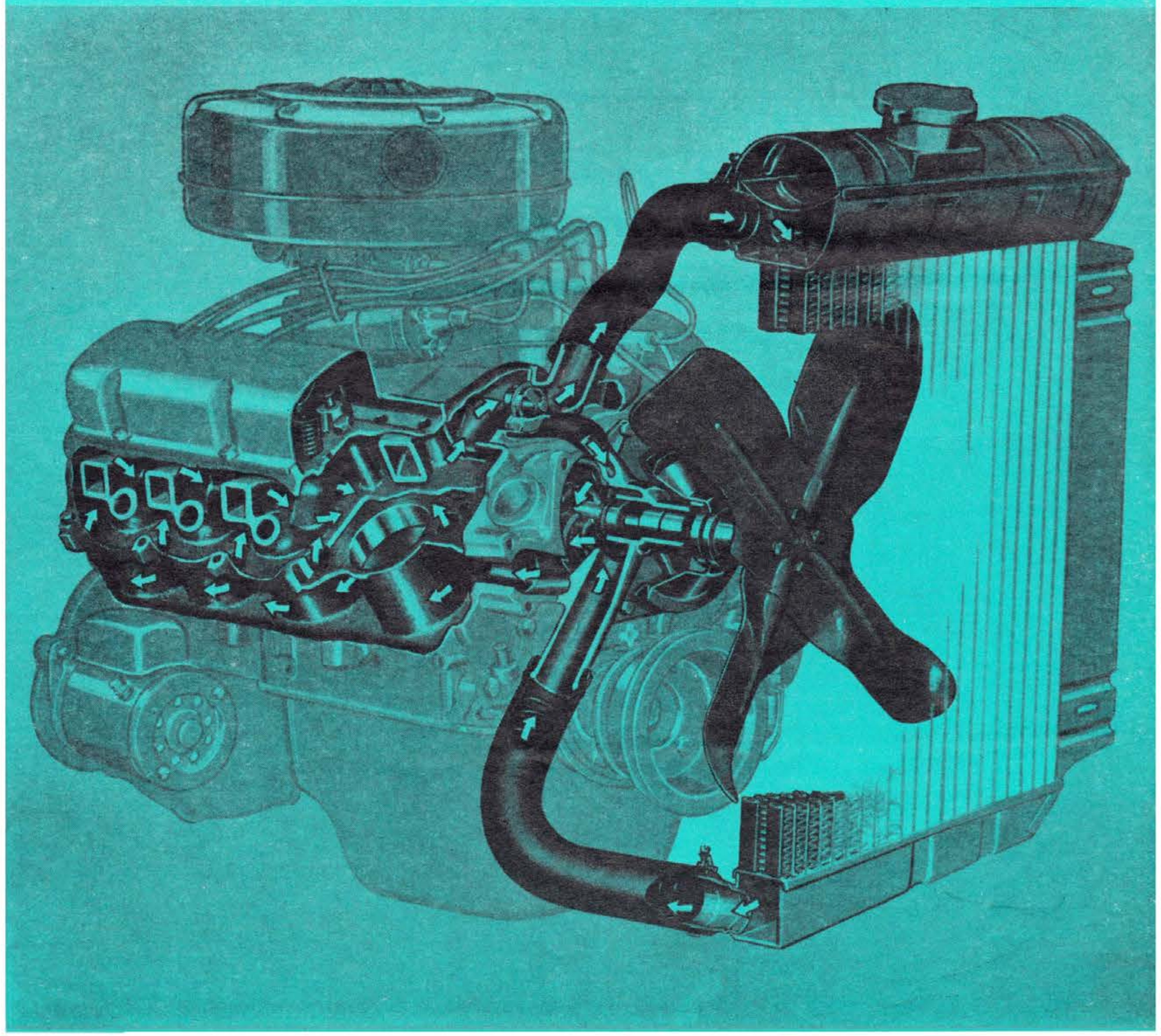
DESIGNING THE MODERN ENGINE PART VII

The Cooling System

BY ROGER HUNTINGTON

MODERN ENGINE'S COOLING SYSTEM is typified by this Ford Fairlane layout. Water flow from belt-driven pump goes into front of block, around cylinders, then passes up to heads through passages in rear of block. Outlet is in front part of the intake manifold.



