

A DOE Approach to Engine Deposit Testing used to Optimize the Design of a Gasoline Direct Injector Seat and Orifice

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ABSTRACT

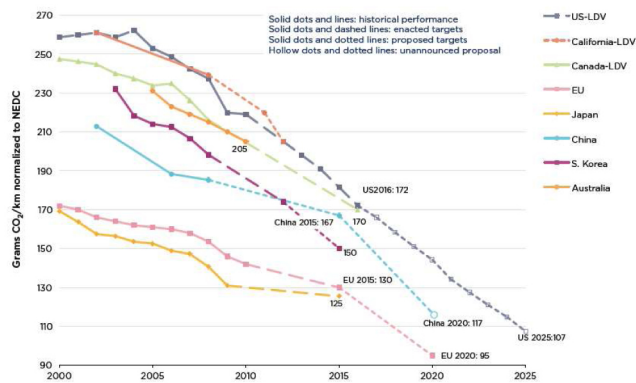
A series of designed experiments (DOE) was used to optimize the seat and orifice designs in a multi stream gasoline direct injector. The goal of the experiments was to minimize the effects of fuel deposits on the injector performance. Two different engines were used in the test campaign. One engine, a centrally injected turbocharged 1.6L four cylinder, was used to run a three factor full factorial DOE that tested the effects of SAC volume design, tip design and combustion seal position. Another, a centrally injected turbocharged 3.0L six cylinder, was used to run a three factor full factorial and a four factor half factorial DOE. The three factors in the full factorial were orifice hole divergence, orifice hole surface finish and the use of an inert amorphous silicon coating. A fourth factor, hydro erosive grinding of the orifice holes, was added to facilitate the calculation of a four factor half factorial DOE with only four additional engine tests. The engines were tested on engine dynamometers using specially formulated fuels to accelerate deposit formation. The specific test cycle for each engine was determined using injector tip temperature data and included multiple engine operating points run in succession. One cycle also included a soak phase. It was found that the optimized configuration included a protruded tip, the orifice hole entrances outside the SAC volume close to the seal band, smooth, straight stepped holes (mechanically drilled in this case) without the use of hydro erosive grinding. Combustion seal position and the presence of this particular type of coating proved to be statistically insignificant. SEM photographs of the seats and orifice holes and were also used to aid in the understanding of the results.

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INTRODUCTION

The spark ignition engine is expected to continue to be one of the most common power plants for light duty automotive applications for decades to come. The global volume of gasoline direct injection engines is predicted to grow and overtake port injection engine volume after 2020 [1]. The primary driver toward gasoline direct injection, especially when combined with other technologies such as advanced valve timing, turbocharging and downsizing is the

reduction of greenhouse gases. Around the world governing bodies have enacted and/or proposed aggressive targets for the reduction of greenhouse gases. Figure 1 shows the NEDC CO₂ equivalent in g/km for targets from California, the United States, Canada, the European Union, Japan, South Korea, and Australia. The targets of the US from 172 g/km in 2016 to 107 g/km in 2025 represent a 38% reduction, Europe, already at a much lower starting point, has targets of 130 g/km in 2015 and 95 g/km in 2020, representing a 27% reduction [2].



[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.
 [2] US and Canada light-duty vehicles include light commercial vehicles.

Figure 1. Greenhouse gas emission targets from various global governing bodies.

Even as publications about the earliest gasoline direct injection production systems made dramatic claims about fuel economy^{3, 4, 5}, the risks and mechanisms of injector deposit formation were also discussed in those early papers^{3, 6}. As combustion chamber deposits were nothing new to spark ignition engines, the mechanisms of deposit formation and removal had been published⁷. As this knowledge base was applied to gasoline direct injector deposits, many papers described the relationship of injector tip temperature and fuel composition [6, 9,10,11,12]. Significant increases in fuel consumption, particulate, HC, CO, and NOx emissions as well as drive-ability as a function of flow decrease due to deposit formation were also documented [10]. These negative effects are attributable to combustion degradation due to cylinder imbalance and injector spray distortion [9, 11, 16]. Gasoline additives to mitigate these negative effects on combustion have also been developed and studied [9, 13,14,15] and found to be quite effective. The effectiveness of fuel additives and the re-formulation of fuels notwithstanding, it is still up to the fuel components supplier to develop injectors that are robust to the deposit effects of any potential fuel with or without additives.

