Design for optimum cooling efficiency

The problem of optimum cooling of air cooled cylinders is an old one and has been extensively researched in the past. It was a subject of major military importance during the 30's and consequently there is a wealth of information to be mined from recently available NACA reports. Admitting my ignorance was easy, while addressing the problem only involved a bit of Eze reading. One might argue that there are more modern references to this type of information. My answer is that although technology has changed, our engines are pretty much the same, and so are the laws of physics. Best of all, this information is "free" because you as a taxpayer have already paid for it.

The information for this article was obtained from the NACA technical report server at http://techreports.larc.nasa.gov/cgi-bin/NTRS.

Why bother?

In an ideal world, all the energy generated from the combustion process would be turned into speed!!! Unfortunately a lot of energy heats the metal of the cylinder head and then more energy has to be used to cool the cylinder heads to stop them from melting. Even more heat energy goes out of the exhaust and is lost to heating up the atmosphere. Altogether, only a small proportion of the energy available gets transformed into forward motion. If we can reduce the energy cost of cooling then we reduce the overall drag of our Eze and we fly faster.
I thought that a good beginning would be to review how different engine characteristics and operating conditions effect how heat is transferred to the cylinder head of an air cooled engine.

Part 1: Where we find out why some engines run hotter than others.

I am just going to list the main conclusions found at the end of each report, and add some of my own comments *in italics* which I hope represent reasonable insights. Please do not hesitate to correct me if I've made any bad assumptions. There are bound to be a few.

Starting with NACA report 787, MIT, studied an engine with fixed compression ratio and valve timing, operating with a fixed mixture ratio, but with ignition timing adjusted to give maximum pressure at the same crank angle position. The timing was adjusted to give maximum cylinder pressure between 12 and 15 degrees after TDC.

The combustion gas temperature at any given point was found to be a function of air/fuel ratio and compression ratio.
The mean heat transfer was found to be a function of engine air consumption only, no matter what changes the volumetric efficiency, inlet air density or mean piston speed might undergo.
Heat transfer to the cylinder head was found to vary with 0.5 the power of air consumption, for both high (3600 rpm) and low (1800 rpm) speed tests.
For an Eze engine with a fixed pitch propeller, the heat generated by the engine is very close to being directly proportional to the r.p.m.

Another interesting finding was that the coating of the combustion chamber by combustion products had a significant effect in reducing heat transfer.
Heat transfer decreased by 20 percent in the first 15 hours of operation and leveled off after 40 hours. The coating was measured at .008 inch after 90 hours.
Now you know at least one reason why new engines run hotter!! On an engine which is consistently run with a rich mixture you can expect this coating to be much thicker and for the cylinder to run relatively cooler.

Other reports, found that maximum CHT occurred with a mixture ratio of 1:13.5 which is 7% richer than the chemically correct mixture of 1:14.7, which gives maximum gas temperature (EGT).

Increasing the compression ratio while keeping the power the same did increase the CHT slightly but lowered the EGT in greater proportion. Hence the total effect would be a lowered total heat transfer for the same power.
Higher compression ratio makes for a more efficient engine. This does have a beneficial relevance to updraft cooling where the exhaust pipes are cooled before the cylinders ☺ For an updraft installation, a high compression engine runs cooler than a low compression engine at the same power settings.

Keeping all other variables the same and increasing the mean piston speed caused an increase in heat transfer in proportion to 0.5 the power of the mean piston speed.
This means that longer stroke engines will be harder to cool for the same power output (O-360 versus O-320).

For a fixed engine geometry, the amount of heat energy transferred to the cylinders is proportionally less when the engine is run at higher power settings.

This means it is more efficient from a cooling standpoint to run a small engine harder than to run a big engine at low power settings. (Klaus smiling again)

If all other conditions remained the same, ignition advance from 25 to 42 degrees caused an increase in heat transfer of 11.4 % in the test engine which resulted in higher CHT's. *Without an ignition advance system you can expect your engine to run cooler than mine. Conversely, if you have Electronic Ignition, you can benefit by turning the ignition advance OFF if the CHT's are getting too hot in the climb.*

