

# Swamp's Diesel Performance

*Competition Parts For Your Diesel*

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## Injector Operation

This version is dated Oct. 24, 2002 and contains various minor revisions in some of the measurements and related calculations. If a number is preceded by +/- that means I had difficulty getting a consistent measurement, with the uncertainty generally being less than .10mm.

Measurements were taken with a digital caliper reading to .0015"/.01mm, and double-checks done with a .0001" micrometer. Both were calibrated with the same 1" standard. Spring rates were calculated using the wire diameter, coil diameter and number of coils, but could have +/-10% error, possibly more.

**Part 2: HEUI Injector Operation Summary:** The solenoid and poppet control the flow of high pressure oil into and out of the injector; the piston, plunger and barrel pressurize the fuel for injection; the check balls/stop plate control fuel flow direction and the nozzle assembly controls when and how fast the fuel sprays through the tip orifices.

**Solenoid and Armature:** When the solenoid is energized by the PCM/IDM it creates an electro-magnetic field, which pulls the armature upwards. The armature's maximum travel is limited to .50mm, the difference in thickness between the armature (4.97mm) and the solenoid spacer (5.47mm). This .50mm can be slightly less during injector operation due to the oil film present, and can be reduced if the adjusting

screw is loosened. When the adjusting screw is fully tightened, the top of the poppet is flush against the bottom of the armature. When the screw is loosened, the armature is able to move freely up and down between the screw head and the adapter.

If the screw is too loose, the armature will contact the solenoid before it contacts the screw head, and the poppet will not open. The screw has a thread pitch of .5mm, so if 1 turn or more loosens it, the poppet will not move. In normal operation, armature does not contact the solenoid. If it did, I believe it could quickly crack or break it.

On this injector, the top of the poppet is flush with the top of the adapter, meaning that if there is any wear on the lower (oil inlet) seat, and the adjusting screw is fully tightened, when the solenoid is de-energized the armature will bottom out on the adapter before the poppet is fully on the lower seat, and it will no longer seal. Thus, high-pressure oil will flow in the lower seat and out the upper seat. The screw can be loosened 1/4 to 1/3 turns to allow the poppet more down-travel to seat more fully without limiting the up-travel.

The top of the armature has 3 lands (raised ridges), which align with 3 bars (coils) on the bottom of the solenoid. This creates 3 parallel electro-magnetic fields when the solenoid energizes, preventing the armature from rotating in relation to the solenoid. If it did rotate, it would jam against the solenoid spacer.

**The Poppet Valve:** The poppet is a 2-way or shuttle valve, controlling both the high-pressure oil's entry into the injector and its exit. In its "down" position (solenoid de-energized) it

is held against its seat in the piston/valve body by the poppet spring. In its "up" position (solenoid energized) it is held against its seat in the sleeve by the solenoid's pull on the armature.

The range of movement for the poppet is  $\pm .43\text{mm}$ , the difference between the seat-to-seat distance of the poppet, and the sleeve seat to piston/valve body seat. That is, when the solenoid is de-energized, the outlet seat is open  $.43\text{mm}$  and when it is energized the inlet seat is open  $.43\text{mm}$ . With this being a used injector, the production specs could be less. The poppet's seats are similar to a cylinder head valve seat. The inlet has a dia. of  $12.15\text{mm}$ , a width or margin of  $.20\text{mm}$ , and the poppet moves  $.43\text{mm}$  up off the seat.

The curtain area, or the opening available for oil to flow through, is  $16.41\text{ sq/mm}$ . The outlet has a dia. of  $11.25\text{mm}$  and a curtain area of  $15.19\text{sq/mm}$ . The spring has a calculated spring rate of  $\pm 165\text{ lb/in}$ , a free length of  $.587\text{"}$ , an installed height of  $\pm .424\text{"}$ , and a seat pressure of  $27\text{ lbs}$ . The design of the poppet is such that the HP oil is exerting equal pressure on the poppet in both directions simultaneously, so it neither pushes the poppet up off the inlet seat nor holds it down.

This way, only a light spring pressure is needed to hold the poppet on the inlet seat, and the solenoid need to exert only enough pull on the armature to overcome the spring's seat pressure and not the high oil pressure. A passage through the center of the poppet allows any oil that accumulates under the lower part of the inlet seat to escape up past the armature into the spacer area, and prevents "hydro-lock" or "vacuum-lock" from immobilizing the poppet, and the spacer

is notched so any oil there drains into the valve cover area.