THE POWERPLANT in your car is essentially a heat engine. The heat energy in the fuel is converted into pressure on the piston, through normal combustion, and this converts into torque on the drive shaft through the crank train.

Unfortunately, no heat engine is 100% efficient. Much of the heat energy in the fuel is bound to be lost in the conversion to useful power. In the internal combustion piston engine the losses go mainly to the exhaust gases, piston and bearing friction, and to direct heat loss through the cylinder walls and combustion chamber surfaces via conduction, convection and radiation. This latter heat loss is the main concern here. There must be some means to absorb this direct heat loss, and then get rid of it to the atmosphere, or there will be trouble. The conventional method is to put water jackets around the cylinders to absorb the heat, then dissipate this heat in an external radiator. That's the normal cooling system, but it's a little more complicated than this.

The heat transferred from one medium to another—like from the gases in a cylinder to the adjacent cylinder walls—depends heavily on the temperature difference between the two mediums. The closer the two temperatures, the less heat is transferred. Since the mean gas temperature in a cylinder will run about 1200° F. in the combustion chamber and around 600° in the cylinder, direct heat losses could theoretically be reduced to zero by letting the cylinder surfaces run at these same temperatures. But of course this isn't practical. The lubricating oil would be burned off the cylinder walls, the valve seats would burn and wear fast, the hot combustion chamber surfaces would pre-ignite the fuel mixture, volumetric efficiency would be reduced through the hot ports and valve gear lubrication would break down. The cylinder surface temperatures must be kept down to the area of 250 to 500° F. to get reliable, long-life operation.

When this is done there is enough temperature difference between the gases and cylinder surfaces to lose between one-fourth and one-third of the total heat energy available in the fuel. In other words, just about the same amount of heat is dissipated to the coolant as goes into useful work at the flywheel. Tests show that roughly 50% of this heat is lost through the combustion chamber surfaces; about 30% goes through the cylinder walls (including the effect of piston friction)—and the other 20% is transferred from the hot exhaust gases to the exhaust port surfaces. Added up, it's a real ball of fire!

Engine "heat rejection" to the coolant is conveniently expressed in BTUs; i.e., the amount of heat necessary to raise the temperature of one pound of water 1° F. The BTUs per minute rejected to the cooling water will be very nearly proportional to the fuel consumption rate in gallons per minute (or hour). This is to be expected, of course, since the loss is roughly a fixed percentage of the heat in the fuel burned. For instance, a modern short-stroke ohv V-8 will reject roughly 380 BTU/min. for every gallon per hour of fuel consumed. With an average fuel consumption of, say, 0.50 lb./bhp-hour, this would mean that an engine developing 200 bhp would reject about 6300 BTU/min. to the cooling water.

This heat rejection rate varies with a number of engine design and operating factors. For example, a long stroke increases piston friction, so more friction heat gets through the cylinder wall into the cooling water. As has been seen, heat rejection can be reduced by raising the temperature of the coolant (and thus reducing the temperature difference between gas and wall). One series of tests showed the rejection rate reduced 17% by raising coolant temperature from 180 to 270° F. (The old Allison aircraft engines ran glycol coolant at 250°.) A higher compression ratio reduces heat rejection by expanding the combustion gases farther, to a lower temperature before exhausting. A lean fuel-air mixture ratio will raise heat rejection by slowing down combustion and exposing the walls for a longer period to hot gases. (But then further leaning will reduce the rejection.)

One of the more important design parameters that affects heat rejection is the ratio of cylinder volume to surface area. Heat transfer is a function of the surface area through which the heat is transferred. If a cylinder has less surface area in relation to volume, it will reject less heat for a given temperature difference. More heat is retained in the fuel-air mixture to do work. The engine will be more efficient, using less gas. This is one of the big arguments in favor of the hemispherical combustion chamber. A sphere has the least amount of surface area in relation to volume of any geometric shape. Thus, a hemispherical chamber with minimum surface area would be expected to show less rejection than a more conventional irregular wedge-shaped chamber. Tests have shown this to be true. Chrysler found very low rejection rates when it developed the Firepower engine in the early '50s.

