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University Transportation Center

U35: Legacy Engine
Final Report

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16. Abstract

The Legacy engine is a new core technology that can be used with existing infrastructure providing for near term benefits while minimizing costs. Also, as a new technology, it will be optimized for many years to come providing the opportunity for continued environmental and economic benefit for the United States. Utilization of the Legacy engine will reduce Greenhouse Gas (GHG) emissions and our dependence on foreign oil, provide the United States a technological advantage in a critical market, and create thousands of "green" jobs. For the Legacy engine to achieve the predicted benefits, optimization of induction and exhaust in the engine is critical. The continued research and development will result in a commercially viable Legacy engine.

The development of an aspiration plate with optimal port geometry is the technical challenge that is addressed in the project. This project consists of design, manufacturing, testing and evaluation of port configuration for the Legacy engine aspiration plate. The results of this research will allow for the continuing development of the Legacy engine. Both inline and counter-rotational flow concepts were investigated. Two aspiration plates were designed and evaluated. Based on the results of the tests, a third aspiration plate, with optimal port geometry was designed and evaluated.

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List of Abbreviations and Acronyms

Abbreviation or Acronym	Definition
APTUS	APTUS DesignWorks, Inc.
DOE	US Department of Energy
GHG	Greenhouse Gas
ISO	International Organization for Standards
NTRCI	National Transportation Research Center, Inc.
ORT-E	Oak Ridge Tool-Engineering, Inc.
PST	Power Source Technologies, Inc.
TDC	Top Dead Center
UT	The University of Tennessee

Units of Measurement

Unit	Meaning
in.	inch
in^2	square inch
psi	pounds per square inch
rpm	revolutions per minute

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Executive Summary

Rudolf Diesel first conceived the compression ignition engine in 1892. His original intent was to burn coal dust, but he soon determined that liquid fuels were required. Since then, the diesel engine has not changed much from its original design as a reciprocating internal combustion engine. Enhancements have been made to diesel engine technology to increase efficiency and reduce emissions in recent years; however, these have largely been incremental improvements. The Legacy engine is a completely new design, transitional diesel engine, replacing the reciprocating engine with a rotary engine.

The commercial Legacy engine would provide the marketplace with a more efficient diesel engine. The benefits of Legacy's efficiency would be the reduction in Greenhouse Gas (GHG) emissions as well as the demand for oil. In a broader sense, it could reduce the United States' dependency on foreign oil, provide a technological advantage in a critical market, and lead to the creation of "green" jobs. The core technology and its deployment uses existing infrastructure which will reduce the cost and time of implementation into the marketplace.

As a new, developing technology, many future opportunities for design optimization may be available. These opportunities would provide continued environmental and economic benefit.

Background

The Legacy engine is a revolutionary, patented engine that offers significant advances over conventional internal combustion engines in 1) power to weight ratio; 2) multiple fuel acceptance; 3) fuel economy; and 4) environmental compliance. These advances are achieved through a combination of innovative design geometry, rotary motion, aspiration simplicity, and manufacturing/part simplicity. Inherent in the design with simplicity is the resultant improvement in reliability and maintainability.

The key technical challenge to the Legacy engine's commercialization, and the focus of a recent research and development project, was the development of a viable roton tip seal. Continued development of the Legacy engine would not have been possible without a solution to this challenge. Validation of the asymmetric tip seal system represents a major milestone in the development of the Legacy engine. The asymmetric tip seal system has functioned as intended and achieved compression pressures adequate for compression ignition. The importance of this achievement cannot be overstated in terms of the continuing development of the Legacy engine.

The Legacy engine relies on scavenging of the exhaust to introduce the fresh charge, similar to a two-stroke conventional engine. Aspiration of the Legacy Engine is accomplished with ports rather than valves. This eliminates a complex subsystem, which lowers cost and improves reliability. To realize these benefits of port induction and exhaust, optimal intake and exhaust port design are absolutely critical to the performance of the engine. The Legacy engine was initially designed with a counter-rotational exhaust flow. The ports in the GEN2.0 aspiration plate were very limited in both size and duration of opening.

To increase the airflow, a new aspiration plate with an inline flow was developed and tested in the GEN2.5 Legacy engine. The port size and duration of port opening were significantly increased in this version. However, the size and location of the ports allowed for cross-flow between the combustion volumes. During testing of the GEN2.5 it was observed that, without boosting, exhaust was exiting the inlet ports. Development of an intake and exhaust port design to resolve this issue and optimize the aspiration of the Legacy engine was the focus of this project.

Brief Overview

The development of an aspiration plate with optimal port geometry is the technical challenge that was addressed in the project. The PST concepts for two aspiration plates, boosted and non-boosted, were developed into manufacturable designs. Boosting refers to the capability of pressurizing the intake charge above atmospheric pressure, typically by super-charging. The two aspiration plate designs were incorporated into the GEN2.5B prototype and tested for achievable compression pressure. Combustion testing was also conducted on each design. Based on the results of testing the first two aspiration plate designs, a third aspiration plate, incorporating boosting, was designed and tested.

Research Strategy

The project was structured in two phases. Each phase was focused on the continued development of the aspiration system.

First and Second Aspiration Plate Evaluation

At the initiation of this project, two viable aspiration plate concepts had been previously developed. One concept was for a forced-aspiration port configuration without boosting, and the second concept port configuration would allow boosting of the intake charge. The first two concepts were developed into detailed designs, manufactured, tested and evaluated.

Third Aspiration Plate Evaluation

The design enhancements incorporated into the third aspiration plate were derived from the data from evaluation of the first two designs. The third aspiration plate was designed, manufactured, tested and evaluated.

An iterative strategy was taken toward optimizing the aspiration system. The strategy is shown in Figure E-1.

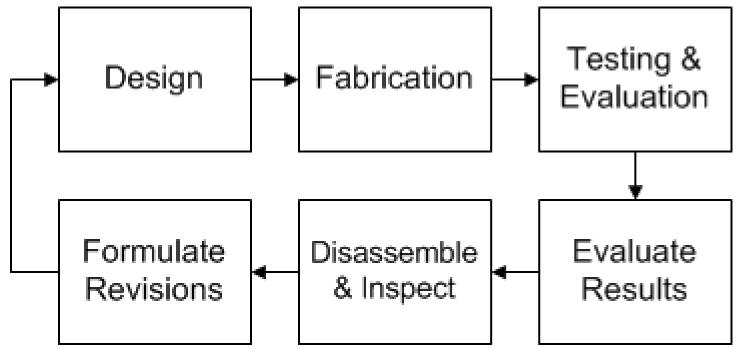

Figure E-1. Diagram. Iterative research strategy.

Conclusion

This project evaluated induction and exhaust performance of three aspiration plate designs to develop optimal inlet and exhaust port geometry for the Legacy GEN2.5 prototype engine. The resulting aspiration plate design will optimize the induction and exhaust for the GEN2.5 Legacy engine prototype and solve the design problem that this project was intended to address , allowing for development and commercialization efforts to continue.

Future Program Efforts

The development of an optimized aspiration plate, completed during this project, allows for the further research required for the continuing development of the Legacy engine. Key areas of required research and development include:

- Combustion Optimization
- Thermal management
- Subsystem Development
    - Controls
    - Fuel injection

Successful completion of research and development in these areas will lead to validation of the predicted improvements in efficiency and will provide the foundation necessary for continued development, and eventual commercialization of the Legacy engine.

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Chapter 1 – Introduction and Background

The commercial Legacy engine would provide the marketplace with a more efficient diesel engine, replacing the conventional reciprocating engine with a rotary engine. The benefits of Legacy's efficiency would be the reduction in Greenhouse Gas (GHG) emissions as well as the demand for oil. In a broader sense, it could reduce the United States' dependency on foreign oil, provide a technological advantage in a critical market, and lead to the creation of "green" jobs. The core technology and its deployment uses existing infrastructure which will reduce the cost and time of implementation into the marketplace.

As a new, developing technology, many future opportunities for design optimization may be available. These opportunities would provide continued environmental and economic benefit.

