# AIRCRAFT ENGINE HISTORICAL SOCIETY
## ANNUAL CONVENTION 2005

### THE DESIGN AND CONSTRUCTION OF WORKING SCALE REPLICAS OF INTERNAL COMBUSTION ENGINES: THE NOT SO OBVIOUS CHALLENGES.

1. SCALING FACTORS.
    a. LINEAR.
    b. AREA.
    c. VOLUME.
    d. THE IMPLICATIONS.

2. THE THINGS YOU CANNOT SCALE.
    a. AIR.
    b. WATER.
    c. GASOLINE
    d. OIL.
    e. THE PRACTICALITIES OF SCALE

3. WORKING METHODS: Variety is the spice of life.
    a. TO DRAW OR NOT TO DRAW.
    b. TO CAST OR NOT TO CAST, TO CNC OR MANUAL MACHINE.

4. NAPIER DELTIC GEOMETRY.
    a. WHAT HAPPENED TO TDC ?
    b. FIRING ORDER.

# 1. SCALING FACTORS

## 1a. LINEAR.

This is straight forward, if you are lucky enough to have dimensioned drawings or you have a cross section illustration or you know the bore and stroke of the prototype you are on your way with the layout of your replica.

These days it is easy to scan a drawing and print it 1:1, then measure a selection of known features in both X and Y to obtain a scaling factor, apply those factors, then print out a very accurate, to scale drawing.

If you reduce a dimension by a factor of 8 it simply becomes one eighth of the length.

## 1b. AREA.

If you reduce both the length and the width by a factor of eight you reduce the area by the square root of the scaling factor i.e. 1/64th.

## 1c. VOLUME.

If you reduce the length, width and height by a factor of eight you reduce the volume by the cube root of the scaling factor i.e. 1/512th

The prototype Deltic Engine has a capacity of 88 litres (5,369cu ins), My replica, to a 1/8th linear scale, is a mere 172cc! (10.49 cu ins).

## 1d. THE IMPLICATIONS.

Managing the thermodynamics of any engine is a fine balancing act. The critical parameters are generally the fuel and the engine construction materials. Heat lost to the cooling system, either air or water, is lost energy. The combustion chambers of large capacity cylinders have a relatively low surface area to volume ratio. The smaller the capacity of a cylinder, the larger this ratio becomes. It is via this surface area that the bulk of the heat transfer takes place.

If you consider the more common scaling factor of 4 to 1 the surface area of the combustion chamber in relation to the volume is four times greater. It is sometimes difficult to get little engines to run hot enough whilst at the same time they are very good at boiling water!

The fact that the dynamics do not scale in a linear fashion has another less obvious effect on the running of scaled engines. The energy “stored” in the flywheel (speed for speed) is reduced by the scaling factor. It is difficult to get these little engines to idle nice and slowly.

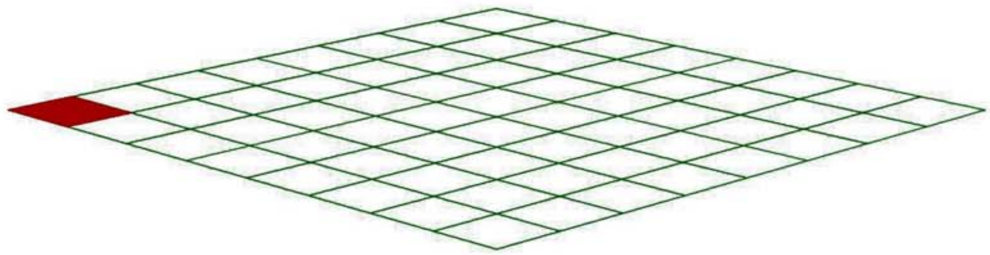
# COMPARATIVE GEOMETRY OF IC ENGINE CYLINDERS

## PROTOTYPE ENGINE CAPACITY: $500cm^3$ / $30.5\ ins^3$
## RATIO of BORE to STROKE: 1:1
## COMPRESSION RATIO: 8:1
## SCALING FACTOR: 1:4