**High Pressure Oil Flow:** The oil from the high-pressure rail enters the piston/valve body through two 3.5mm holes, which end under the poppet's lower seat. When the solenoid is energized, the poppet moves up off its lower seat, allowing the high-pressure oil to flow through the seat, around the poppet, and down a passageway in the side of the piston/valve body, which ends above the piston.

This oil then pushes the piston down, beginning the actual injection portion of the cycle. When the poppet moves up, it seats against the sleeve, preventing the HP oil from escaping through the sleeve and adapter plate. When the solenoid de-energizes, the poppet moves down away from the sleeve (outlet) seat, seating on the piston/valve body inlet seat, stopping the flow of HP oil into the injector and allowing the oil that has just activated the piston to exit the injector. When the piston is pushed down, the plunger spring is compressed, and it will stay compressed as long as the solenoid is energized.

When the solenoid is de-energized, the spring pushes the piston back up in its bore, and the oil above the piston is ejected through the oil passage, past the poppet's sleeve seat, through the adapter, and out under the valve covers. Whereas the 2 HP oil inlet holes are 3.5mm; the outlet holes in the sleeve are  $\pm 1.65$ mm.

This restriction limits the rate of travel of the piston as it returns to its seat, preventing it from hammering the seat. The inlet holes have an area of 19.24 sq/mm; the outlet has an area of 4.27 sq/mm for a ratio of 4.5:1.

**The Piston:** The piston is a hollow cup with the open end down. In this injector it is 16mm OD and 32.2mm long. (Other sizes are also used, depending on application. See FI-115A) [Note: I measured the plunger as having a dia. of 5.98mm, and the piston of 15.98 but I'm not sure if that allows .02mm shaft-to-bore clearance, or if it is .02mm wear. I think it is clearance, but I used 6mm and 16mm in all the calculations.] Based on the 16mm OD, it has a surface area for the oil to push on of 201.06 sq/mm.

The piston can move down up to 3.50mm, before bottoming on the barrel.  $201.06 \text{ sq/mm} \times 3.5\text{mm} = 703.71 \text{ cu/mm}$  (max.) of oil usage per injector pulse. Thus, at 3,000 rpm the HP oil pump could theoretically have to supply  $703.71 \text{ cu/mm} \times 8 \text{ cyls} \times (3000 \text{ rpm}/2) / 1000 = 8,444 \text{ cc}$  (2.23 gal.) of oil per minute. The actual amount of piston movement for a given injection pulse is regulated by the amount of time the solenoid is energized and the oil rail pressure.

**The Plunger and Barrel: (See FI-069)** The plunger and its spring are nestled inside the piston and retained by the barrel, with the plunger entering 2/3 of the way into the barrel. The barrel is 18.97mm long, and when assembled the end of the plunger is 6.98mm from the outlet end of the barrel. The plunger is 6mm in dia, giving a surface area of 28.27sq/mm. Dividing the piston surface area by the plunger surface area gives a ratio of 7.11:1, meaning that the fuel is pressurized 7.11 times more than the high pressure oil.

If the oil is at 3,000 psi, the fuel is being injected at 21,336 psi. The spring has a calculated spring rate of 174 lb/in, a free length of 1.116", an installed height of .934", for a seat

pressure of 31.66 lbs. It requires a minimum of 102-psi oil pressure (31.66lbs / .3097sq/in piston area) for the plunger to move. A hole in the top of the barrel leads through to the side allowing any oil that leaks down past the piston seal, or any fuel that leaks up past the plunger, to be ejected into the fuel supply, near where it enters the stop plate.

A check ball at the outlet, held in place by the retaining spring that girdles the barrel, prevents fuel from entering due to either fuel pressure or suction created when the piston retracts. Although the plunger could move up to 6.98mm before coming out of the barrel and bottoming on the stop plate, it can move only as much as the piston moves, or 3.50mm maximum. Multiplying 3.5mm travel by 28.27sq/mm gives a maximum fuel delivery rate of 98.94 cu/mm per stroke. The emissions sticker on my valve cover (1995 with SOD4 PCM Code) says 73.8 cu/mm per stroke, which leads me to conclude that the PCM/Solenoid limits the piston travel on time to a stroke of 2.61mm.