Many engine and vehicle tests have been developed by OEMs, additive suppliers, fuel component suppliers and others to study the effect of deposits. Steady state engine dynamometer tests have been developed that choose operating points based on injector tip temperature with strict control of fuel and coolant temperatures [8, 18]. Another found soak cycles to be an important parameter [19] in addition to strict coolant temperature control. This approach is similar to standard approaches for port injector testing. All wrote of the importance of a severe deposit forming fuel to accelerate deposit formation. Vehicle tests have also been related to injector tip temperatures [8, 10], typically include a soak [8, 10, 15], and are often related back to real world driving [8, 15] or standard port fuel injection vehicle tests [10]. Severe fuels are also typically required to accelerate the

testing [8, 10, 15]. OEMs have also developed their own proprietary tests and fuels. There has been an international effort by the Coordinating European Council (CEC), Coordinating Research Council (CRC), USA, and the Oil and Automobile Cooperation for International Standards (OACIS), Japan, to standardize testing. After extensive work, the group recommended not abandoning current tests and proposed that the future test development be pursued on a regional basis.

Engine testing and Six Sigma methods have been used previously in injector design. Injector deposit testing on engines was used by Von Bacho, et al. [21] to optimize a port injector for deposit resistance. Rivera, et al. [22] used a rigorous Design for Six Sigma Methodology to design a next generation gasoline direct injector.

In the environment of ever increasing volume and demands on gasoline direct injection engines, the authors of this paper have combined the collective experience in engine deposit testing with proven Six Sigma methods to optimize the design of a gasoline direct injector.

BACKGROUND

Continental has been continuously developing the design of its Gasoline High Pressure Direct Injectors to minimize flow loss from deposit formation. Through previous internal and contracted testing it was known that the injector SAC volume design, orifice hole geometry and tip design were important injector design factors effecting flow loss as a result of deposit formation. The previous work had shown that the SAC volume should be minimized, the holes should have a stepped design and the length to diameter ratio of the orifice hole minimized. In addition, other system level factors were explored such as fuel pressure, fuel temperature and fuel effects [8, 9,12]. These system level influences are beyond the scope of this paper.

With this background of previous work and experience, a team was formed to participate in a Five Why Exercise to develop focused experiments and other efforts including injector flow and thermal analysis. A summary chart of the Five Why is included in Table 1. The Table shows that the exercise spawned multiple activities including two Designed Experiments (DOE), Computational Fluid Dynamic Analysis (CFD) including internal flows and thermal analysis of the injector tip, high speed video analysis of the injector spray both at atmospheric conditions in the laboratory and in the combustion chamber of a running engine. The two DOEs are the subject of this paper.

Table 1. Summary table from the Five Why Exercise that generated a series of activities including the experiments described in this paper.