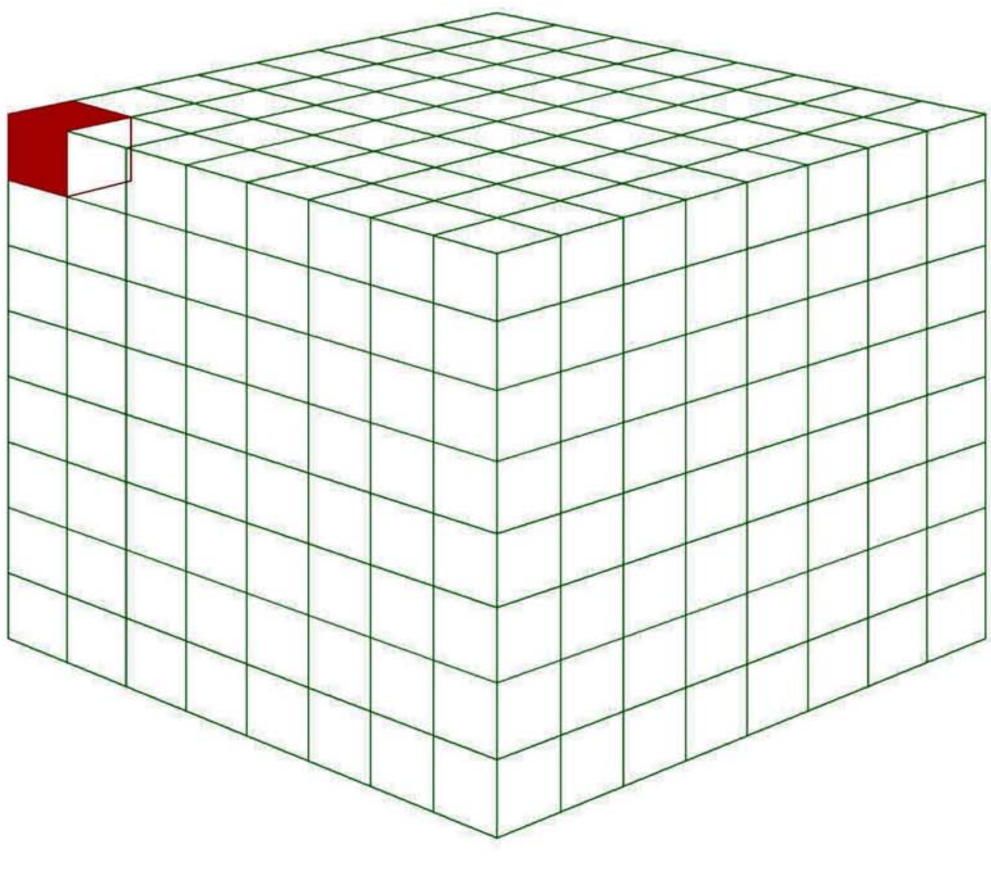
| FEATURE | FORMULA | PROTOTYPE | | REPLICA | | FRACTION |
|---|---|---|---|---|---|---|
| | | METRIC | IMPERIAL | METRIC | IMPERIAL | |
| A. BORE / STROKE | | 7.94 cm | 3.125 ins | 1.98 cm | 0.78 ins | 1/4 |
| B. CAPACITY | C x A | $500\ cm^3$ | $30.5\ ins^3$ | $7.81\ cm^3$ | $0.48\ ins^3$ | 1/64 |
| C. PISTON AREA | $\Pi$ x $(A/2)^2$ | $49.51\ cm^2$ | $7.67\ ins^2$ | $3.09\ cm^2$ | $0.48\ ins^2$ | 1/16 |
| D. CYLINDER CIRCUMFERENCE | $\Pi$ x A | 24.94 cm | 9.82 ins | 6.24 cm | 2.45 ins | 1/4 |
| E. COMBUSTION CHAMBER VOL | B / 8 | $62.5\ cm^3$ | $3.81\ ins^3$ | $0.97\ cm^3$ | $0.06\ ins^3$ | 1/64 |
| F. DEPTH OF COMBUSTION SPACE | E / C | 1.26 cm | 0.50 ins | 0.32 cm | 0.12 ins | 1/4 |
| G. SURFACE AREA OF E | (2 x C) + (D x F) | $130.44\ cm^2$ | $20.25\ ins^2$ | $8.18\ cm^2$ | $1.25\ ins^2$ | 1/16 |
| H. SURFACE AREA TO VOLUME | (1/16) / (1/4) | | | | | 4/1 |

**LINEAR:- 1/8**

**AREA:- 1/8 X 1/8 = 1/64**



**VOLUME:- 1/8 X 1/8 X 1/8 = 1/512**



# 2. THE THINGS YOU CANNOT SCALE.

## 2a. AIR.

A molecule of air is just that, they only come in one size. To achieve the same volume flow rates through reduced cross sectional passages you can squeeze them closer together/raise their energy, i.e. increase the pressure differential. This has it's own difficulties, There is an optimum tip speed for a centrifugal pump (in this case the blower), reduce the diameter by a factor of 4 and it needs to rotate four times faster.

Almost all replica engines make no allowance for valve/port timing. A set valve pattern of lead/lap is correct for one engine speed (ignoring throttle/load) of say 2krpm for an aero engine. The timing geometry required for an engine running at anything up to 50krpm (5cc 2 stroke tether race car engine) is much more extreme.

## 2b. WATER.

There are similar problems with water. In this case however you cannot squeeze the molecules closer together; you cannot compress a fluid. Increasing the operating pressure to maintain flow rates in reduced passage sizes increases turbulence.

## 2c. GASOLINE.

Same as water, carburettor jet sizes are a problem but fortunately both air and gas remain unchanged.

## 2d. OIL.

There is a particular problem with lubricating oil; it is more viscous than water or air. An oil film and its wedging action within a solid bearing arrangement cannot be scaled. Operating clearances cannot be scaled. Generally the same physical clearance is required regardless of the diameter of the bearing.

