

Development of a Structurally Optimized Heavy Duty Diesel Cylinder Head Design Capable of 250 Bar Peak Cylinder Pressure Operation

2011-01-2232

Published
09/13/2011

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doi:[10.4271/2011-01-2232](https://doi.org/10.4271/2011-01-2232)

ABSTRACT

Historically, heavy-duty diesel (HDD) engine designs have evolved along the path of increased power output, improved fuel efficiency and reduced exhaust gas emissions, driven both by regulatory and market requirements. The various technologies employed to achieve this evolution have resulted in ever-increasing engine operating cylinder pressures, higher than for any other class of internal combustion engine. Traditional HDD engine design architecture limits peak cylinder pressure (PCP) to about 200 bar (2900 psi). HDD PCP had steadily increased from the early 1970's until the mid 2000's, at which point the structural limit was reached using traditional methods and materials. Specific power output reversed its historical trend and fell at this time as a result of technologies employed to satisfy new emissions requirements, most notably exhaust gas recirculation (EGR). While future incremental improvements to specific power are predicted to occur through refinements in existing technology, a significant change in HDD structural architecture is required to allow higher PCP operation. Many proposed combustion, emissions reduction and high efficiency technologies for the future are also pointing to the need for increased PCP. Once higher PCP operation can be achieved, HDD performance can return to its historical trends and enable much of the advanced diesel combustion research ongoing throughout the world today to become more commercially viable. The challenge is to determine what this structural architecture must be.

Southwest Research Institute® (SwRI®) has undertaken an applied research and development program with the goal of evaluating key design features which limit PCP for modern HDD engines and to analytically derive structural solutions that would extend the limit to what is predicted to be required for high specific power model year (MY) 2015 (and beyond) engines. This program focused on identifying combinations of structural parameters and feasible material options in the cylinder head to achieve commercially viable 250 bar PCP capability with minimal impact on existing machining lines. This paper reviews the multi-phase/multi-year program approach and results as well as discusses a new casting method developed for HDD cylinder head manufacture.

INTRODUCTION

TECHNICAL BACKGROUND

Historically, HDD engine designs have evolved along the path of increased power output, improved fuel efficiency and reduced exhaust gas emissions, driven both by regulatory and market requirements. The various technologies employed to achieve this evolution have resulted in ever-increasing engine operating cylinder pressures, higher than for any other class of internal combustion engine. This trend and its current predicted future are illustrated in [Figure 1](#), along with the associated trend of specific power (power output per displaced volume).

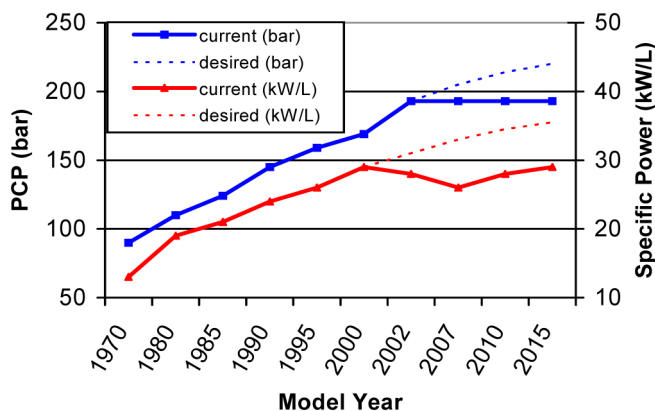


Figure 1. Trends in HDD Engine Specific Power and Peak Cylinder Pressure

Traditional HDD engine design architecture limits PCP to about 200 bar (2900 psi) [reference benchmarking data]. From the chart it can be seen that HDD PCP had steadily increased from the early 1970's until 2002, at which point the structural limit was reached using traditional methods and materials. Specific power output reversed its historical trend and fell at this time as a result of technologies employed to satisfy new emissions requirements, most notably exhaust gas recirculation (EGR) [1].

While future incremental improvements to specific power are predicted to occur through refinements in existing technology, a radical change in HDD structural architecture is required to allow higher PCP operation. Many proposed combustion research technologies for the future such as Homogeneous Charge Compression Ignition (HCCI) and High Efficiency Dilute Gasoline Engine (HEDGE) are also pointing to the need for increased PCP. Another trend which will benefit from higher PCP capability is down-sizing/boosting. Once higher PCP operation can be achieved, HDD performance can return to its historical trends and enable much of the advanced internal combustion engine research ongoing throughout the world today. The challenge is to determine what this structural architecture must be.