1.1 Background

The Legacy engine, depicted in Figure 1-1, is a revolutionary, patented engine that offers significant advances over conventional internal combustion engines in 1) power to weight ratio; 2) multiple fuel acceptance; 3) fuel economy; and 4) environmental compliance. These advances are achieved through a combination of innovative design geometry, rotary motion, aspiration simplicity, and manufacturing/part simplicity.

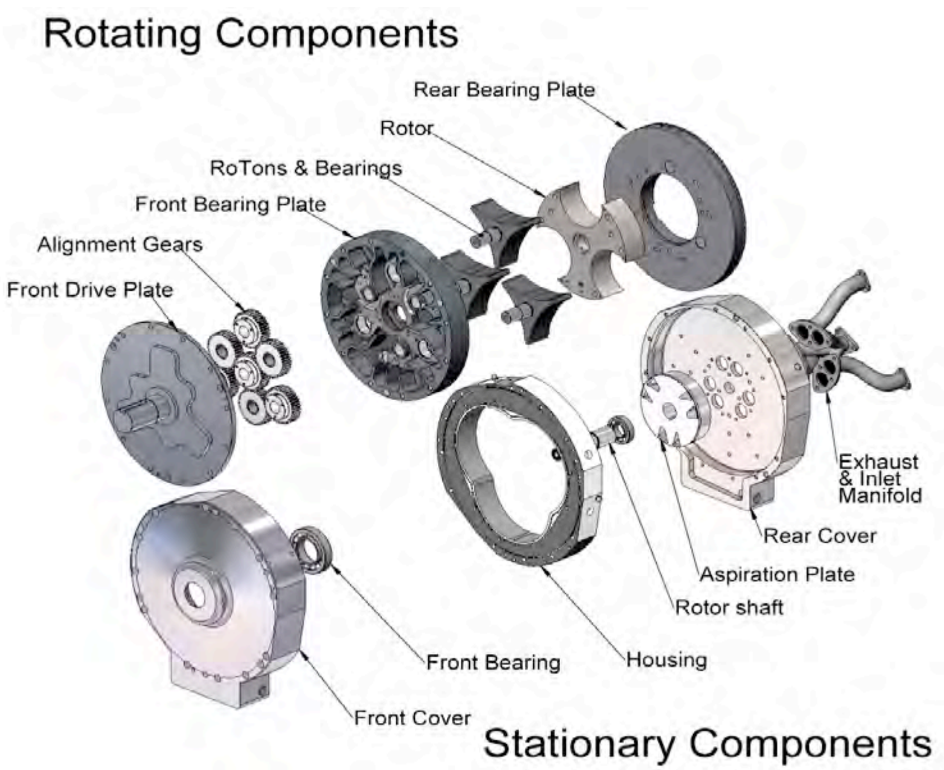

Figure 1-1. Illustration. Legacy engine exploded view.

Engine aspiration refers to an engine's ability to flow air in and out of the engine. The Legacy engine's aspiration plate is the component that controls the flow of fresh air into the engine and exhaust gases out of the engine. Size, location, and shape of the intake and exhaust ports determine several aspects of the engine. In the Legacy Engine, intake and exhaust ports are “closed” and “opened” by the moving components in the engine blocking or not blocking the port openings. The ports determine which direction air scavenges through the engine, whether or not the engine can be boosted, and can be used to tune the engine. Figure 1-2 illustrates one thermodynamic cycle of the Legacy engine. In the figure, blue indicates fresh air and red indicates combustion products. From left to right:

- Fresh air is displacing combustion products near the end of the scavenging process
- Fresh air is compressed in the compression process
- Fuel is injected near top dead center
- Combustion products expand in the expansion process
- Combustion products are expelled as fresh air is introduced near the start of the scavenging process

Figure 1-2. Illustration. One thermodynamic cycle of the Legacy engine.

1.2 Project Team

1.2.1 APTUS DesignWorks, Inc. (APTUS)

APTUS was responsible for engineering design of all of the components and design modifications. APTUS was also responsible for configuration control of the design documents.

1.2.2 National Transportation Research Center, Inc. (NTRCI)

NTRCI was responsible for overall project management, sub-contract management, cost management and reporting.

1.2.3 Oak Ridge Tool-Engineering, Inc. (ORTE)

ORT-E was responsible for fabricating, purchasing, or modifying all components required to build the prototypes as identified by the parts list provided by APTUS/PST.

1.2.4 Power Source Technologies, Inc. (PST)

PST acted as the technical lead for the project. PST had technical oversight of the design, engineering, testing, data collection, analysis and reporting.

1.2.5 The University of Tennessee (UT)

UT provided the project with professional assistance in automotive engineering, related to the evaluation and testing of the Legacy engine.

1.3 Project Description

The development of an aspiration plate with optimal port geometry is the technical challenge that was addressed in the project. The PST concepts for two aspiration plates, boosted and non-boosted, were developed into manufacturable designs. Boosting refers to the capability of pressurizing the intake charge above atmospheric pressure, typically by super-charging. The two aspiration plate designs were incorporated into the GEN2.5B prototype and tested for achievable compression pressure. Combustion testing was also conducted on each design. Based on the results of testing the first two aspiration plate designs, a third aspiration plate, incorporating boosting, was designed and tested.

First and Second Aspiration Plate Evaluation

At the initiation of this project, two viable aspiration plate concepts had been previously developed. One concept was for a forced-aspiration port configuration without boosting, and the second concept port configuration would allow boosting of the intake charge. The first two designs were manufactured, tested and evaluated.

Third Aspiration Plate Evaluation

The design enhancements incorporated into the third aspiration plate were derived from the data from evaluation of the first two designs. The third aspiration plate was manufactured, tested and evaluated.

1.4 Project Schedule

This project was conducted in the first six months of calendar 2012. Figure 1-3 is the project schedule. The tasks are identified and their lead organizations are named in Table 1-1.

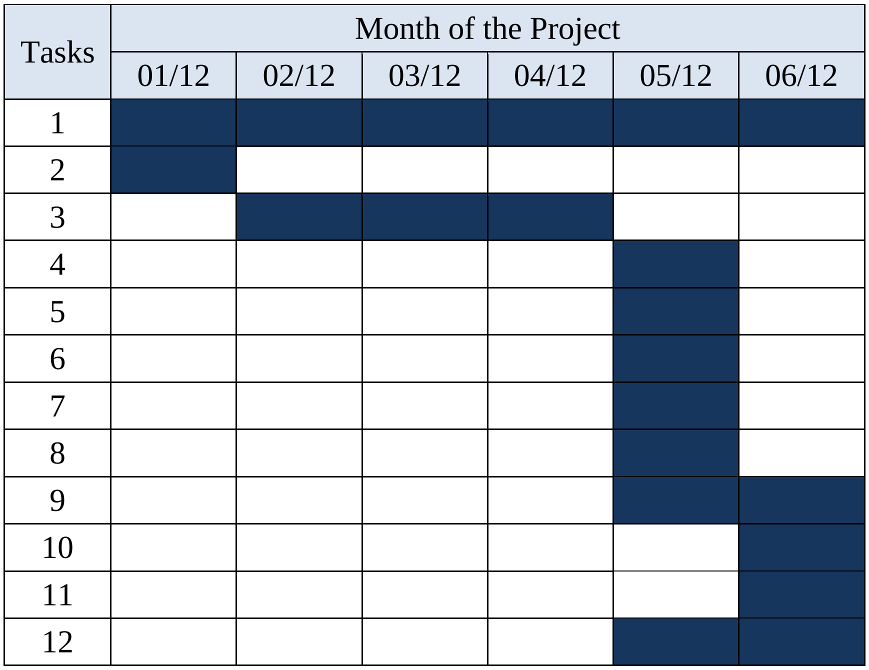

Figure 1-3. Chart. Project Schedule.

Table 1-1. Task Identification and Responsibility.