This is also one of the big secrets of the short-stroke, over-square engine. Cylinder volume increases as the first power of the stroke, and as the square of the bore—whereas surface area is proportional to the first power of both dimensions. Thus there is less surface area in relation to volume when using a larger bore and a shorter stroke. Test reports on the effect of stroke-bore ratio on heat rejection are not readily available, but it would seem there is a substantial effect here.

Our modern large-bore, short-stroke ohv V-8 engines reject between 10 and 15% less heat to the cooling water than the old long-stroke L-head engines, largely as the result of reduced piston friction and less cylinder surface area in relation to volume. Higher compression ratios also have helped. And the BTUs saved mean that much more useful work out of every gallon of fuel—literally free horsepower via smart, modern design.

Few enthusiasts realize that the rate of flow of the cooling water through the engine jacket system is a very important factor in cooling efficiency. The water pump must be carefully designed for an optimum pumping rate. For one thing, the heat transfer co-

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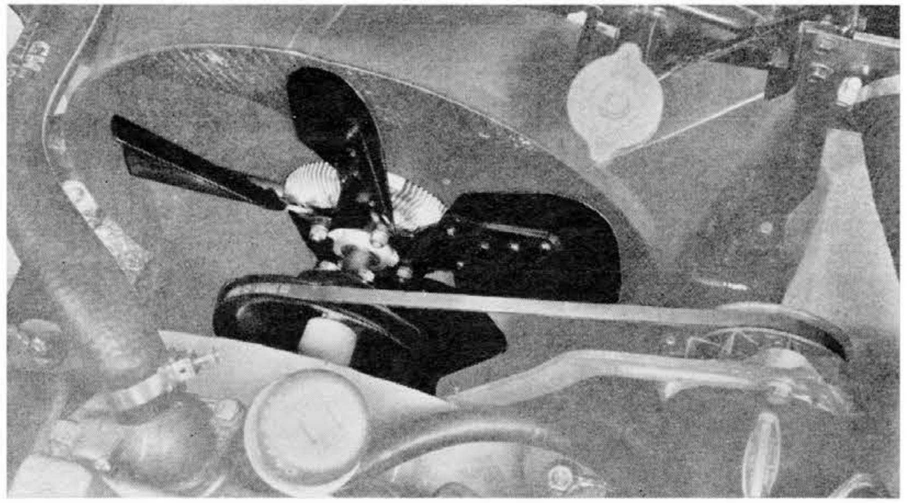
FANS THAT de-clutch at high engine rpm and low temperatures save a lot of horsepower, as much as 10-12 at 5000 rpm. This is the temperature-sensitive unit for a Corvette.



The Cooling System

efficient rises rapidly as the velocity of the water flowing through the jackets is increased. Another reason for having a vigorous flow rate through the system is that this is the only way to assure a narrow temperature drop as the water filters down through the radiator core. Too great a temperature drop through the core is undesirable because the transfer rate depends on the temperature difference—in this case between the water and the outside air flowing through the core. If the water temperature dropped too much the difference at the bottom of the core would be much less—and cooling efficiency would be reduced. More core area would be necessary to do the same cooling job.

A typical example of a cooling system flow balance would be a 350-cu. in. American passenger car engine with a water pump that flows roughly 45 gal./min. when the car is cruising at 60 mph at a crankshaft speed of 2400 rpm. This engine would be developing some 35 bhp under these conditions. The heat rejection to the cooling water would be around 1500 BTU/min. (assuming 15 mpg fuel economy, and thus a fuel flow rate of 4 gal./hour). Knowing that one BTU is the amount of heat necessary to raise the temperature of one pound of water 1° F., and the cooling system is flowing 45 x 8.33 = 375 lb. of water per minute, then the temperature rise of the water going through the jackets would be 1500/375 = 4° F. This is a typical radiator core temperature drop under cruising conditions for an American passenger car. The water will typically come into the top tank at 180° F., and exit from the bottom at 170°. The mean coolant temperature is thus 178° F. and the effective temperature differential will be anywhere from 80 to 100° on a warm day.