Utilizing the results of a parametric Design of Experiments (DOE) study, a new cylinder head has been comprehensively designed and evaluated using SwRI's standard cylinder head analysis and fatigue testing techniques. It has been fully designed with manufacturing intent, including casting core models that were developed in conjunction with Grainger and Worrall, Ltd. (G&W) (who prototyped the design), and has successfully achieved the project goals.

OBJECTIVES

The goal of the project was to determine what key design features cause the observed limit in PCP for modern HDD engines and to analytically derive structural solutions that

would extend the limit to what is predicted to be required for high specific power MY 2015 engines. The five basic objectives were therefore:

- Identify MY 2015 HDD specific power and PCP targets
- Identify weakest links in current engine design architecture, primarily in cylinder head design.
- Investigate the influence of basic cylinder head design parameters on peak pressure capability
- Use the results of the study, and any intellectual property (IP) developed to design a new high- pressure-capable cylinder head for an existing HDD engine using techniques, materials, and manufacturing processes available to original equipment manufacturers (OEM's) today. Especially critical was the goal to design a head which could be adapted to current engine machining and assembly lines.
- Procure prototypes for the new cylinder head design and demonstrate their pressure capability on a cylinder head structural fatigue rig test.

TECHNICAL APPROACH

As an applied research project, analytical techniques common to the art were employed to determine the root causes (e.g. thermal stress, mechanical strain, etc.) of the PCP limit and to evaluate proposed remedies for those causes. All proposed solutions were evaluated for their commercial viability as well since we seek to expand the horizon of current and future cylinder head designs. The comprehensive effort to produce and test a novel cylinder head based on the research results followed a multi-phase approach. For reference, the task overview associated with each phase of the comprehensive effort is presented below:

Phase 1:

- Perform thermodynamic cycle simulation studies to estimate the required MY 2015 PCP value.
- Perform structural analyses to benchmark current cylinder head designs at MY 2015 PCP levels.
- Conduct an extensive DOE concept study on cylinder head structural features and their influence on PCP capability.
- Based on the rapid iteration computer aided engineering (CAE) models developed for the DOE above, evaluate design options until a viable solution is obtained.
- Conduct a probabilistic sensitivity study on the optimized cylinder head geometry.

Phase 2:

- Using the results from Phase 1, design a new cylinder head for an existing HDD engine with the objective of establishing structural durability at the target PCP level.

- Conduct a casting study to determine the design and production feasibility of key structural features identified in Phase 1.

Phase 3:

- Design casting tooling and prototype cylinder head samples suitable for fatigue and on-engine testing.
- Test prototype cylinder heads using SwRI's structural fatigue rig test to validate the high cylinder pressure design methodology.

DISCUSSION AND RESULTS

BACKGROUND ANALYSIS

The purpose of the background analysis was to establish a reasonable target peak cylinder pressure for future heavy-duty diesel engines and to demonstrate that a current state-of-the-art cylinder head design cannot successfully operate at this target pressure. To achieve these goals two analysis tasks were conducted, as described below:

Thermodynamic Analysis

An existing big-bore class HDD engine thermodynamic model was used to investigate various performance and emissions related concepts that could be used to take advantage of increased PCP capability. The purpose was to clarify the advantages of higher pressure operation of an engine, and to help define a realistic PCP target for the architecture study. GT-POWER, a thermodynamic engine cycle simulation modeling environment, was used for this task.

The baseline HDD simulation model was calibrated to engine data for conformance to power, air and EGR flows, fuel consumption, PCP and NO_x (oxides of Nitrogen) emissions. The baseline engine utilized EGR flow percentages of approximately 12-20% on the full power curve from 1200-2000 RPM. The target overall brake-specific-NO_x (BSNO_x) emissions level was approximately 3.35 g/kW-hr, but values at individual operating points were above or below this overall average. The start-of-combustion (SOC) timings are usually set to produce BSNO_x levels higher or lower than the average, depending upon the engine configuration and application, to achieve the best fuel economy for the application duty cycle.

After calibration to the engine data, the baseline simulation model was modified for simulation at future, much lower emissions levels, which involved major increases in the amount of EGR to reduce BSNO_x. This requires much higher turbocharging boost pressures to maintain the same air/fuel ratios necessary for complete combustion, and to trap the increased EGR mass in the cylinder. [Figure 2](#) and [Figure 3](#) show PCP and BSNO_x results versus SOC timing sweeps at two points on the full load power curve, with EGR increased

to 27-29%. Fuel flow and air flow were maintained at the same levels as the baseline model for equivalent comparison.