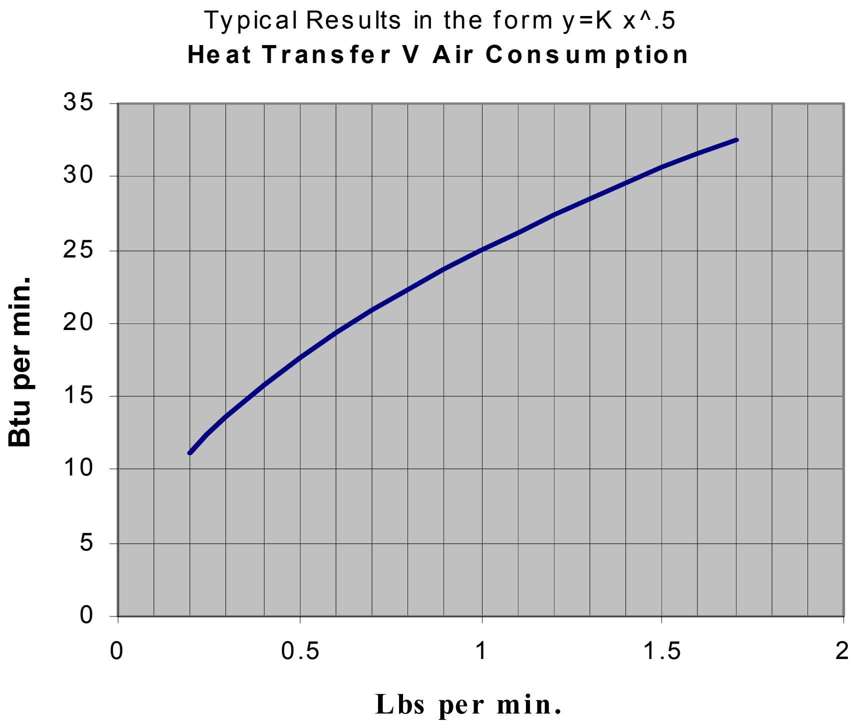
For geometrically similar engines, heat transfer decreases as engine size increases.
One assumes therefore that cooling big engines will require proportionally less cooling air, than one would expect from the size increase. This is expected given that the combustion chamber surface area increases to the power of 2, whereas its volume (and mass of air consumed) increases to the power of 3. Proportionally more heat exits from the exhaust on bigger engines.
(The opposite effect is true for large pilots, who overheat more easily than small ones because they have a proportionally larger internal volume relative to their skin surface area. So, loose weight, stay cool, fly faster!)

Overall Conclusion:

The overall conclusion seems to be that, for cooling efficiency, one should use a small, high compression engine and run it fast and lean with ignition advance so maximum cylinder pressure occurs at between 12 and 15 degrees after TDC.
(Just what Gary Hunter has been saying all along).
You only need to get rid of heat that stays behind. Insulating coatings in the combustion chamber will stop heat transfer to the engine and allow more heat to go out of the exhaust port.

I remember reading somewhere else that a ceramic coating of the combustion chamber would have a dramatic effect on lowering heat transfer to the cylinder head, and greatly improve efficiency of the engine cooling system.
Also, leaning way past EGT peak suddenly looks very attractive because CHT and EGT would both go much lower.

The graph below has a curve typical of how most engine parameters effect heat transfer to the cylinder head.



Part 2: How to cool air-cooled cylinders efficiently.

There are many NACA reports that look at optimum fin spacing, fin depth and fin thickness. Optimum baffling is the holy grail of air cooling, because we not only want to cool the cylinder heads but we want to do it with minimum energy cost to the aircraft.

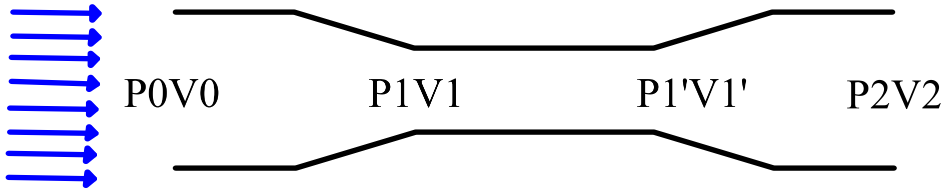
Several NACA Reports deal with this problem. Here is my short list of required reading.

Report 488	Heat transfer from finned metal cylinders in an air stream.
Report 555	Air flow around finned cylinders.
Report 620	Energy loss, velocity distribution, and temperature distribution for a baffled cylinder model.
Report 649	The effect of air-passage length on the optimum fin spacing for maximum cooling.
Report 655	Principles involved in the cooling of a finned and baffled cylinder.