A radiator is nothing more than a device to transfer heat from a liquid to the atmosphere through a large area of high-conductivity metal, generally copper. The fin-and-tube radiator is the most common type used today. The upper and lower tanks are connected by dozens of small-area vertical tubes that carry the coolant. These tubes then pass through dozens of thin sheets of metal that run across the radiator. (The metal sheets are punched with slots for the tubes to pass through.) Or the sheets can be crimped and run parallel with the tubes. The whole assembly is soldered into more or less one piece to give optimum heat conduction. It will be obvious that this design gives a tremendous surface area of metal that is exposed to the coolant on one side and the air on the other (though in the case of the fin sheets the coolant heat filters through the metal and is absorbed by the air flowing over the outside of the sheets).

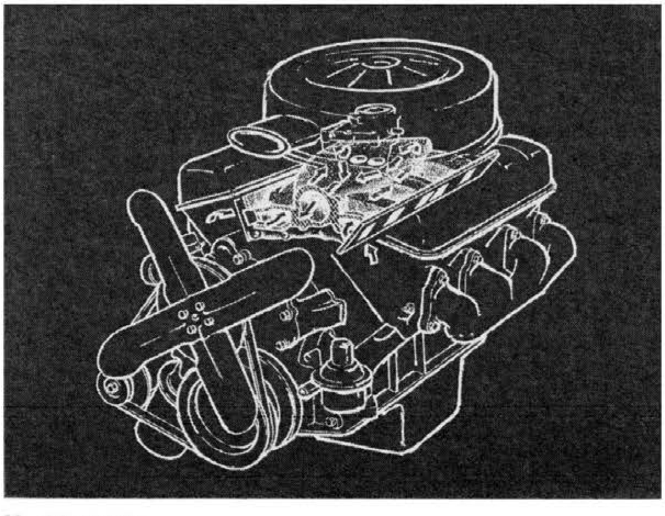
The cooling capacity of a given radiator core depends on a number of factors—the frontal area of the core, the thickness, the number of tubes per inch, number of fins per inch, flow area through the tubes, the material of the tubes and fins (copper is best, but aluminum has been used to save weight) and whether the tubes are staggered. The main idea is to get maximum heat dissipation area per cubic inch of core volume, without causing excessive restriction to the air or coolant flow. Some sophisticated core designs (not the fin-and-tube) may have 18 or 20 sq. in. of surface per cubic inch of core volume! When this kind of dissipation area is combined with the terrific conductivity of copper at 0.006 to 0.010 in. thickness, a lot of heat can be dispersed with amazingly little core.

Detroit engineers now know enough about core performance to easily design cooling systems on paper with confidence they'll work in the car. The toughest problem is to set some minimum cooling standard that will allow for every condition likely to be met in the field. In other words, modern cars have built into them a tremendous reserve cooling capacity that is rarely used by 99% of the drivers. For instance, Pontiac used to design its systems so they would keep the coolant temperature at just boiling indefinitely —when the car was pulling at full throttle at 20 mph, with 110° F. ambient air temperature. How often would that much cooling capacity be needed? In this type of test the 110° is called the "air-to-boil index" at 20 mph. With the same radiator this air-to-boil index was 121° at 60 mph—and an index of 117° F. at 20 mph was achieved on the air-conditioned cars by using a special core and high-pitch 6-blade fan.