Why 1	Why 2	Why 3	Why 4	Why 5	Action
Why do we have Deposits?	Seat is Wet	Needle speed at closing is slow, leaving fuel on tip	Hydraulic damping too high (sac?)		CFD
			Lift too low		HS Video, Nexus, then decide to include in engine test
			Spring load too low		HS Video, single shot flow analysis, then decide to include in engine test
			Mass of ATB too high		on hold
		SAC Volume causes ligaments during closing wetting seat	Volume too high causing after injection		OFAT testing SAC/Stepped Hole: Minimize SAC
			Shape of SAC not optimized		CFD Analysis
			Position of hole in SAC incorrect		CFD Analysis
			Distance between ball and hole inlet too large		CFD Analysis
		Fuel in SAC boils and pushes liquid and vapor out			High Speed Engine Videos
		Hole outlet shape	Exit angle improper	Tip shape	DOE, Thermal Simulation
				Step Hole	OFAT testing SAC/Stepped Hole: Stepped Hole
				no step	OFAT testing SAC/Stepped Hole: Stepped Hole
			Outlet Radius present/incorrect	Step Hole Geometry (drill point on step)	long term producibility improvement
		Step hole shape/seal shape not optimal	Radius straight hole		Document edge conditions of samples
			Divergence		Re-visit in DOE?
			Spray interaction with step during closing		Benchmarking
			Spray interaction while open		HS Video verification of all samples
		Tip Shape	Spray interaction under flash boiling		HS Video study in combustion chamber
				Temperature in deposit range	DOE, Thermal Simulation
			Negatively effects temperature	Temperature not in oxidation range	DOE, Thermal Simulation
				Temperature not low enough	DOE, Thermal Simulation
		Needle Bounce	Effects capillary action		on hold to be defined
			During bounce seat is wetted.		All samples to be verified with HS videos to have no bounce
	Insufficient cleanup mechanisms	Leak	Leak covers seat with fuel between injections		Characterize injectors
			Leak covers seat with fuel during soak (start/stop)		Characterize injectors
					HE Grinding to form radiused hole entrance; include in engine DOE; improves flow capability, desirable from manufacturing perspective (no in previous DFSS; smaller the better, function of stepped hole
		Cavitation not sufficient in hole	Entrance conditions wrong		Hole surface in DOE
			Lid too long		DFSS: Higher is better, impacts Qdmin, parasitic losses
			Surface conditions wrong		DFSS: Higher is better, impacts Qdmin, parasitic losses
		Fuel pressure not high enough	Shear forces not high enough		
			Cavitation not high enough		
		Deposit adheres to hole	Surface finish too rough	EDM surface	Surface finish in DOE
			No coating		Coating in DOE
	Metal is too reactive	Presence of chromium and nickel	required for corrosion resistance		Coating in DOE
			No coating		Coating in DOE
	Temperature in deposit range	Shape of tip is wrong			Tip shape in DOE
			Protrusion is improper		Normal Application work
	Fuel vapor present near tip	Heat transfer from head too high			Thermal Analysis: Combustion seal location.
		High temperature evaporating sac volume	large sac, heat transfer to sac		SAC Volume in OFAT testing; smaller is better. SAC design in DOE
					In Cylinder in HS videos, measures on injector to prevent tip wetting
	Fuel in sac volume carbonizes	High temperature s in SAC	Combustion system	transport of vapor to injector tip	Out of our control, noise factor
			SAC not empty		Section dirty injectors, and at various stages of coking

EXPERIMENTAL DESIGN

Two experiments were designed from information gained from the Five Why Exercise. The first was a two level, three factor, full factorial DOE with SAC volume design, combustion seal position, and tip design as factors. The second experiment used orifice hole divergence (conical taper), orifice hole surface finish, and the presence of an amorphous silicon coating in a two level, three factor, full factorial design. A fourth factor, hydro-erosive grinding of the orifice holes, was added to allow calculation of a four factor, half-factorial design. This approach was used as it was believed that there could be meaningful interactions among the first three factors that could be calculated with the full factorial approach while it was less likely that the fourth factor, hydro-erosive grinding, would interact with the other factors. The approach also eliminated the need for four engine tests compared to taking a full factorial approach for all four factors.

DOE 1

The treatment combinations used in the first DOE are shown in Table 2.

Table 2. Treatment combinations used in DOE 1

DOE 1			
Treatment	SAC_Design	Tip Design	Combustion Seal Position
1	Holes Inside	Flat	Low
2	Holes Outside	Flat	Low
3	Holes Inside	Flat	High
4	Holes Outside	Flat	High
5	Holes Inside	Protruded	Low
6	Holes Outside	Protruded	Low
7	Holes Inside	Protruded	High
8	Holes Outside	Protruded	High