Fin Tubes:

Cooling an air-cooled aircraft cylinder is not very much removed from cooling a hot pipe. Imagine you are heating the outside of an aluminum pipe from one side with a blow torch and you are trying to keep the pipe from melting by blowing cold air through the pipe. Curve the pipe into a semi-circle and put lots more next to it and you have a typical aircraft cylinder with baffle. Baffles are used to turn adjacent fins into pipes. The fin tubes so formed have a length that is controlled by the shape of the baffle and by the cylinder head casting.

If the pressure difference across the tube is fixed, how wide should the tube be, and how long should it be for maximum heat energy removal.
It turns out that the objective is to move as much mass of air through the pipe, for any given pressure drop across the two ends of the pipe, and that means getting maximum velocity of air to flow through the tube.



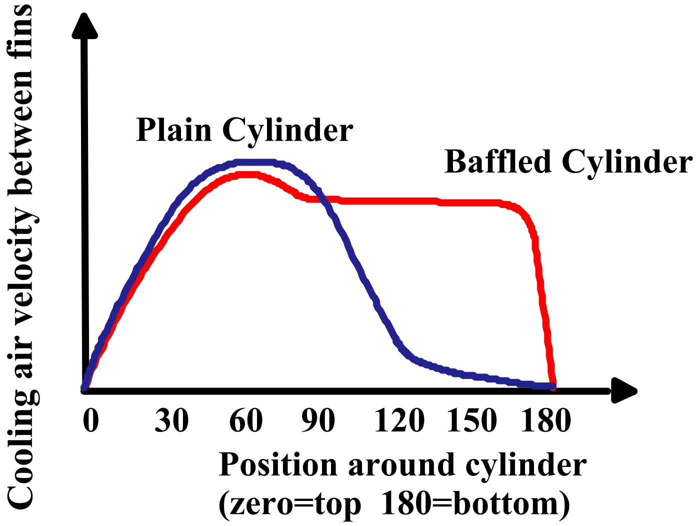
A simple representation of an idealized fin tube is shown above.
The air enters at P0V0 and accelerates at the P1V1 region, slowing due to friction to emerge from the fin tube at P1’V’1. If the fin tube ends here, we will loose a great deal of energy.
The expansion which follows to P2V2 is very important and allows the recovery of kinetic energy that would otherwise be lost. Between P0 and P2 there is a pressure difference we would like to use to overcome friction losses in the tube. In this way all the pressure difference is used to maximize the velocity of air in the tube and so maximize the cooling effect.

In the best baffle arrangement discussed below, only 36% of the pressure drop occurred across the fin tubes, while 50% was lost at the entrance to the exit duct (P1’V1’), and a further 14% at the exit from the exit duct.
Keeping the flow laminar to minimize friction losses, and recovering some of the energy at the exit of the fin tube can make a huge difference to the cooling drag of our installation.

Optimum baffles for an air cooled cylinder

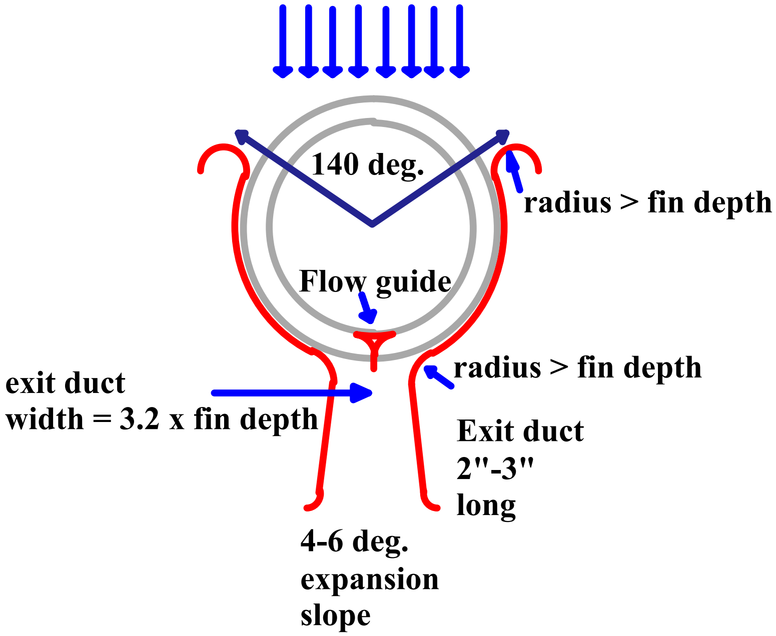
With increasing sophistication, the NACA reports conclude that the baffle exit width and exit radius, the duct length and duct exit width are most critical, and when optimized can lead to 20 % improvement in cooling efficiency.