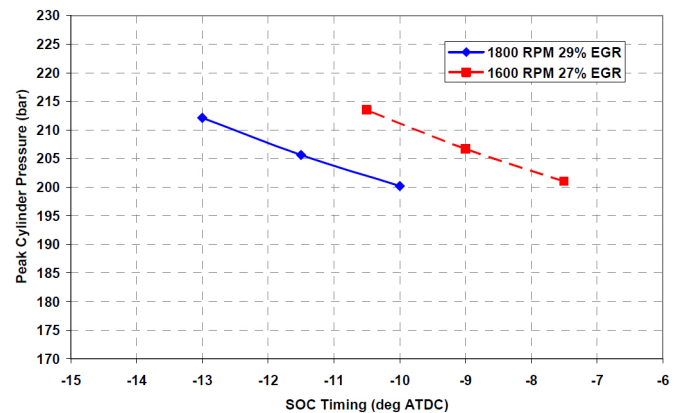


Figure 2. Peak cylinder pressures versus SOC timing with increased EGR

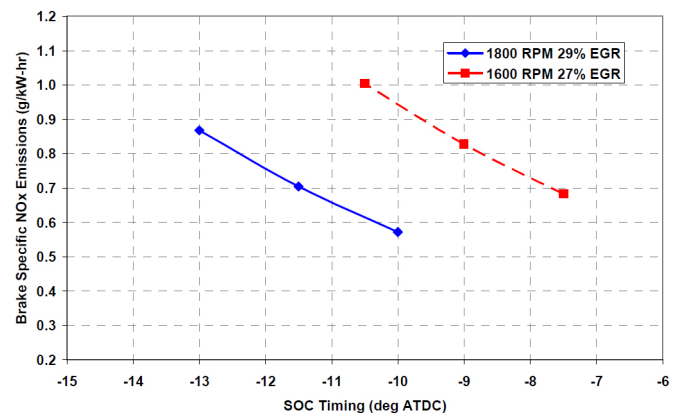


Figure 3. BSNO_x versus SOC Timing with Increased EGR

Note that PCP levels increased substantially with the major increase in EGR, but the EGR increase produced the desired effect of a major decrease in BSNO_x levels. The BSNO_x targets for the future depend upon the emissions year regulations, and level of exhaust aftertreatment which will be applied to further reduce NO_x. Current Environmental Protection Agency (EPA) regulations require ≤ 0.2 g/kW-hr BSNO_x tailpipe emissions [2].

The HDD engine industry is very competitive for fuel consumption levels. Even an increase of 0.5 % is considered a major disadvantage, and a few percent can cause drastic loss in market share. In order to recover the previous fuel consumption values with the increased EGR, most manufacturers are expected to increase cylinder compression ratios, which will cause another major increase in peak cylinder pressures. [Figure 4](#) shows PCP results versus compression ratio sweeps at the same two points on the full load power curve, with the previous EGR increase to

27-29%. Fuel flow and air flow were maintained at the same levels as the previous sweeps for equivalent comparison. The baseline compression ratio of 17.3:1 was increased to 19:1, which was considered to be a major change. Above that value, combustion bowl design for adequate space for fuel injection sprays is considered much more challenging.

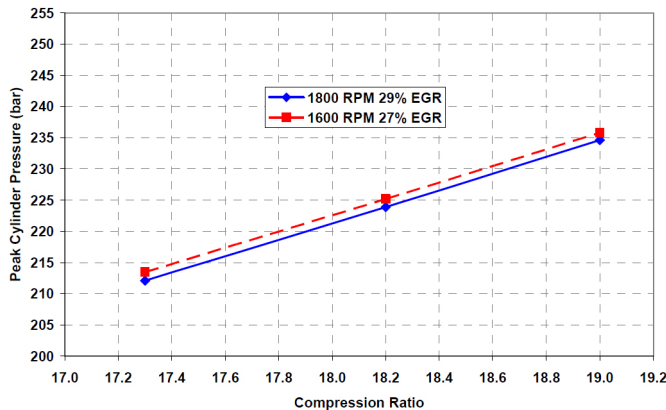


Figure 4. Peak Cylinder Pressures versus Compression Ratio with Increased EGR

All of the results shown have assumed that current power levels are maintained. As [Figure 1](#) in the Background section shows, historical trends have been for increasing specific power, and these trends are expected to continue. As such, although the highest PCP levels shown in [Figure 4](#) are 235 bar, it will be necessary to build in further margin for the expected increase in specific power. Therefore, a future PCP target of at least 250 bar is not unreasonable and was selected as the starting point for structural design improvements.