The two SAC volume designs used in DOE 1 are distinguished primarily by the position of the orifice holes relative to the SAC volume. The first design, which was used as a baseline design in both DOEs, includes the holes in the SAC volume. This approach was carried over from previous injector designs where the volume is used as a sort of plenum to provide equal flows through all the orifice holes. In addition, the design has advantages in improving the manufacturability of the seat by providing room for oscillation of the grinding stone while grinding the seal area of the seat. The second design has the holes outside of a volume directly under the sealing ball. Such a design places the hole entrances as close to the surface of the ball as possible while providing a flow stagnation zone directly below the ball. Minimizing the distance between the hole entrances and the ball limits the volume of fuel below the

injector seal band with access to the holes and the atmosphere of the combustion chamber. This theoretically reduces the amount of fuel in the holes that can turn into deposits while the injector is closed. Flow modeling also showed that providing a stagnation zone below the ball increases the pressure below it, thus reducing the hydraulic force on the Armature Tube Ball Assembly (ATB) in the direction of closure. This raises the maximum fuel pressure at which the magnetic circuit can hold the injector open. [Figure 2](#) contains cross-sections of the seats used in the DOE showing the two designs.

[Figure 2](#) also shows the two tip designs used in DOE 1. One is a flat tip design whereby the face of the seat is simply flat and flush with the surface of the combustion chamber. The step holes intersect the face at angles appropriate for the target injector spray pattern. The second design includes a 0.6mm high conical protrusion on the seat face. In this design the step holes intersect the surface of the protrusion approximately perpendicularly. The injector is installed in the engine such that the flat circumference of the protruded seat is flush with the surface of the combustion chamber. In both designs the L/d ratio of the orifice holes are identical. The protrusion reduces the likelihood of the spray impacting the seat by providing a roughly uniform step hole depth around the circumference of the step. The protrusion also reduces the likelihood of the spray contacting the face of the seat or combustion chamber surface by positioning the hole exit further away from these surfaces. The temperature profile of the seat is also affected by the protrusion.

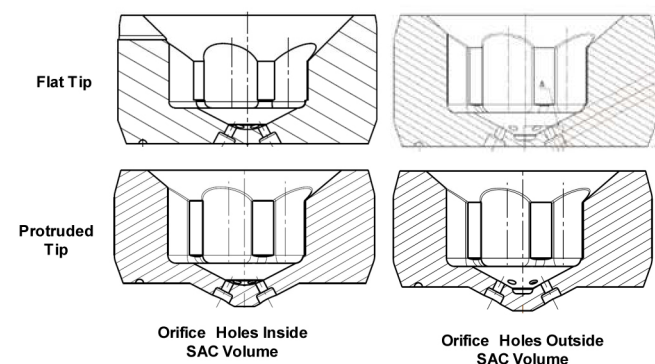


Figure 2. Seat designs used in DOE 1 showing tip and SAC volume details.

[Figure 3](#) shows the valve body combustion seal positions. The lower position is 7.7 mm from the tip surface and the upper position is 12.8 mm from the tip. By changing the annular volume below the seal, which combustion gases flow in and out of, it is believed that the temperature profile of the tip is changed. The upper seal position also has the advantage that the seal stays cooler in operation and thereby increases its durability.

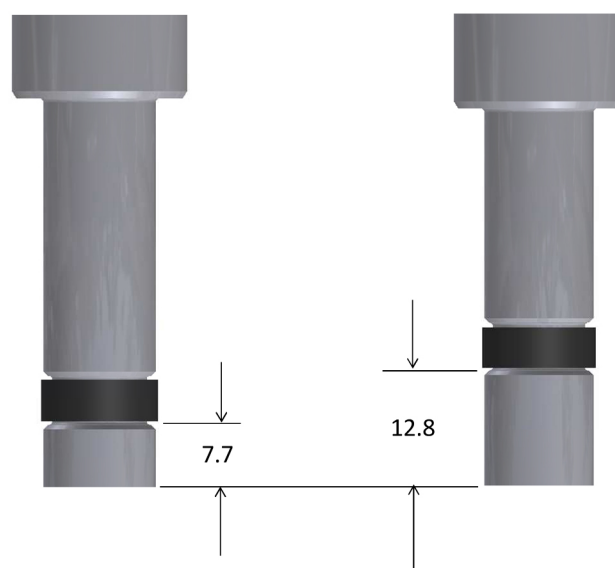


Figure 3. Injector valve body designs used in DOE 1 showing the upper and lower combustion seal positions.