In one report the velocity of the cooling air between cylinder fins was measured, with, and without a baffle. The results are shown below. The front/top of the cylinder is referenced as zero degrees and 180 degrees is at the back/bottom of the cylinder, where the air exits



What this velocity distribution shows is that the first 70 degrees around the cylinder are better off without a baffle, while the last 90 degrees will benefit most.

The diagram below shows the idealized cooling baffle arrangement for an air-cooled cylinder.



The conclusions from the above reports can be summarized as follows;

The front/top of the cylinder is adequately cooled and needs no baffling for an arc of 140 degrees.
The baffle entry and exit bend radius should all be greater than 1.5 x the fin depth.
There should be a flow guide where opposing airflows meet at the 180 degree position.
Baffle exit duct entrance width should be 2 X 1.6 X fin depth.
Baffle exit length should be between 2 and 3.5 inches long for Eze size cylinders.
(The longer length is impractical in our engines. In fact any length you can get away with is better than none at all.)
The baffle exit duct should expand gradually, the expansion angle should be about 4 to 6 degrees.

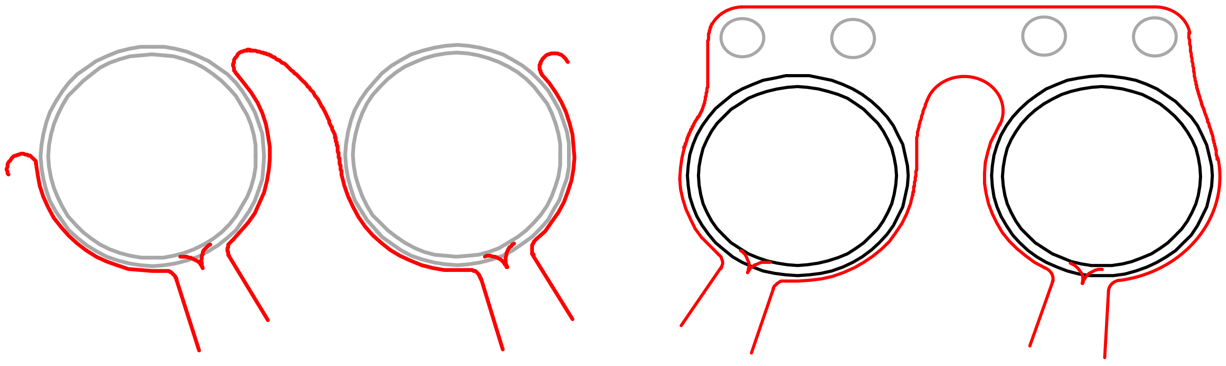
The problem with horizontally opposed Engines

All the above research by NACA was conducted for radial engines, which had much simpler airflow through their cowling.
Radial cylinder heads are a good distance apart from each other and there is lots of space for cooling fins.
The principles can still be applied to horizontally opposed engines although not with the same efficiency.
The cooling airflow in a typical Eze has to turn through at least two 90-degree bends, and in an updraft Eze has to flow past all manner of obstructions before entering the cylinder baffles. To make matters worse, the cylinders are placed so very close together, to minimize the bending loads on the crankshaft, that there is virtually no room for cooling fins in the intervening space.
A close look at some typical cylinder heads can be very educational. I borrowed one each of an O-200-A, O-235-L2C, and O-320 cylinders from my local engine builder, Pine Mountain Aviation.

Baffles at the base of the cylinder (fin pack)

All three cylinder types (200/235/320) have similar cylinder base fin arrangements. It is relatively easy to provide the ideal baffle solution for each of them.