Task	Task Description	Responsible Organization
Task 1	Program Management	NTRCI
Task 2	Design two GEN 2.5B aspiration plates	APTUS
Task 3	Fabrication and Procurement	ORTE
Task 4	Assembly	PST
Task 5	First aspiration plate Testing and Evaluation	UT, PST
Task 6	Assembly	PST
Task 7	Second aspiration plate Testing and Evaluation	UT, PST
Task 8	Design optimum GEN 2.5B aspiration plate	APTUS
Task 9	Fabrication and Procurement	ORTE
Task 10	Assembly	PST
Task 11	Optimum aspiration plate Testing and Evaluation	UT, PST
Task 12	Final Project Reporting	PST

Chapter 2 – First and Second Aspiration Plates

Engine aspiration refers to an engine's ability to flow air in and out of the engine. The Legacy engine's aspiration plate is the component that controls the flow of fresh air into the engine and exhaust gases out of the engine. Size, location, and shape of the intake and exhaust ports determine several aspects of the engine. In the Legacy Engine, intake and exhaust ports are "closed" and "opened" by the moving components in the engine blocking or not blocking the port openings. The ports determine which direction air scavenges through the engine, whether or not the engine can be boosted, and can be used to tune the engine.

For a two stroke engine, intake and exhaust ports are generally not controlled by poppet valves like a four stroke engine. The ports are usually opened and closed when components of the engine uncover and cover the ports. The Legacy engine shares this trait with conventional two stroke engines.

The exhaust port is always the first port to be uncovered. This allows some of the highly compressed combustion products to evacuate before exposing the intake port. The lower the pressure is in the volume, the less work is required to pump the fresh charge into the engine. The time between the exhaust port opening and the intake port opening should be sufficient for the combustion products to blow down to nearly one atmosphere.

Unlike a conventional two stroke engine, the Legacy engine can leave the intake port open after the exhaust port is closed. This allows the Legacy engine to operate in a boosted (intake charge greater than one atmosphere) configuration.

2.1 Aspiration Plate Design

The initial scope of the aspiration plate design task was to design two aspiration plates. One aspiration plate allows for forced aspiration without the ability to generate a positive gage pressure in the intake charge. The second aspiration plate does allow positive gage pressure in the intake charge

Since the Legacy engine has no motions dedicated to pumping air in and out of the engine, there are two options for which direction air can flow through the engine during the scavenge portion of the engine's cycle. The two options are referred to as forward flow (air scavenges in the same direction as the rotor turns) or reverse flow (air scavenges in the opposite direction as the rotor turns). Reverse flow has a much more limited ability to aspirate the engine than forward flow. For this reason, all aspiration plate designs within the current project have been forward flow designs only.

The Legacy engine has a power stroke every 120 degrees of output shaft rotation. The range of motion required to fully analyze a complete aspiration cycle is 240 degrees of output shaft rotation. All analysis below is across a 240 degree range.

2.1.1 Forced Aspiration, Non-boosted Plate

The forced aspiration, non-boosted, plate (designated *A25*) allows for forced aspiration without the ability to generate more than atmospheric pressure intake charge. This occurs by leaving the exhaust port exposed the entire time that the intake port is exposed. Within these criteria, the size of each port and the time that it is exposed has been maximized. The intake and exhaust ports on the manifold side of the aspiration plate are each 1.5 in. in diameter. That gives a cross-sectional area of 1.77 in^2. On the engine side of the aspiration plate, the intake ports are 1.18 in^2. The exhaust ports are 1.51 in^2.

Below is an event summary (Figure 2-1- Figure 2-5) for one aspiration cycle of this aspiration plate. The aspiration cycle begins with the roton uncovering the exhaust port.

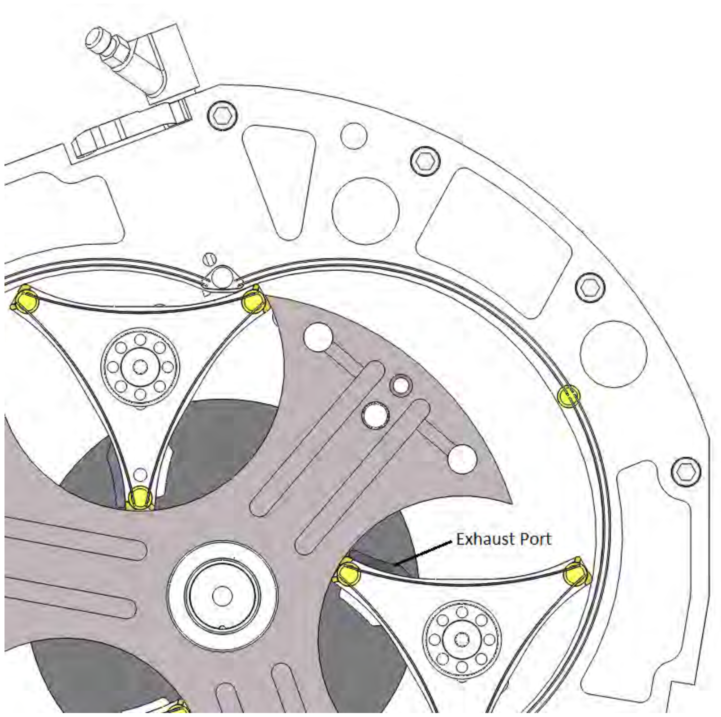

Figure 2-1. Illustration. Exhaust port opens at 98° after TDC.

Exhaust gases begin to exit the working volume through the exhaust port.

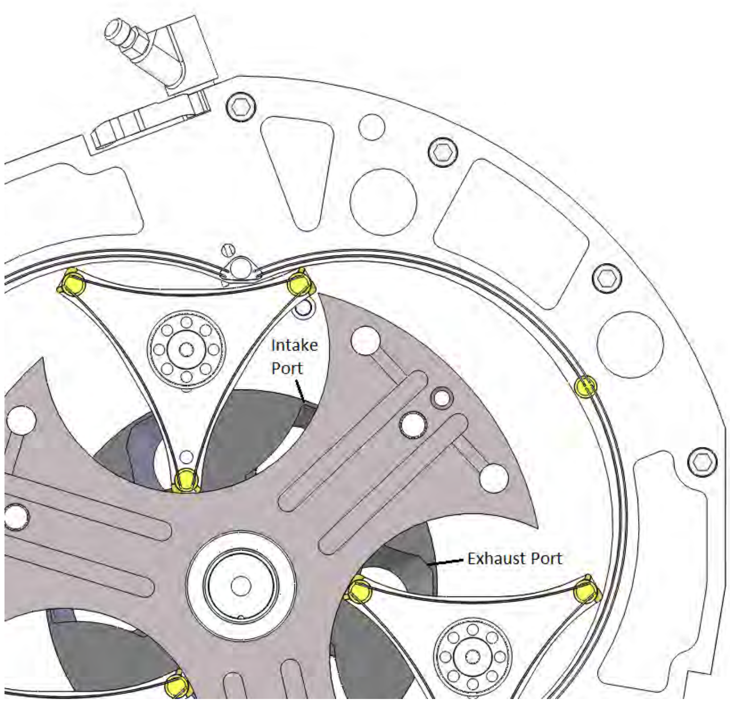

Figure 2-2. Illustration. Intake port is exposed to working volume at 106° after TDC.

Fresh charge is introduced to the working volume through the intake port, displacing exhaust gases through the exhaust port.

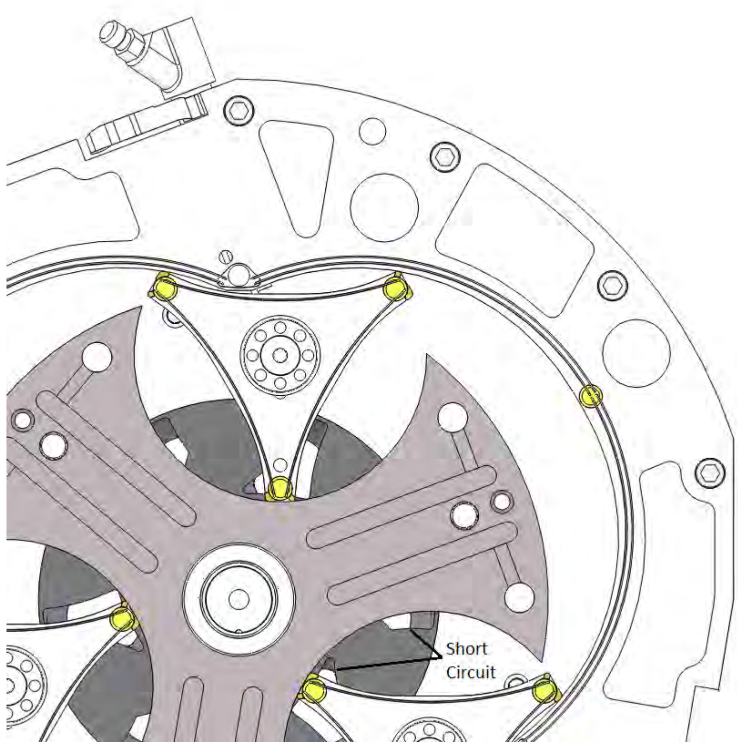

Figure 2-3. Illustration. Short circuit in dead volume exists at 125° after TDC.