DOE 2

The baseline seat design for DOE 2 is shown in [Figure 4](#) and includes stepped holes inside the SAC volume, and a protruded tip. Details of the hole geometry and surfaces are factors in the DOE and are described in detail below.

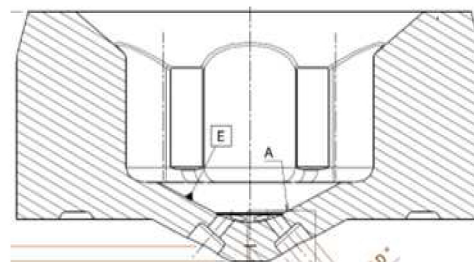


Figure 4. Baseline seat configuration used in DOE 2 includes stepped holes inside the SAC volume and a protruded tip.

The treatment combinations used in DOE 2 are shown in [Table 3](#). The treatment combinations for the two level three factor full factorial DOE are shown in treatments 1 through 8. The additional treatment combinations that allowed the calculation of a two level four factor half factorial DOE are treatment combinations 9 through 12.

Table 3. Treatment Combinations for DOE 2 showing the two level three factor full factorial DOE and the additional combinations that allowed calculation of a two level four factor half factorial DOE.

DOE2 Treatment	HoleDiverge	HoleSurface	HoleCoating	HydroErosive
1	0	Drilled	NoCoat	NoGrind
2	3	Drilled	NoCoat	NoGrind
3	0	EDM	NoCoat	NoGrind
4	3	EDM	NoCoat	NoGrind
5	0	Drilled	Coated	NoGrind
6	3	Drilled	Coated	NoGrind
7	0	EDM	Coated	NoGrind
8	3	EDM	Coated	NoGrind
9	3	Drilled	NoCoat	Ground
10	0	EDM	NoCoat	Ground
11	0	Drilled	Coated	Ground
12	3	EDM	Coated	Ground

3 Factor
Full Factorial

4 Factor
Half Fractional

Two technologies were used to machine the holes in the injector seats; Electrical Discharge Machining (EDM) and mechanical micromachining. In each case both the step hole and the orifice hole were made from the same technology whether it was EDM or micromachining. EDM represents Continental's current production process, while the tooling and micro-machining process were developed specifically for this program to generate a surface significantly smoother than the EDM. In the micro-machined part, the hole step was first machined using an end mil, the orifice hole drilled and finally reamed before the seat was thermally de-burred. Dimensions on the holes were verified with both a white light interferometer and with a Scanning Electron Microscope (SEM). Holes were machined with either no taper or 3° per side.

Figure 5 shows SEM photographs of holes manufactured with each technology. The photos clearly show the textured surface characteristic of the EDM process and the very smooth surface of the mechanically micro-machined surface. The edge conditions on the hole entrance are also visible in the photographs.

SEM techniques were also used to verify the presence and coverage of the inert amorphous silicon coating. Figure 6 shows SEM photographs of the seat with and without backscatter electron detection. In backscatter mode, organic materials appear white which shows that the coating appears uniform and covering both the orifice hole and the step hole. According to the manufacturer of the coating, the thickness is typically 100 to 250 nm.

SEM-EDS (Scanning Electron Microscope - Energy Dispersive Spectroscopy) was also used to verify the presence of the coating. In Figure 7 the spectrum measured on the seat surface shows silicon, the major constituent of the coating, in addition to the other elements associated with the seat material.