On my O-235-J2A, the fin depth on the fin pack at the base of the cylinder is constant at 3/8. The exit opening for each airflow path is fin depth x 1.6 . We double this because we have a clockwise and anti-clockwise flow around the cylinder, so the exit opening should be 6/8 x 1.6 or approximately 1 3/16". The exit opening lip should have a curve of radius at least equal to 1.5 x the fin depth. If possible, there should be a divider at the exit duct entry to deflect the air as it arrives from opposite directions. If we can add a short 2" exit duct with a 6 degree expansion slope we will have the best possible baffle.
I have not made this baffle shape yet. I imagine it would best be implemented using aluminum, perhaps with one layer of BID/RTV so it can be glued to the cylinders.



The cylinder base baffles can be oriented to suit the air flowing into the cowling as on the left. The orientation of each baffle can be different as in the plenum version on the right.

Oil temperatures can be brought under control with good cylinder base baffles. This is the region where oil is used to splash-cool the underside of the piston. The oil gets very hot. Why not cool the oil here as much as possible, instead of taking it for a tour through the engine before it finally gets to the oil cooler?.

NOTE: Please be very careful when working near the push rod tubes. I recently removed No.3 cylinder to fix a slightly leaky exhaust valve, and found that a small dent in the intake push rod tube had been touching the push rod and had nearly sawed thought it!! Even the slightest dent is cause to replace the damaged tube. I checked all the rods by removing each one and doing a visual inspection. Only took 45 minutes and worth the effort for the peace of mind.!

Baffles for the O-200 and O-235 Cylinder Head

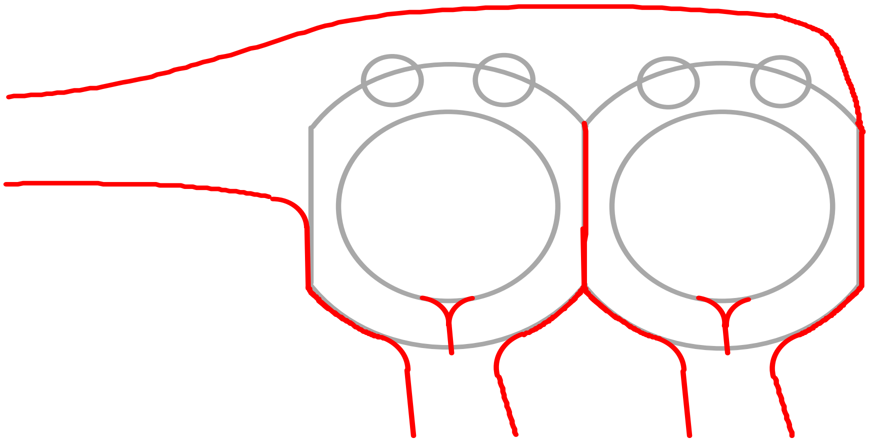
This is where the rubber meets the road in terms of CHT control.
As might be expected, the Continental O-200-A with the smallest capacity, has proportionally the larger fins. (The ratio of fin area to cylinder volume favors the larger cylinders). There is no problem with using individual cylinder baffles on the cylinder heads and cylinder base fin pack. This engine was made for efficient plenum and baffle cooling. In fact there is a study on the cooling of an A-75 in report 816. The engine was tested for a plenum based, downdraft pusher configuration. It's all been done before folks!!

The Lycoming O-235-L2C Cylinder head is similar to the O-200. It has less fin depth at the sides, and some attempt has been made to increase cooling on the exhaust valve side of the cylinder. The fin depth next to the exhaust valve is slightly more than on the intake valve side. There is enough fin depth to justify using Bid/RTV baffle material between the cylinders so that the flow of cooling air is divided into two sets of fin tubes. This will distribute more cooling air to the exhaust valve side and will also keep hotter air from the exhaust side from heating up the intake side and consequently raising the temperature of the incoming fuel air charge.

The lower side of the cylinder is the most difficult to (downdraft) cool so I have put the electronic ignition spark plug on the upper side of the cylinder. This plug runs hotter, because it runs with ignition advance, and it ignites the charge first. The magneto plug is just along for the ride.

The cylinder head fin depth is different for each fin and also different for the same fin at different locations around the head. As an example, one particular fin depth is at a minimum of .75 inch at 270 and at 090 degrees and 1.0 inch at the 170 and 200 degrees (lowest point where the air exits). The average is .82, so multiplying by 1.6 gives 1.4 inches per side or 2.8 inch exit opening for that particular pair of fin tubes.