CYLINDER HEAD GEOMETRY SENSITIVITY STUDY

The purpose of this task was to investigate basic cylinder head geometry design features and their effect on cylinder head structural performance at high firing pressures. To accomplish this goal in a reasonable timeframe, analysts used a simplified parametric cylinder head model that did not include complex geometry like rounds and fillets in the water jackets. This simplification removes the ability to use fatigue behavior as a response variable due to the dependency of stress on these features. Instead, deflection of the primary decks was used as a response variable. SwRI has developed a correlation between stresses that cause fracture and deck deflection based on its extensive analysis, testing, and field performance database. This allowed assessment of many major geometric features in a reasonable amount of time.

Generation of Cylinder Head Parametric Computer-Aided-Design (CAD) Models

The first step in generating the CAD models was to identify the critical cylinder head design features to be included in the sensitivity study and set up the DOE. Ten factors were chosen to be included in the DOE, and are shown in [Table 1](#) along with their associated evaluation levels.

Table 1. DOE Parameters

Parameter	Evaluation Levels	
Port Arrangement (PTA)	45 deg	90 deg
External Water Jacket (EWJ)	Yes	No
Injector Bore Diameter (IBD)	26 mm	38 mm
Upper Water Jacket (UWJ)	Full	Half
Fire Deck Thickness (FDT)	12 mm	17 mm
Upper Deck Thickness (UDT)	10 mm	15 mm
Mid Deck Thickness (MDT)	5 mm	10 mm
Port Wall Thickness (PWT)	5 mm	10 mm
Valve Diameter - mm	Int-45.5	Int-49.5
	Exh-43.5	Exh-47.5
Injector Bore Wall Thickness	5 mm	10 mm

From these ten factors, a full factorial study would require creation and analysis of 1,024 models, which would have been prohibitively large in scope within available budget and schedule constraints. Therefore, a Resolution V fractional factorial design was chosen as the most effective way to conduct the parametric study. As a result, the number of models required for the base DOE was reduced to 128. Eight additional parameters were ultimately identified to be analyzed outside the base DOE requiring eight additional CAD models. [Table 2](#) lists the revised set of additional parameters that were investigated.

Table 2. Additional Cylinder Head Parameters Evaluated

Parameter	Evaluation Levels		Level Included in DOE
Number of Decks	2	3	3
Number of Head Bolts	6	8	6
Injector Bore Diameter at Fire Deck	7 mm	14.5 mm	7 mm
Full Cast Injector Sleeve	26 mm	40 mm	None
Mid Deck Location	Low	Middle	Low
Head Height	130	150	130
Single Lower Jacket	Individual	Single	Individual
Fire Deck Cuts Between Bolt Bosses	None	1 set	None

A new process for CAD model generation and alteration was developed to minimize the time required to create each individual model. [Figure 5](#) shows an example of the parametric CAD cylinder head model.

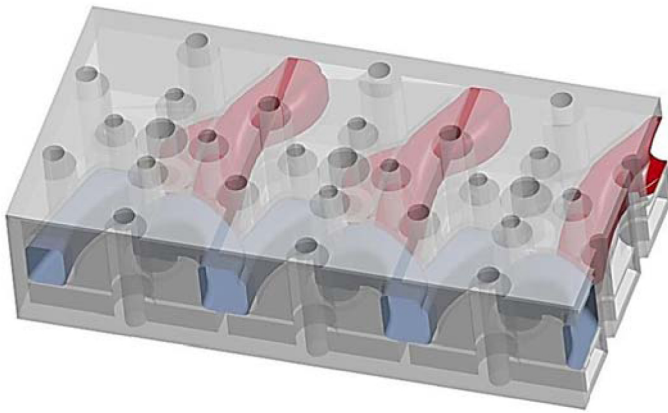


Figure 5. Example of Parametric Cylinder Head CAD Model

Structural Parameter Sensitivity Study

This task involved analyzing a matrix of geometric design parameters for the cylinder head utilizing the parametric models created previously. DOE techniques were used to design a factorial test matrix for assessing the impact of the parameters described above. The primary response variable for this study was deflection of the primary (upper and lower) decks. The full matrix of geometry treatments were analyzed using the SwRI standardized cylinder head analysis process. The only difference was that deck deflection was considered as the dependent variable rather than equivalent fully reversed (EFR) fatigue stress. The following steps were followed in conducting this sensitivity study:

1. Factorial Experiment Design: Using parameters defined above, a factorial experiment was designed to test for deck deflection sensitivity as a function of the main effects and their interactions. The experimental resolution used was sufficient to provide un-aliased 2-way interactions.
2. Structural boundary conditions were applied based on SwRI's standard process, including application of 250 bar combustion-side firing pressure to the combustion deck of each treatment.
3. The models were fully analyzed according to SwRI's standard finite element analysis (FEA) process and displacement solutions were obtained for both assembly and cylinder pressure load cases.
4. Deflection results from each replication were recorded and fed into MiniTab® for an analysis of variance (ANOVA).
5. Results from the ANOVA were used to identify the primary factors that lead to reduced deck deflection, including 2-way interactions.
6. Factor main effects and 2-way interactions were ranked according to their influence on deck deflection.

Figure 6 shows a sample contour plot of the displacement solution for the parametric DOE finite element models.

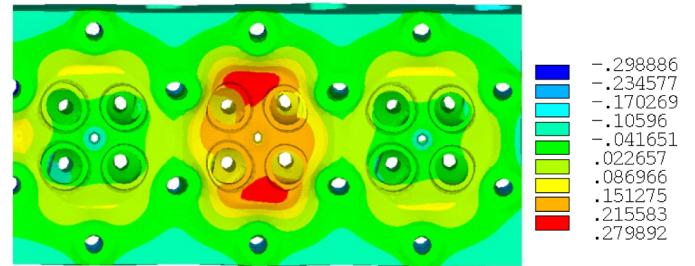


Figure 6. Plot of Vertical Displacement for Assembly and Cylinder Pressure Loading

Twelve locations were evaluated for deflection. Those locations on the primary decks are shown in Figure 7 and those located in the fuel injector bore are shown in Figure 8.

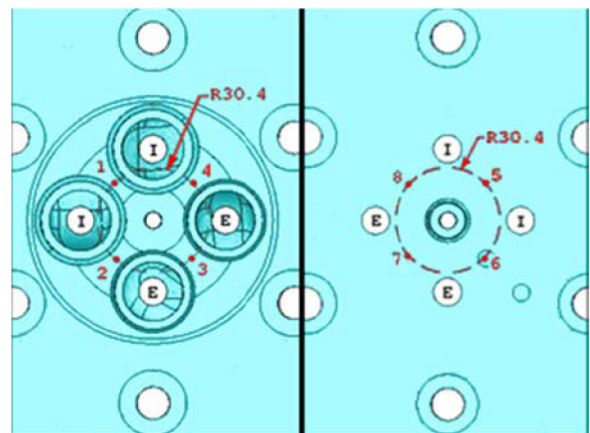


Figure 7. Deflection Locations on the Fire Deck (Left View) and Top Deck (Right View)

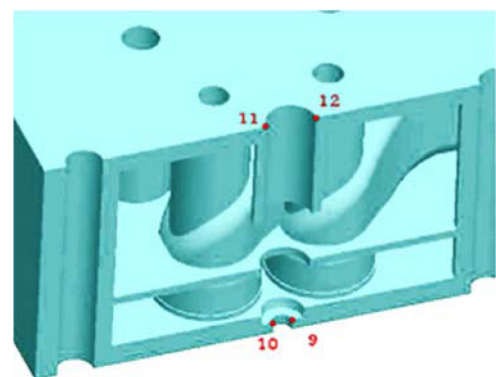


Figure 8. Deflection Locations in the Fuel Injector Bore Feature

The results obtained from the matrix of cylinder heads analyzed for the DOE are summarized in Table 3, which lists the relative effect of each variable (or interaction of variables) on cylinder head stiffness. The parameters are ranked in descending order of significance according to their

F-statistic values. Examples of several key effects are explained below.