The exhaust and intake ports are both open in the dead volume, which allows fresh air to pass through the dead volume. This aids cooling of the rotor and rotons.

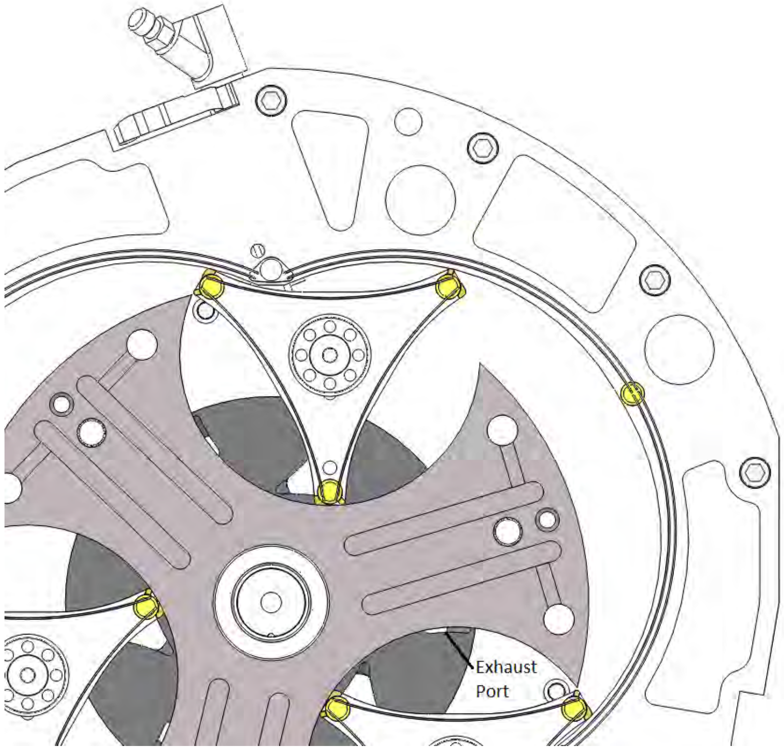

Figure 2-4. Illustration. Exhaust and intake ports close at 135° after TDC.

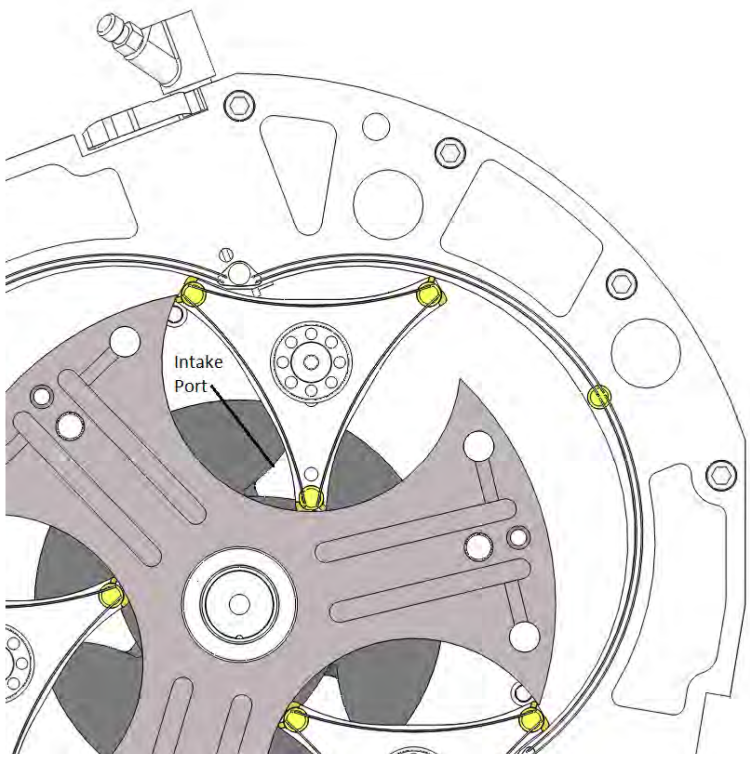

Figure 2-5. Illustration. Compression process begins with both ports closed.

Once both the intake and exhaust ports are covered, the working volume is sealed and compression of the fresh charge begins.

2.1.2 Boosted Aspiration Plate

The boosted plate (designated *A26*) allows for forced aspiration with the ability to generate greater than atmospheric pressure intake charge. This occurs by leaving the intake port exposed to the intake charge after covering the exhaust port. Within these criteria, the size of each port and the time that it is exposed has been maximized. The intake and exhaust ports on the manifold side of the aspiration plate are each 1.5 in. in diameter. That gives a cross-sectional area of 1.77 in^2. On the engine side of the aspiration plate, both the intake and exhaust ports are 1.54 in^2 cross-sectional area.

Below is an event summary (Figure 2-6 - Figure 2-9) for one aspiration cycle of this aspiration plate. The aspiration cycle begins with the roton uncovering the exhaust port.

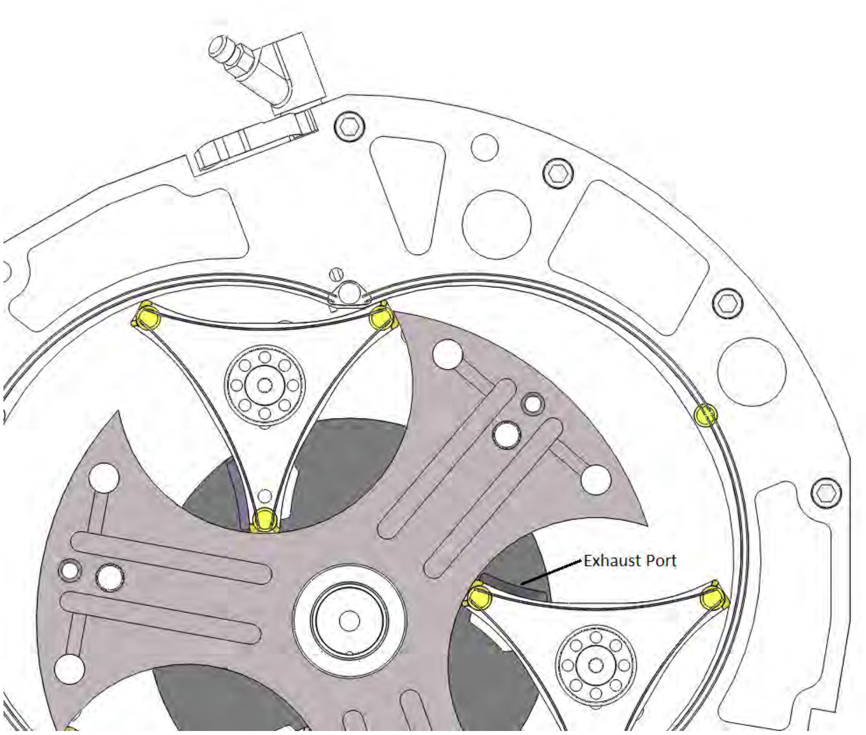

Figure 2-6. Illustration. Exhaust port opens at 98° after TDC.

Exhaust gases begin to exit the working volume through the exhaust port.