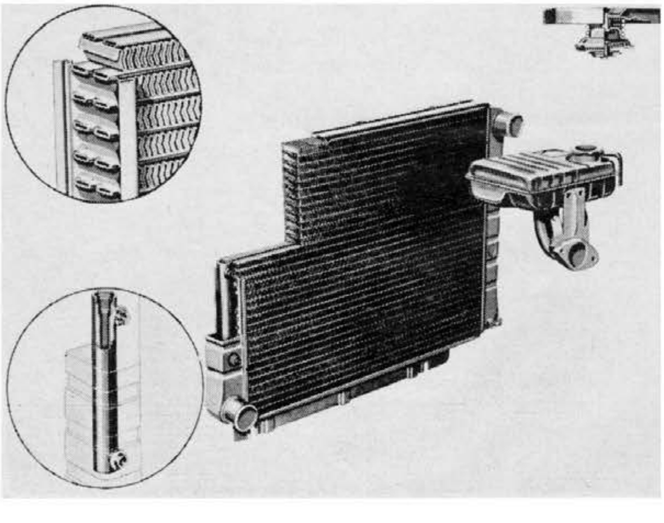
This is probably a more critical cooling test than most companies require of their cars. Several companies use an air-to-boil index of 105° F. at 30 mph. It is felt that this will allow for any likely conditions, such as pulling a trailer up a steep grade with full throttle in very hot weather. Some companies supplement these moving tests with an "idle-to-boil" test. They require that the cooling system prevent boiling for at least 30 min. when the engine is idling in 100° F. ambient temperature. This also takes some core and fan capacity.

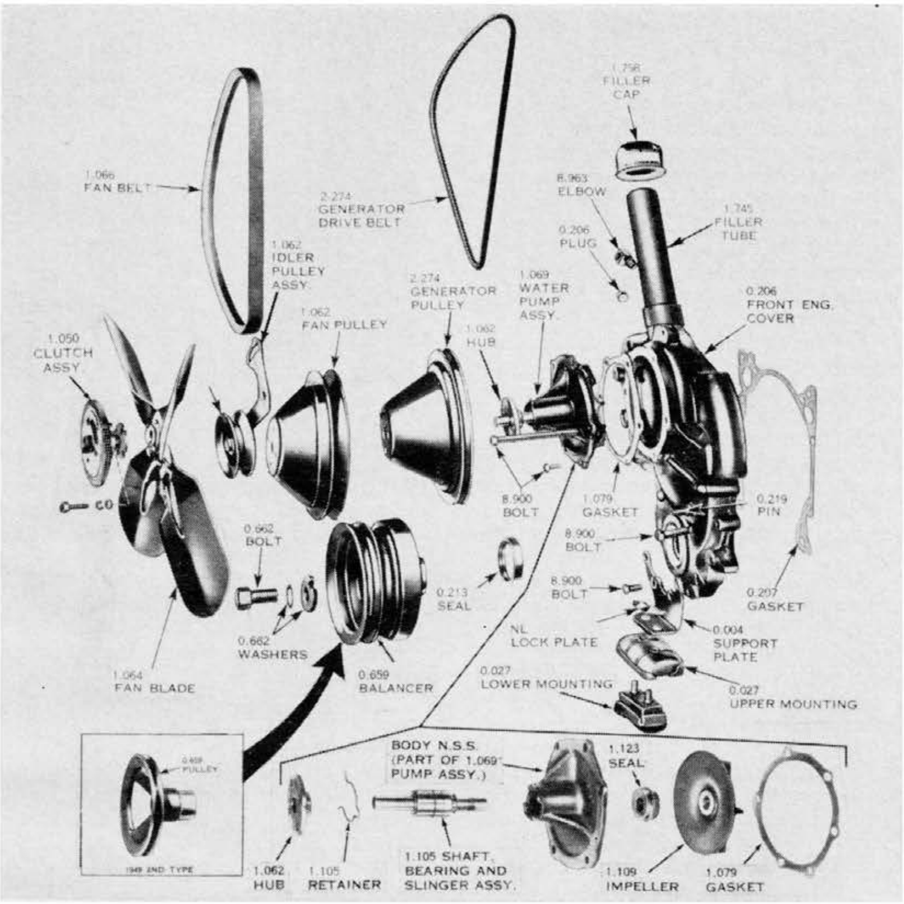
Many enthusiasts have wondered how sufficient air flow can be achieved

BUICK-OLDS aluminum V-8 engines had intake manifold hot spot heated by water instead of exhaust gas; it warmed quicker but boiled fuel.



SECTIONAL OF A typical fin-and-tube radiator (Ford). This is a cross-flow type, where water flows across the core instead of from top to bottom.