On this injector there is a very faint ring on the barrel where the piston has bottomed out on it, but the wear marks on the piston are 2.50-2.70mm wide. This injector was used with a Hypermax modified PCM, which explains the piston marks on the barrel.

**The Stop Plate:** Although called a stop plate; its most important function is as a valve body or metering block. The check ball controls the fuel inlet, opening for fuel to enter the barrel when the plunger retracts, and closing when the plunger extends, to keep the fuel in. The check plate serves the opposite function; it opens to let the pressurized fuel flow from the barrel to the nozzle, and closes when the

nozzle needle returns to its seat, acting as a damper or cushion for the needle and preventing the fuel pushed up by the needle from holding the check ball closed, which could prevent the barrel from refilling with fuel.

There are no springs holding the check ball and check plate; they stay in or move out of their seats based on the pressure differential between their inlet and outlet. The fuel outlet hole in the check plate is  $\pm 1.15\text{mm}$  dia., the bore for the inlet is  $\pm 3.25\text{mm}$ , but with a  $3.17\text{mm}$  ball in it there isn't much clearance ( $.40\text{sq/mm}$ ) for fuel to flow. The spacer sleeve would block off where the fuel inlet is on the bottom of the stop, so there is a channel in the stop across both sides of the inlet hole  $.08\text{mm}$  deep and  $3.3\text{mm}$  wide that allows fuel to reach the inlet. The area of this opening is  $.30\text{sq/mm}$ . The dowel pins that align the stop to the spacer are  $1.58\text{mm}$  ( $1/16"$ ) dia, but the holes they go in are  $1.78\text{mm}$  so there is quite a lot of slop, compared to the rest of the tolerances.

This slop can affect where the fuel inlet hole is in relation to the inner edge of the sleeve, in turn affecting fuel inlet flow. Seeing all these restrictions, I'm surprised the engine even runs! This is probably why so many people find performance gains by increasing the fuel pressure. How long does it take for  $73\text{cu/mm}$  of fuel to flow through a  $.30\text{sq/mm}$  opening at  $40\text{psi}$ ? Can it do it 25 times in  $3/4$  second?

**The Nozzle: (See FI-068; the spacer sleeve is not shown.)** The nozzle assembly controls the minimum pressure at which the fuel can be injected, the rate of fuel flow through the nozzle tip and the spray pattern. After the pressurized fuel leaves the barrel and flows through the

check plate, it travels through a passage in the side of the spacer sleeve (not through the center) which mates with a passage in the side of the nozzle tip.

The passage then angles in to the center of the tip, coming in just below where the needle necks down. The needle is held on its seat by the nozzle spring which has a calculated spring rate of 460 lb/in, a free height of  $\pm .654$ " (spring is out of square and worn unevenly), an installed height of  $.566$ " for a seat pressure of 40.23 lbs. It is calibrated to open at  $2675 \pm 125$  psi; with a 7.11:1 pressure ratio, there must be 376 psi of oil pressure in order to pressurize the fuel to 2675 psi. This is at least part of the reason why the PCM won't try to fire the injectors unless there is 400+ psi of oil pressure. Do not confuse seat pressure with Valve Opening Pressure (VOP): seat pressure is how much force the spring exerts on the needle, regardless of the surface area the force is applied over; opening pressure is the seat pressure divided by the surface area of the needle which fuel is able to push on.

As fuel enters the chamber around the needle in the tip, it pushes the needle up off its seat, and fuel then is sprayed through the tip orifices into the cylinder. As the needle lifts off its seat, it pushes on the lift spacer, which in turn pushes on the nozzle spring, compressing it. Due to the stop pin inside the spring, the needle is only able to move  $.41$  mm before the pin bottoms out on the stop.

A hole in the side of the spacer sleeve allows it to fill with fuel for cooling & lubrication, and acts as a vent when the needle rises and falls. When the fuel injection pressure falls below the VOP, the needle returns to its seat and injection

stops. As the needle seats, there can be a slight pressure surge in the opposite direction the fuel entered from, and if this occurs the check plate will close, keeping the fuel in the nozzle. Out of all the parts in this injector, the stop where the pin hits shows the only actual damage, while the nozzle spring has the most wear of any part, followed by the lift spacer and stop pin.