## 2e. THE PRACTICALITIES OF SCALE.

Although the process of reducing the size of all features of a design is straight forward one must not loose sight of the real world situation. It is not unusual to find a wall thickness of say 1/8th inch within a real life engine. This could easily scale down to a mere 15 to 30 thousandths. The same goes for gaps or the space between features. For larger parts, and those with deep recesses, I try not to use cutters of less than 3mm diameter. Ideally I would have liked to make the sabre engines to 1/5th scale but that would have meant operating with 2mm cutters to a depth of 12mm, possible but not practical.

# 3. WORKING METHODS: Variety is the spice of life!

There are many model engine builders scattered throughout the world, most make single cylinder 2 strokes, there are a relatively small number who get involved with highly complex replicas. I know of only two clubs catering for IC engine builders;(there must be more) The BAEM (Bay Area Engine Modellers, San Francisco) and the Engine Builders Group back home in the UK. We all tend to specialise in various ways and have different ways of working. The Americans tend to make lots of “hit and miss” singles, V8s, round aero engines and the occasional Offy. The Brits make more straight engines (unless you originate from Bristol) and more race engines.

We all seem to approach our activities in different ways:

## 3a.TO DRAW OR NOT TO DRAW: CAD.

Most seem to be traditionalists! They cannot operate without a full set of drawings, items and material lists, all correctly numbered and catalogued with a complete change history. This process is absolutely necessary if you have to have drawings from which to machine parts. This is to be admired but takes a great deal of time away from making chips and can delay the start of that process for many months.

At the other end of the spectrum you will find me! There are no drawings or sketches in my machine shop. I do not make inputs into my main machine by means of handles and dials. All I require is a bunch of numbers that represents a series of tool paths and operating sequences. I often don’t measure things!

Back in my drawing office (spare bedroom) there is the PC. There are no piece part drawings, I need tool paths. I am not able to work with cutter offsets as in many places the machined aperture is only a cutter diameter wide. I do have a basic General Arrangement (GA) for the Deltic but this only sufficient to position the 3 cranks and determine the six angular dividing lines between the 3 crank cases and the 3 cylinder assemblies. I draw the next part and as that almost always fits to the last I just copy it across and “attach” the next bit. I tend to have just a few but very large sheets of paper in my PC.

## 3b.TO CAST OR NOT TO CAST, TO CNC OR MANUAL MACHINE.

Some people are very good at small castings for multiple parts, I do not need that, while I am making the patterns etc I can make a prototype. I then put up as many billets, in turn, as required and press the button.

The engine builders I admire are the likes of my friends Brian Perkins and Norman Laurence who make each component individually. They have to be “ there” every second of the process with sets of elaborate tooling etc.

Then there are the likes of Eugene Corl over in Oregon, he has nearly finished a ¼ scale small block Chevy. Everything that should be cast in iron is! including the block, crank and camshafts and exhaust headers. The pistons are cast aluminium.

# 4. NAPIER DELTIC GEOMETRY.

## 4a. WHAT HAPPENED TO TDC ?

The traditional starting point when setting the valve or ignition timing on an internal combustion engine is Top Dead Centre. That is when the piston is at the top of the cylinder with the centre of the big end journal coincident with a line from the centres of the small end and the crankshaft main bearings.

With this engine the combustion chamber is formed between the crowns of the two pistons in a cylinder therefore, top dead centre has to be defined as the point when the two pistons in a cylinder are at their closest point. This is not as you may expect in the centre of the cylinder and neither of the cranks are at the TDC position.

This is because, as with any IC engine, the valve timing has to have lead, lag and overlap. The two pistons in a cylinder each perform a different function apart from compressing the charge and translating the expansion into force on the crankshaft. One piston is opening and closing the inlet ports and the other the exhaust. To provide the lead and lag the exhaust crank leads the inlet by 20o Therefore, when the two pistons are at their closest (TDC) the exhaust crank is 10o past TDC and the inlet 10o before.

This gives rise to unusual piston movement over the complete cycle. Remember, this is a uniflow two stroke engine but like all other IC engines it has to perform the four strokes or operations; induction, compression, expansion and exhaust. Compression and expansion take place during the period when both inlet and exhaust ports are closed and both pistons are moving relatively fast. The exhaust and induction “strokes” occur while the pistons are relatively stationary at the bottom of their strokes as the arc of movement of the crank throw matches the swing of the big end of the connecting rod about it’s small end.

Approaching the effective TDC position both piston are travelling in the same direction in the cylinder, the exhaust piston has reached the end of its inward stroke and is already moving outwards while the inlet piston has not yet completed it’s inward movement. If you study the “see through” demonstration model you will notice that at the point of ignition the inlet piston is relatively stationary as its big end passes over the top of it’s arc and it is the exhaust piston that is “doing the work.” Conversely, on the compression stroke, it is the inlet piston which moves the greater distance.

## 4b. FIRING ORDER.

Finally, when you look at the three cylinders in a single bank arranged in an equilateral triangle you would expect them to fire at regular intervals of 120°. However all three cylinders fire within 80°. That is 0°, 40° and 80° of engine rotation with a gap of 280° and in the opposite direction to the engine rotation, that is cylinders C B A.