WATER PUMP assembly for the modern OHV V-8 engine. Driven by a belt from the crankshaft pulley, it incorporates both a de-clutching device and a fan.

through the radiator core with some of the wild grille designs nowadays. Actually this doesn't seem to be a problem. Designers can easily get adequate core air flow with a grille opening area of only half the core area. The reasons are obvious: The actual air flow area of the radiator core is by no means equal to the core frontal area. The tubes and fins fill much of the area—and if the tubes are staggered the flow area may be only half of the frontal area, or less. Also, the fan helps to pull air through the core, at least up to 20 mph or so. Above 30 mph engineers generally consider that the air velocity through the core is substantially equal to forward speed.

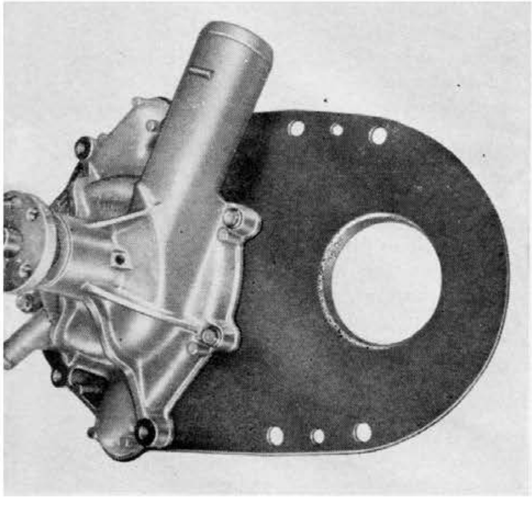
There are a number of tricks available to make cooling systems more efficient in terms of bulk, weight and cost. Possibly the most promising avenue is to raise the working temperature of the coolant. This increases the temperature differential between coolant and air, so less core area is needed to give the necessary BTU dissipation. For instance, an increase in coolant outlet temperature from 180 to 260° F. will reduce core area requirements by about 70%.

This coolant temperature problem is much more vital in aircraft engines than in cars because of the need for minimum weight and wind resistance. For this reason the World War II military liquid-cooled aircraft engines used ethylene glycol (Prestone) for a coolant. This boils at 387° and permits coolant outlet temperatures up to 250 or 260° without the complication of a pressurized system. All the liquid-cooled warplanes used it. It is also an antifreeze, and can be mixed with water in various amounts to give any desired degree of protection. It's the basis of most of our premium antifreezes.

Or, of course, the water system can be pressurized to get much the same effect (though without the antifreeze protection). That is, the boiling point of water goes up roughly 3° for every pound of pressure over atmospheric. By putting a 13-lb. pressure cap on the radiator, the water in the system can run up to 250° F. or so without boiling. Actually this is only emergency overload protection. Most modern cars carry pressure caps from 6 to 13 lb. rating from the factory and radiator core sizes have been reduced some in recent years to allow for the higher effective boiling point in the range above 230°. But the actual working temperature of the coolant in the system is still generally between 170 and 200°. Only under special conditions would the temperature go above 200°. This reserve cooling capacity is provided because the very high jacket temperatures could trigger destructive detonation and pre-ignition with poor fuel under lugging conditions.

One of the exciting future possibilities on passenger and sports cars is the ducted cooling system. Here the radiator core is positioned in a closed duct that brings ram air to the core and then conducts it back to the atmosphere. By thus carefully controlling the core flow the total wind resistance chargeable to the cooling system can be substantially reduced. And there's another point: The heat added to the air as it passes through the core will expand the air and thus cause it to jet out of the exit opening at a higher velocity than it entered at the front. This would theoretically give a certain amount of net forward thrust if the ducts are properly placed. Of course there is a certain pressure drop (restriction) as the air passes through the core. But the theory is that a carefully designed ducted cooling system can recover all the core restriction in effective jet thrust—so the cooling actually costs nothing in wind drag. ■

ALUMINUM WATER pump on new Olds Rocket bolts to engine front cover plate, provides a simple unit.



EARLY CHEVROLET V-8 water pump moved 48 gal./hour at 4400 rpm engine speed, was enlarged for later engines.