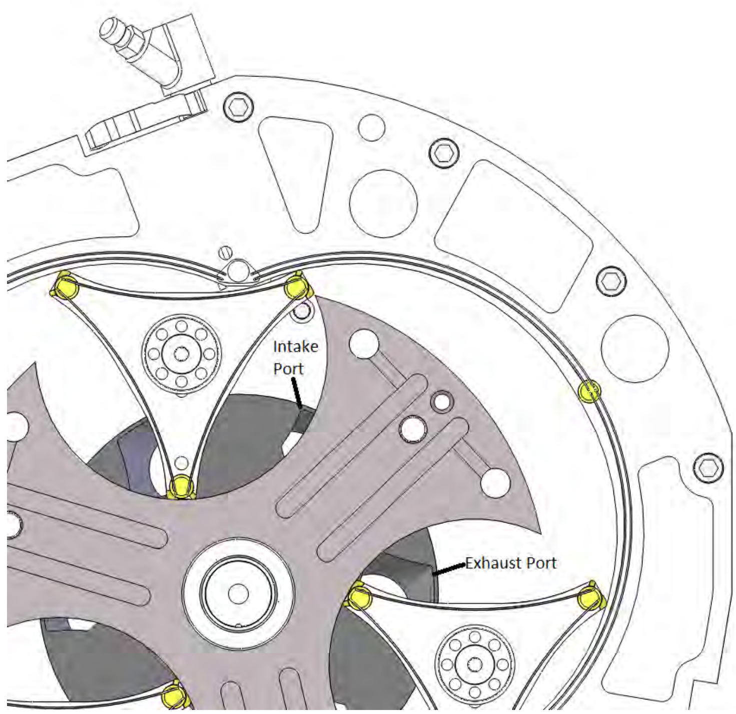

Figure 2-7. Illustration. Dead volume is opened to main volume at 106° after TDC.

Fresh charge is introduced to the working volume through the intake port, displacing exhaust gases through the exhaust port.

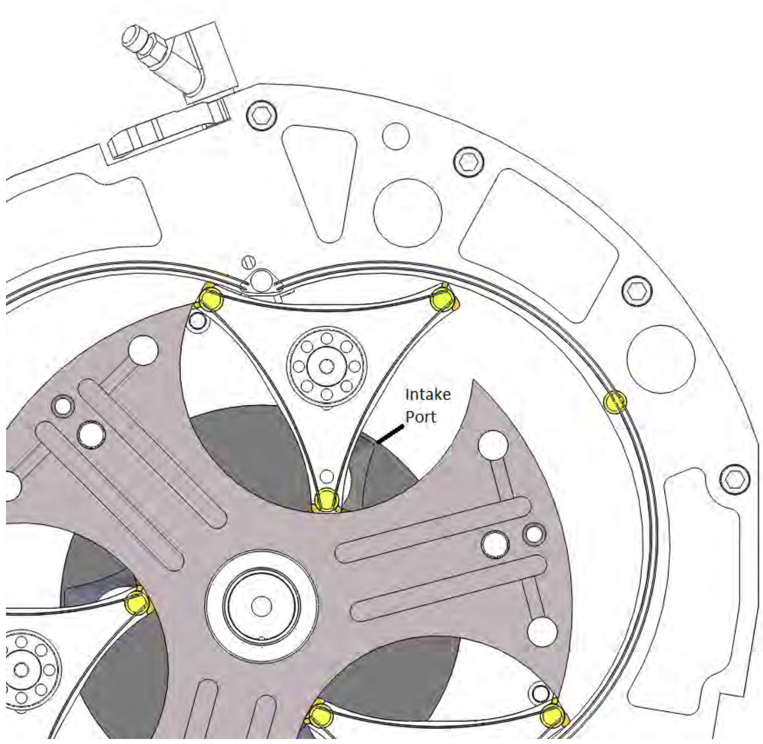

Figure 2-8. Illustration. Exhaust port closes at 135° after TDC.

The intake port is still open, allowing the working volume to be pressurized.

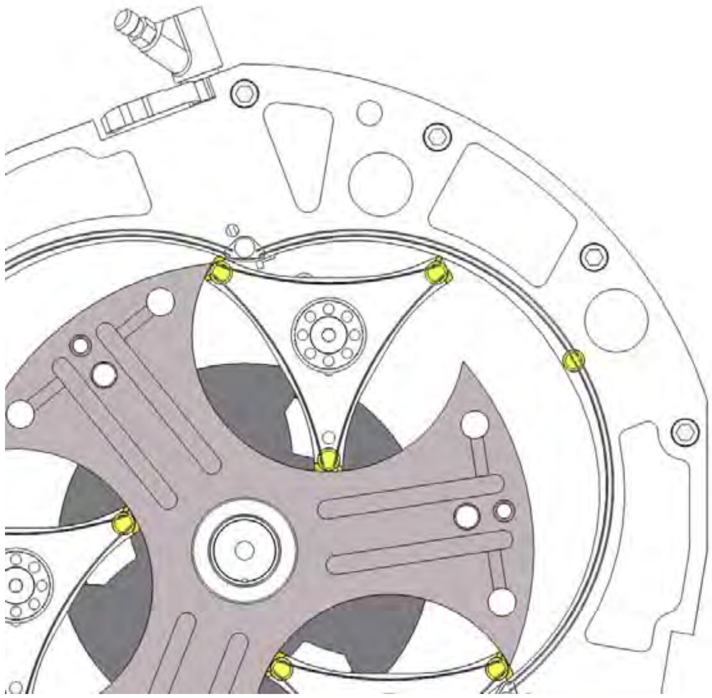

Figure 2-9. Illustration. Intake port closes at 140° after TDC and compression process begins.

Once both the intake and exhaust ports are covered, the working volume is sealed and compression of the fresh charge begins.

2.1.3 Aspiration Timing

See Figure 2-10 for graphical representation of intake and exhaust timing. The graph shows only the time (rotor degrees of rotation) when the ports open and close. The y-axis has no significance other than to separate the four port timing plots such that they may be shown on the same plot.

Figure 2-11 and Figure 2-12 show a graphical representation of the port area exposed during the aspiration cycle for the first and second aspiration plate designs, respectively. The boosted aspiration plate clearly has a larger port opening and a longer duration of opening than the non-boosted plate. This allows for increasing the amount of fresh charge introduced into the engine during the intake process.