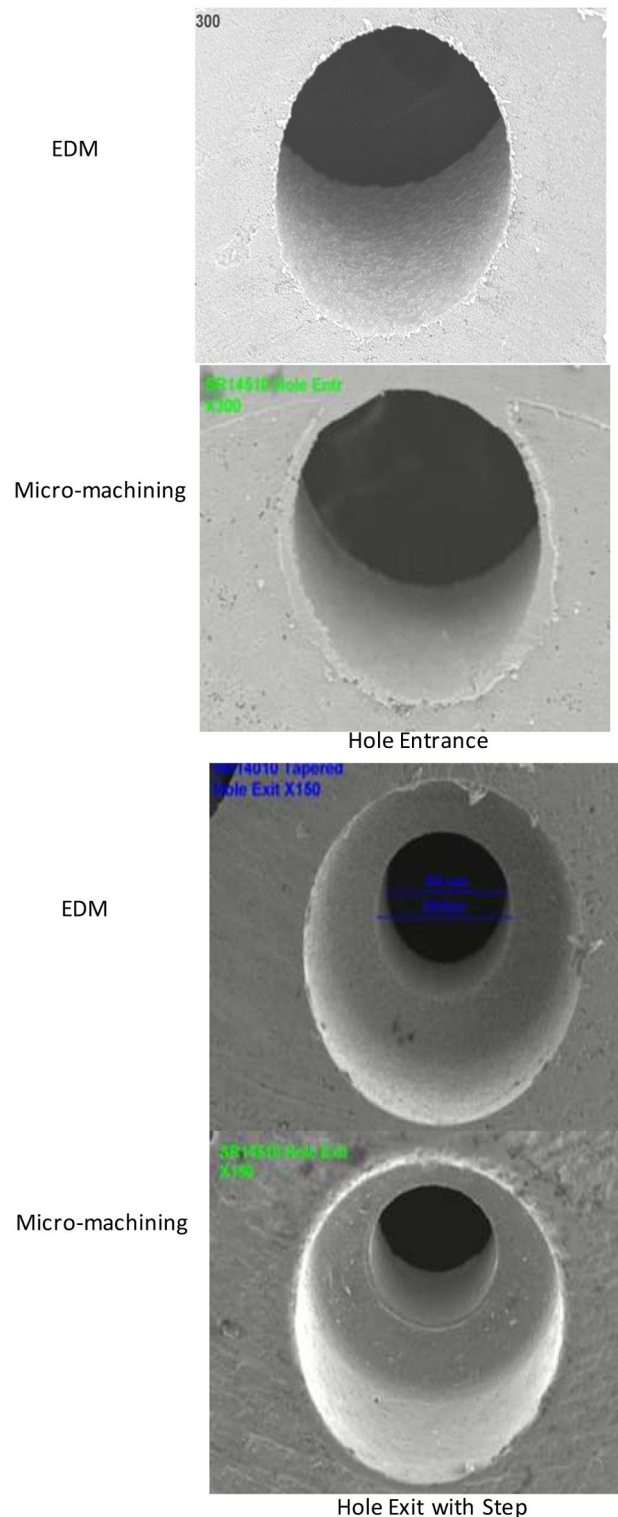


Figure 5. SEM photographs showing the textured surface characteristic of the EDM process and the inherently smoother surface of the mechanically micro-machined parts.

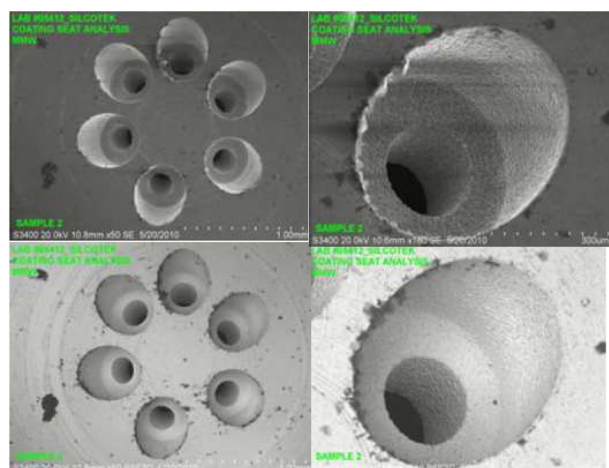


Figure 6. SEM images with (lower images) and without backscatter (upper images). In the backscatter images the coating appears white, indicating that the coating is uniform and covers the seat surface, orifice and step holes.

