.00        .072          508.00     .0205    .0241      .162    4.27     .158      .569        9.2     1.667     1.645
 4.00        .096          508.00     .0244    .0286      .193    6.41     .199      .514       13.0     1.773     1.750
 5.00        .120          508.00     .0278    .0325      .219    8.94     .244      .476       17.3     1.915     1.889
 6.00        .144          508.00     .0306    .0358      .241   12.64     .313      .456       23.5     2.228     2.198
 7.00        .168          508.00     .0332    .0388      .261   15.66     .357      .440       28.1     2.344     2.313
 8.00        .192          508.00     .0346    .0404      .272   20.82     .456      .442       36.8     2.878     2.840
 9.00        .216          508.00     .0363    .0423      .285   23.55     .493      .436       41.0     2.966     2.927
10.00        .241          508.00     .0377    .0440      .296   27.15     .546      .442       45.8     3.159     3.118
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                                   ANALYSIS OF SwRI FLOW BENCH RESULTS
                                 Test Number 17       Date: 10 APR 92

03-4764-280. Standard Test using valve w/shroud @ #3 pos.

SwRI Project 03-4764-280.  Labeco Variable Compression Ratio Engine.

Bore              96.52(mm)     Inner Valve Seat     41.58(mm)     Valve Opens      -30.00 deg    Compression Ratio  16.00:1
Stroke            95.25(mm)     Maximum Valve Lift    8.38(mm)     Valve Closes     230.00 deg    Engine Speed with
Connecting Rod   166.62(mm)     Number Of Valves      1            Engine Speed      900.  rpm    11.2 m/sec Mean
                                                                                                  Piston Speed       3527 rpm

SwRI Method    = Simulating Gas Exchange Based on Mass and Energy Conservation
Ricardo Method = Flow Dependent Upon Valve Lift
AVL Method     = Flow Equals Rate of Piston Displacement

                                   SwRI           Ricardo            AVL
RPM                             900    3527     900    3527      900    3527
Swirl Ratio                   3.097   2.612   2.403   2.403    3.071   3.071
Mean Flow Coefficient                          .158    .158     .187    .187
Gulp Factor                    .217    .755    .285   1.116     .240    .939
Mean Pressure Loss (kPa)       3.96   39.45    2.72   41.74     4.02   61.69
Port Effectiveness (%)                        16.06   16.06    17.91   17.91
Volumetric Efficiency (%)      .997    .734
Maximum Mach Number            .576    .968

Max Flow Coeff =  .277

Valve    Valve Lift    Differential  Volume   Mass      Flow    Torque   N-D    Coeff of      Theta   Momentum   AVL Swirl
Lift     -----------     Pressure    Flow     Flow      Coeff            Swirl Performance             Ratio      Number
(mm)    Seat Diameter  (mm water)  (m**3/s)  (kg/s)     (Cf)    (N.mm)   (Nr)      (Cp)        (deg)    (Vr)      (nd/n)
 1.00       .024         508.00     .0080    .0097      .064     -.46    -.043     .668         -2.1    -1.142    -1.127
 2.00       .048         508.00     .0165    .0199      .132     -.26    -.012     .688          -.6     -.155     -.153
 3.00       .072         508.00     .0207    .0248      .165     3.39     .123     .577          7.1     1.274     1.257
 4.00       .096         508.00     .0245    .0293      .195     6.02     .184     .519         11.9     1.620     1.599
 5.00       .120         508.00     .0276    .0330      .220     9.72     .264     .482         18.5     2.059     2.032
 6.00       .144         508.00     .0301    .0360      .240    13.42     .334     .459         25.0     2.386     2.354
 7.00       .168         508.00     .0323    .0385      .257    16.83     .391     .444         30.8     2.617     2.583
 8.00       .192         508.00     .0342    .0408      .272    20.24     .444     .437         36.1     2.797     2.760
 9.00       .216         508.00     .0358    .0426      .284    23.26     .488     .433         40.8     2.947     2.909
10.00       .241         508.00     .0372    .0443      .295    26.47     .534     .436         45.2     3.097     3.057
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