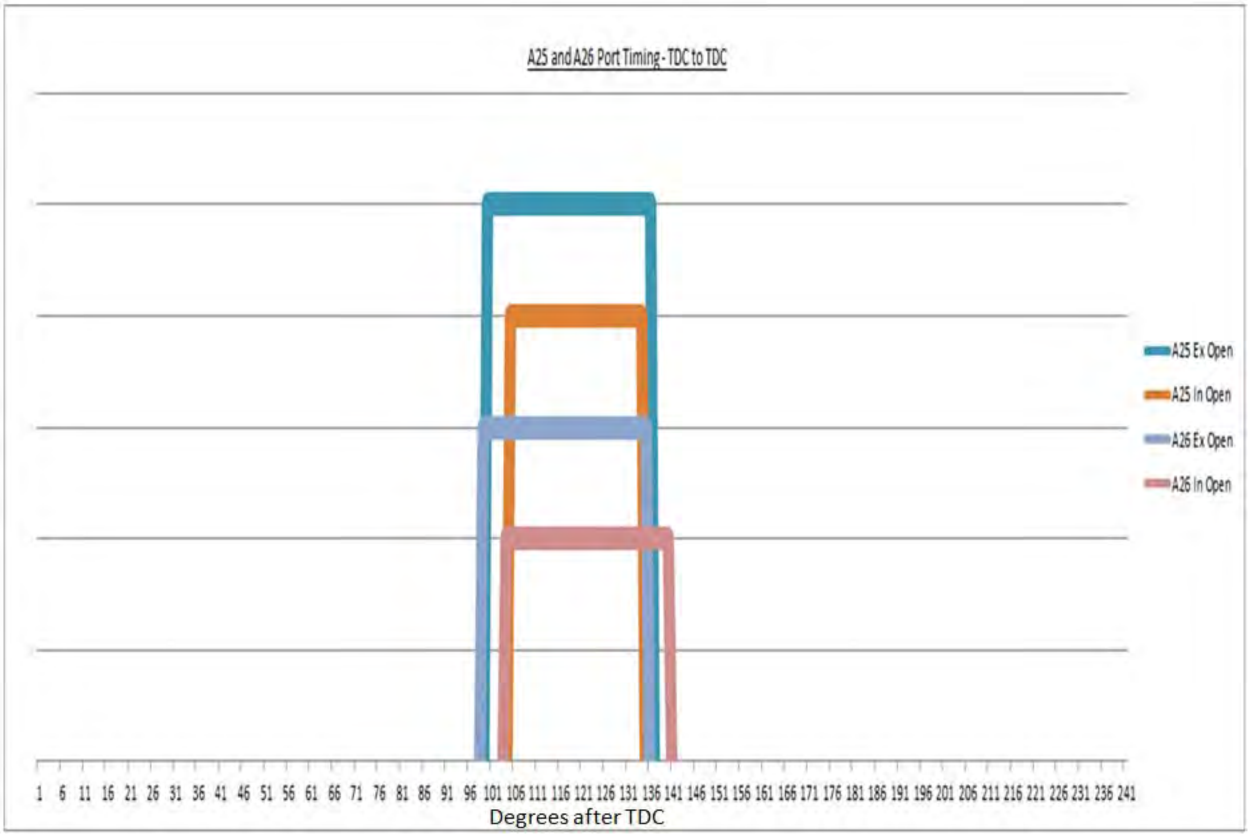

Figure 2-10. Graph. Port timing for first and second aspiration plate designs.

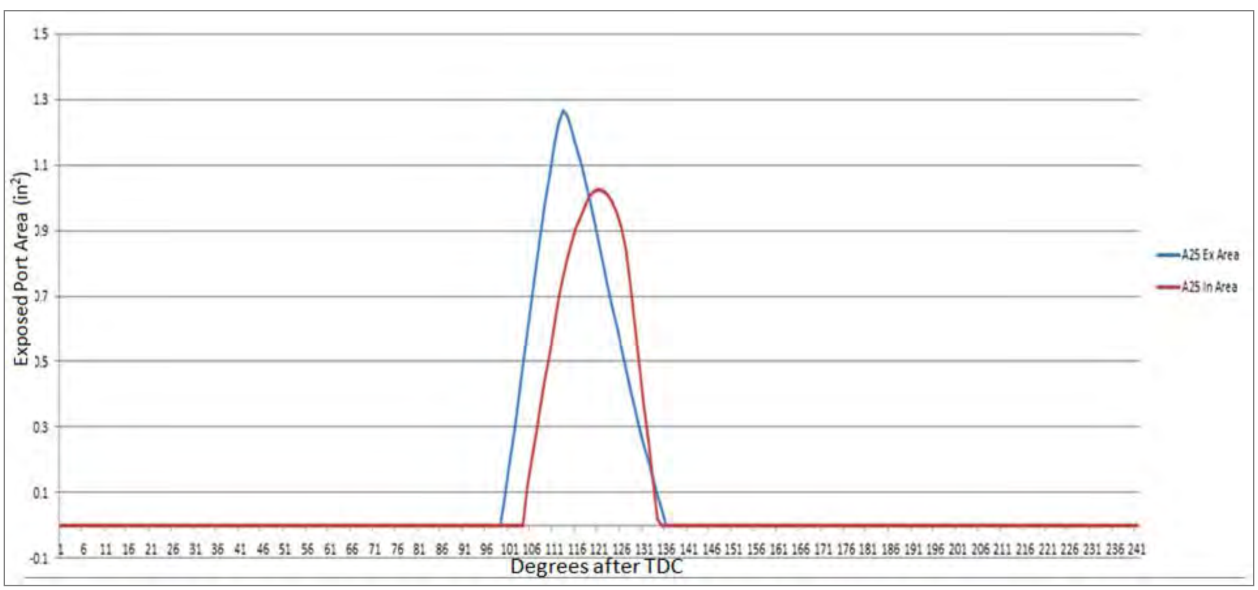

Figure 2-11. Graph. Exposed port area for first aspiration plate design.

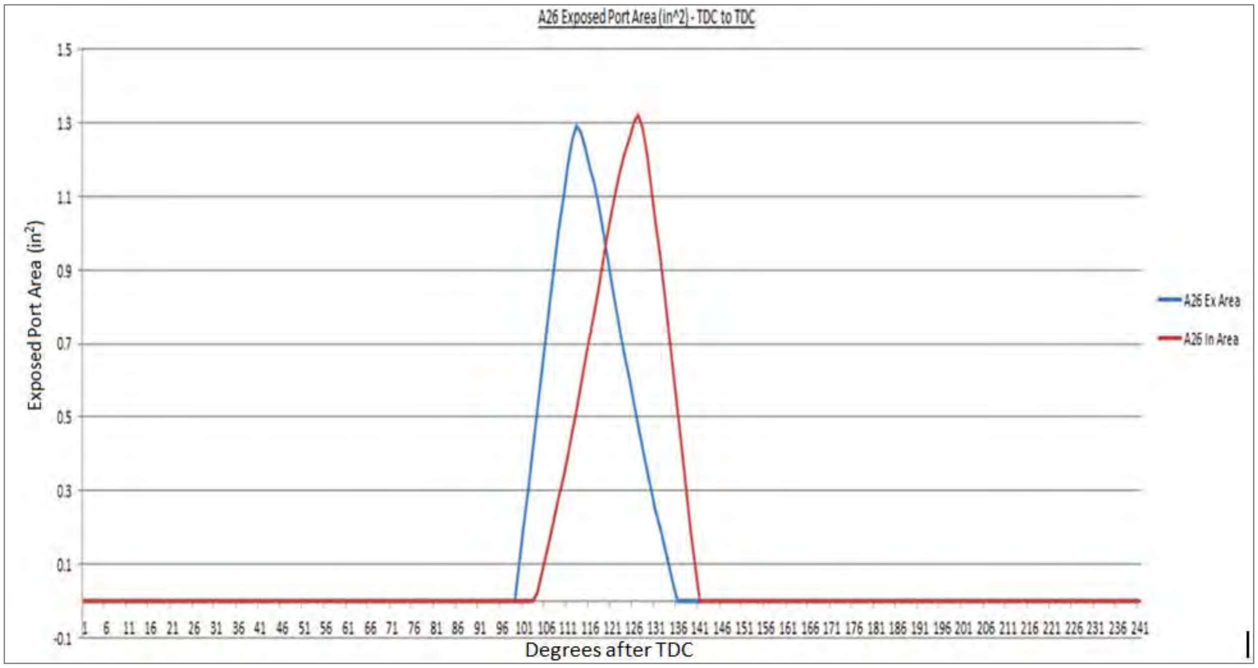

Figure 2-12. Graph. Exposed port area for second aspiration plate design.

2.2 Testing and Evaluation

2.2.1 First Aspiration Plate

The first aspiration plate was assembled into the GEN2.5B prototype and compression tested. Pressure transducers are installed in the engine to measure pressure within the working volume. These transducers are located in the leading volume and trailing volume as indicated in Figure 2-13 .

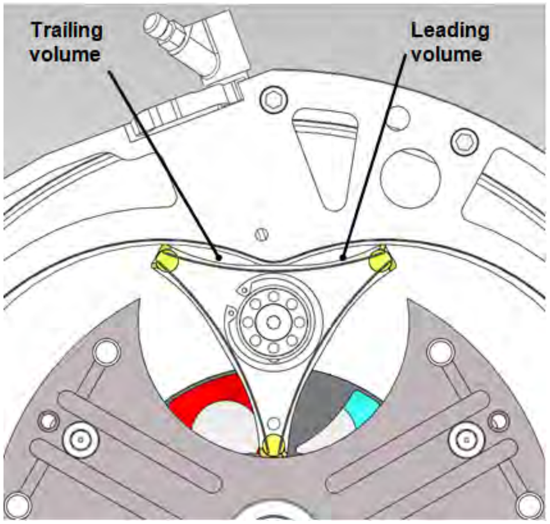

Figure 2-13. Illustration. Location of pressure transducers.