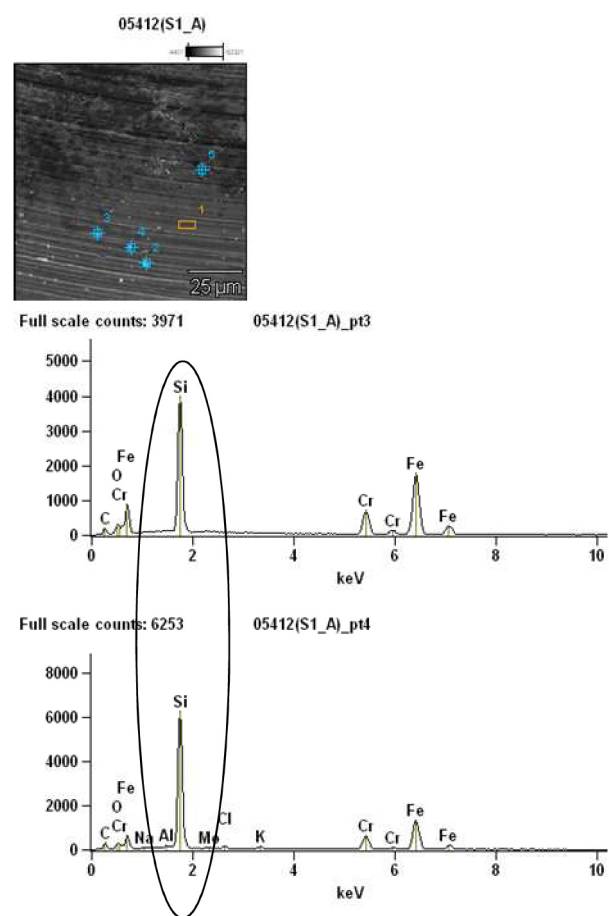


Figure 7. EDS Spectrum from two different points on the seat surface, showing the presence of silicon, the major constituent of the coating.

The fourth factor used in the DOE was the use of hydro-erosive grinding on the orifice holes. The process, common in the manufacture of Diesel injectors, is used to balance the flow from one injector seat to the next. It modifies the flow of the seat by forcing abrasive slurry (grinding media) through the seat in the normal direction of flow. During the grinding process the flow of the slurry is monitored and stopped once a target flow is reached. The grinding media changes the orifice flow by grinding a radius on the entrance of the hole and improving the surface finish. [Figure 8](#) shows the relationship between the orifice hole flow and the entrance radius formed by the hydro-erosive grinding process.

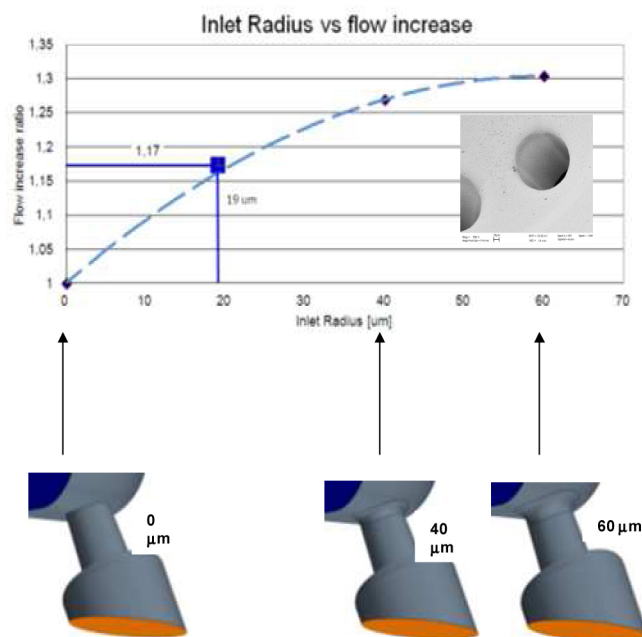


Figure 8. The relationship of the orifice hole flow and the inlet radius formed by hydro-erosive grinding.

The injector seats used in this study were purposely manufactured approximately 17% lean before grinding. Per the relationship in [Figure 8](#) and verification through measurement, hydro-erosive grinding to the target flow resulted in a 19 μm orifice inlet radius. The seats were ground using oil based slurry with 2% boron carbide as the abrasive. The upstream pressure was 100 bar and downstream pressure was 1 bar. The average grinding time was between 26 and 28 seconds. [Figure 9](#) shows the resulting inlet radius appearance, size and seat flow.