Table 3. ANOVA Structural Stiffness Results Ranked by F-Statistic for Top 11 Factors

Source	Adj MS	F
UWJ-Upper Water Jacket	0.08503	32167
FDT-Fire Deck Thickness	0.009313	3523
MDT-Mid Deck Thickness	0.004872	1843
PWT-Port Wall Thickness	0.002952	1117
UDT-Upper Deck Thickness	0.002783	1053
EWJ-External Water Jacket	0.002624	992
UWJ*MDT	0.001198	453
UWJ*FDT	0.000978	370
UWJ*IDT	0.000765	290
PTA*UWJ	0.000231	87
PTA-Port Arrangement	0.000154	58

1). Upper Water Jacket Design (UWJ)

The two levels studied for upper water jacket design included a full upper water jacket (a water jacket that spans the full width of the head, from the exhaust side of the head to the intake side), and a half upper water jacket (a water jacket that spans only the exhaust side of the cylinder head). The analysis shows that this is the most influential of all parameters investigated and that the full water jacket provides much less stiffness than a half water jacket. This is consistent with SwRI's experience in HDD diesel cylinder head design, but is not widely practiced or accepted by industry. [Figure 9](#) and [Figure 10](#) show the full versus half upper water jacket design.

[Figure 11](#) shows the averaged fire deck deflection results at location D2 for the 64 cylinder head models with a full upper water jacket as compared to the 64 cylinder head models with only a half upper water jacket.

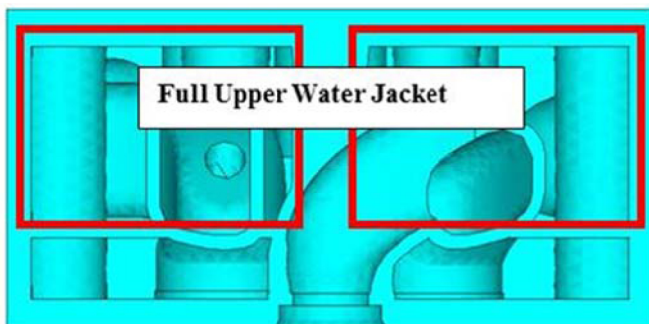


Figure 9. Cylinder Head Section View-Full Upper Water Jacket

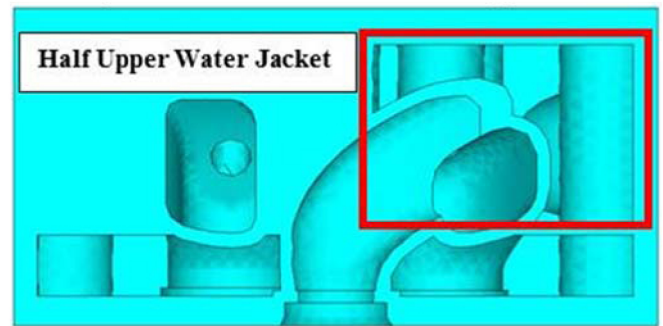


Figure 10. Cylinder Head Section View-Half Upper Water Jacket

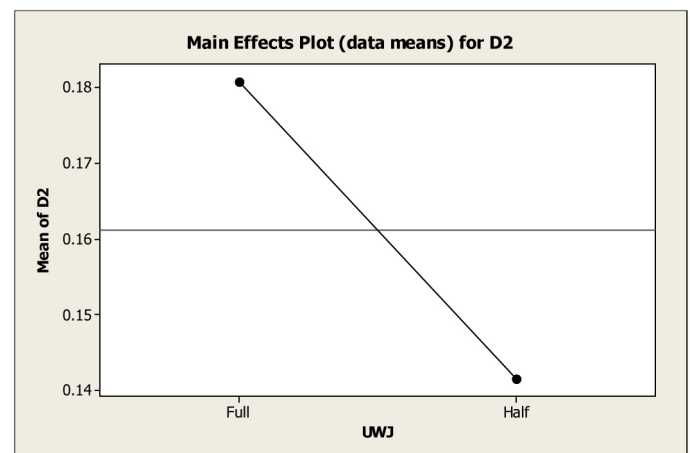


Figure 11. Main Effects Plot for Fire Deck Deflection at Location D2 for Upper Water Jacket Design Levels

2). Fire Deck Thickness (FDT)

The fire deck is the wall or deck that is exposed to combustion at the bottom of the cylinder head. The two levels included in the study were 12mm and 17 mm. The results show that a thicker fire deck is better for structural integrity.

[Figure 12](#) shows the feature that is changed to control fire deck thickness in the parametric study, in addition to MDT, PWT, and UDT.