Typical results are shown in Figure 2-14. These results are consistent with results obtained with the previous aspiration plate design, although slightly lower pressures. Note that the x-axis is time based. With the engine controller installed, the rotor position signal is not available for data acquisition; therefore, the data cannot be presented based on rotor angle. However, the engine was operated at a constant speed of 600 rpm. Therefore, the relative rotor position is represented by the time-scale plots; though the absolute rotor position is not available. Also note that the pressure appears to shift lower with time; this is due to a drift in the electronics associated with the pressure transducers.

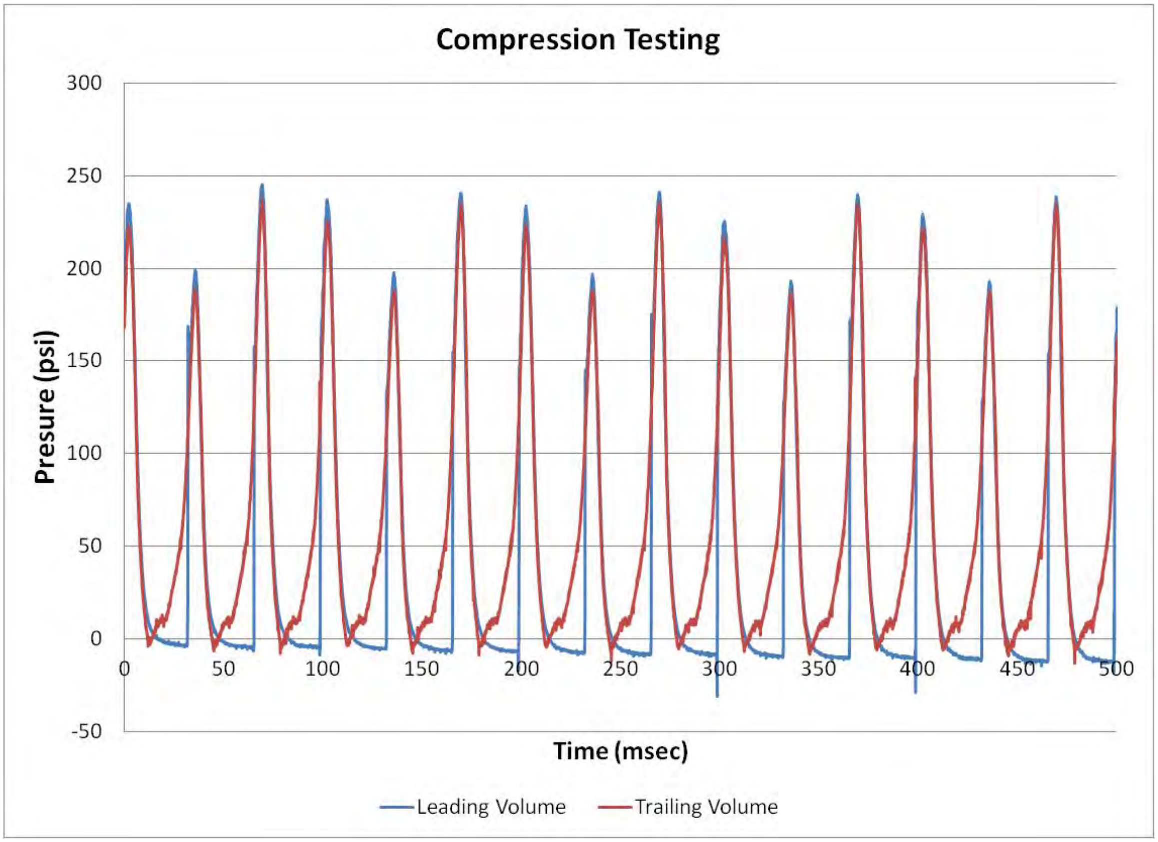

Figure 2-14. Graph. Typical compression testing results for first aspiration plate.

Combustion testing was also performed with this plate assembled in the GEN2.5B prototype. Typical results are shown in Figure 2-15. The air/fuel ratio was purposely limited to a very lean calibration. The amount of fuel injected was controlled by the injector-on time via the engine controller. The exact amount of fuel injected is not known, since the flush-mount fuel injectors have not been flow tested. The results are consistent with the compression testing results; one of the roton faces is not achieving compression pressures as high as the other two; therefore, the achieved combustion pressure is also lower.

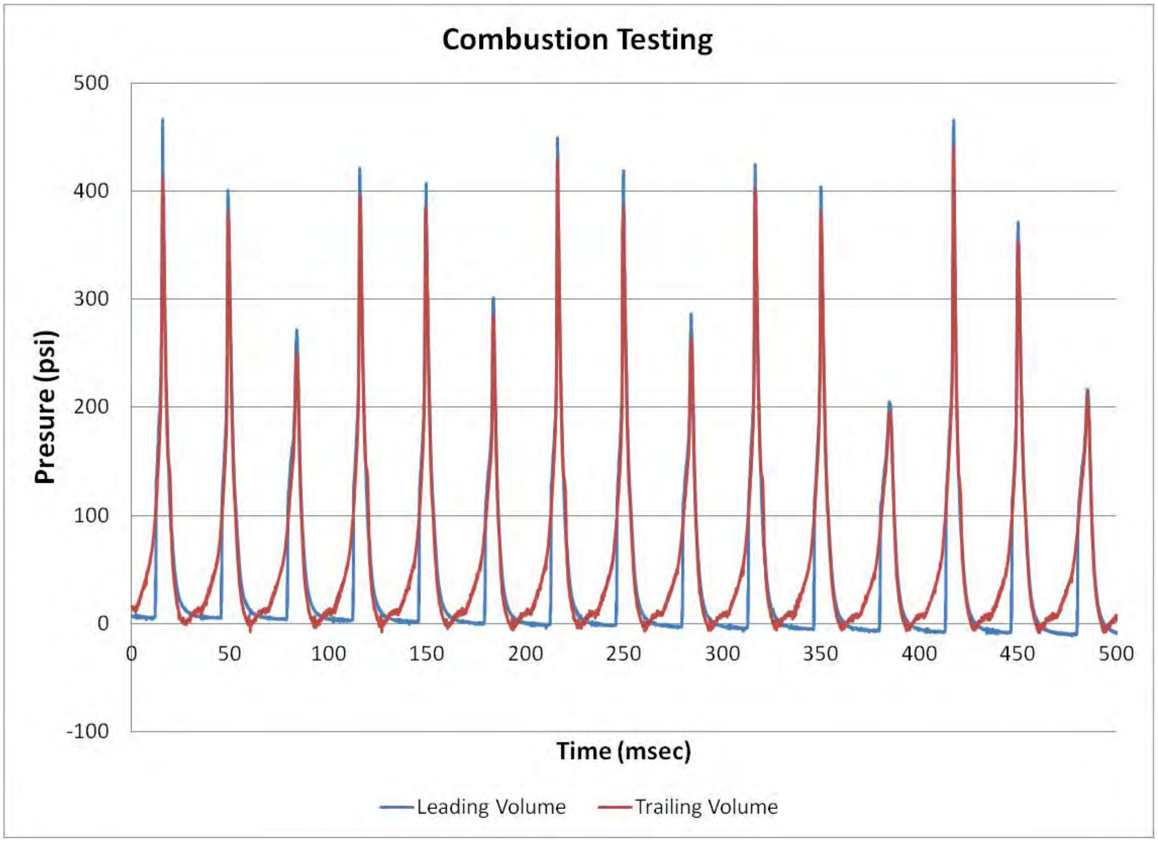

Figure 2-15. Graph. Typical combustion testing results for first aspiration plate.

2.2.2 *Second Aspiration Plate*

The second aspiration plate was assembled into the GEN2.5B prototype and compression tested. Typical results are shown in Figure 2-16. These results show approximately the same compression pressures as the first aspiration plate design; however, the boosted intake charge is evident from the trailing volume pressure trace. The pressure trace for the trailing volume shows compression beginning at approximately 10 psi.