The entry opening at the top (cold side) is not as critical. Research on the radials showed that an opening of 140 degrees was best when the airflow was normal to the top of the cylinder (70 degrees either side of the top). Given that the airflow on horizontally opposed engines is coming from one side, I decided to have an opening from 270 degrees towards the plenum intake (on the left) and 050 degrees towards the back of the plenum giving 140 degrees opening total.
The flow guide already exists in the form of the lower spark plug and the lower thermocouple boss. The fins at the 180 degree position curve towards the spark plug and the thermocouple boss.
The position of the intake manifold and of the exhaust pipes will make the implementation of an exit ducts very difficult.
The exit ducts in the drawing below, are a fanciful expression of the desire to include them. 14% pressure recovery can be lost here! A large radius at the exit from the baffle would be a good alternative. An idealized baffle is shown below.

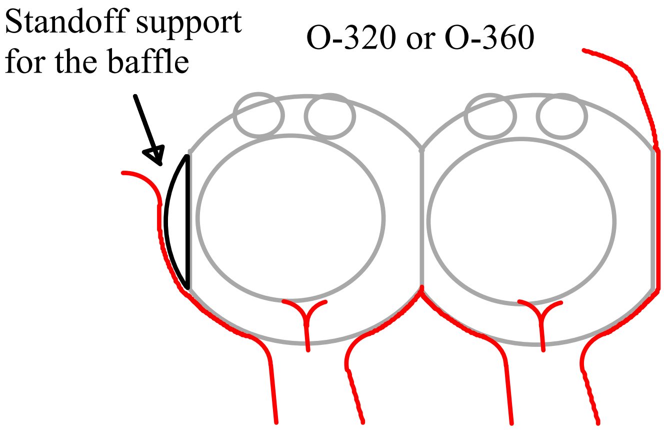


Cylinder head baffles for the O-360.

The Lycoming O-320 cylinder head has a fin depth of only 1/8 th inch on the side nearest the intake valve and just above the base fin pack. The cylinder head fins have been displaced sideways relative to the bore, so that most of the fin area is on the exhaust valve side of the cylinder head. You can see this clearly if you look at the fins from the crankcase end of the cylinder.

This engine has the same cylinder head as the O-360, which obtains its extra capacity by having ½ inch longer stroke. The bore is also slightly different.
Very likely that the O-360 will run hotter oil temperatures and CHT's than a O-320 when they are both at maximum power. The O-360 will be cooler than the O-320 when they are both producing the same power.

Placing Bid/RTV baffle material between the fins of the cylinder heads would do more harm than good. Any inter- cylinder baffle material would block the flow of air past the intake side of the cylinder.
For the same reason, any baffle on the front of No. 3 cylinder should be held away from the cylinder side with a standoff , to allow a gap for cooling air. The same applies for the intake valve side of No. 2 cylinder. An idealized baffle for an O-360 is shown below.



Casting roughness and Engine paint thickness

One common feature of all three cylinder types, was the distinct ridge left over from casting. This is at the 90 and 270 degree positions on each cylinder head fin. The casting ridge is at just the right place to trip the airflow from laminar (if it ever was) to turbulent and so increase cooling drag considerably.
I am less than confident about removing the ridge with a file, but my engine builder tells me it would do no harm to smooth the ridge off and perhaps smooth the rough sandy texture of the fins. (We want to maximize velocity of air through the fin tubes with the least pressure drop across them in order to cool the engine efficiently).
Do this at your own risk. Filing fins is not a practice I would recommend to anyone unless they have lots of metal working experience and lots of engine know-how.

If you choose to sand the fins smooth, you will need to repaint them. One more finding from the NACA reports; to further aid cooling, you should paint the engine with a VERY thin black enamel. The paint should not be thicker than .002 " This will improve cooling by three (3) percent over bare metal. If the paint is thicker than .005" you get no benefit and in fact thicker paint will insulate the cylinders.
Use black RTV for the wraps and paint everything under the cowling with a thin coat of black high temperature grill paint.

Please note that the above article was researched for my own education and written to foster discussion. In no way should it be taken as a mandate to change your engine cooling system. If you decide to experiment with your cooling system then please do so on the understanding that it is done entirely at your own risk.

All comments are very welcomed.
Have fun, fly safe, and stay cool!

Andreas Christou /June 2001