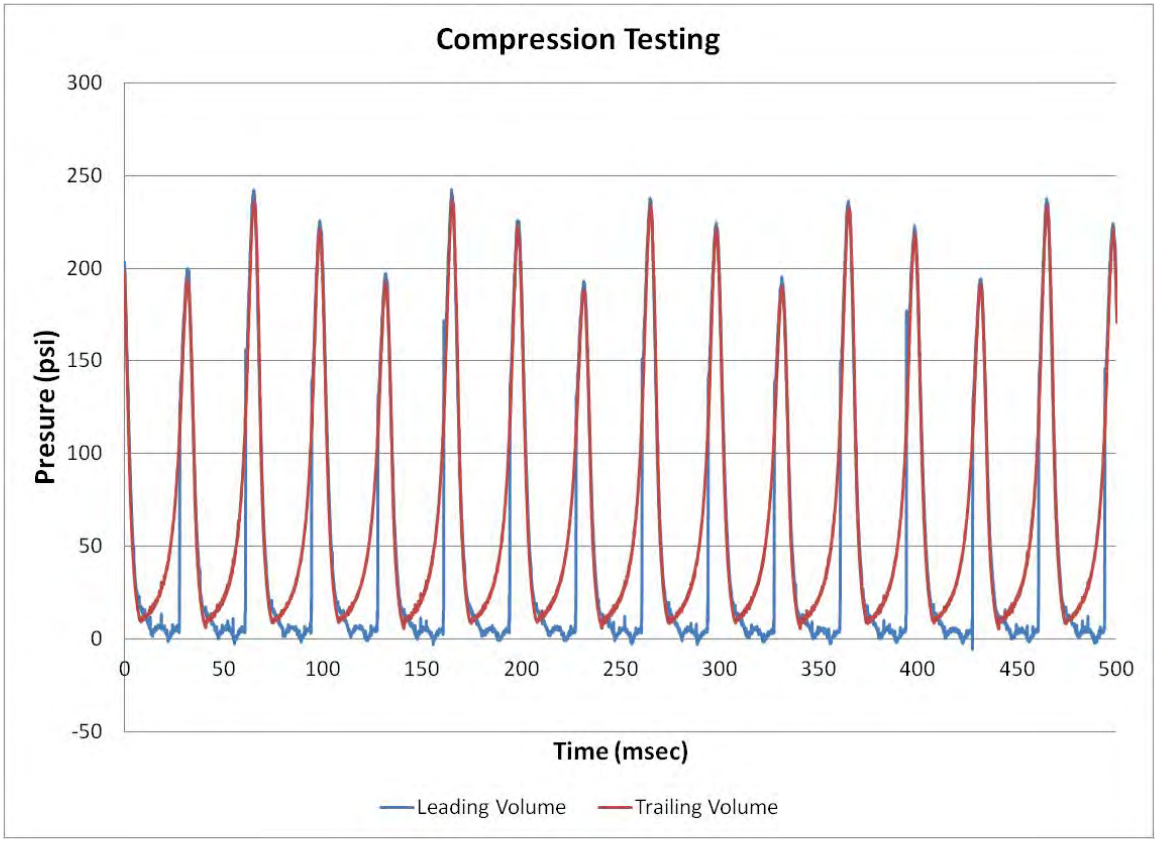

Figure 2-16. Graph. Typical compression testing results for second aspiration plate.

Combustion testing was also performed with this plate assembled in the GEN2.5B prototype. Typical results are shown in Figure 2-17. The air/fuel ratio was purposely limited to a very lean calibration. Combustion was not consistent. This was believed to be due to low pressure output from the fuel injection pump, coupled with the increase in the intake air charge due to the revised port timing. Previous combustion testing has been conducted at approximately 12,000 psi fuel pressure; however, the achievable fuel pressure was only 3000 psi for this round of testing. It is believed that the inconsistent combustion is due to poor atomization of the fuel due to the low injection pressure. Due to the short turnaround time between testing the first and second aspiration plates, the fuel injection system could not be upgraded for testing the second aspiration plate

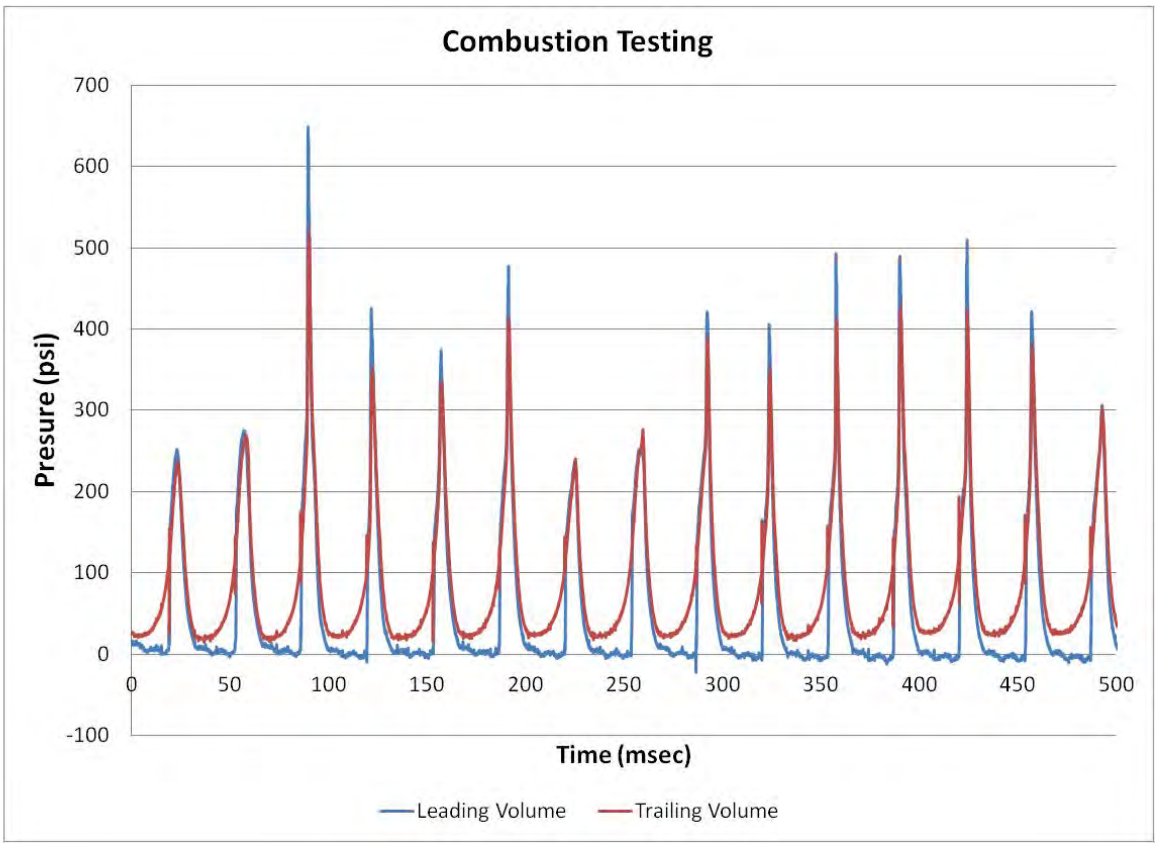

Figure 2-17. Graph. Typical combustion testing results for second aspiration plate.

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Chapter 3 – Third Aspiration Plate

The third aspiration plate created for the project has been designed based on results of testing the first two aspiration plates, designated A25 and A26. The A25 plate allowed for forced aspiration without allowing for greater than atmospheric pressure of the intake charge. The A26 plate allowed for forced aspiration and also allowed for greater than atmospheric intake charge. Testing revealed that the boosted aspiration plate is superior to non-boosted. It was also decided that more air should be allowed into, and exhaust out of, the engine.

3.1 Aspiration Plate Design

The boosted plate (designated A35) allows for forced aspiration with the ability to generate a more than atmospheric pressure intake charge. This occurs by leaving the intake port exposed to the intake charge after covering the exhaust port. Within these criteria, the size of each port and the time that it is exposed has been increased compared to the A26 plate. Increasing those areas created a compromise resulting in slightly less time for combustion product expansion. The intake and exhaust ports on the manifold side of the aspiration plate are also larger than the A26 plate, at 1.7 in. in diameter. That gives a cross-sectional area of 2.27 in^2 (28% larger than A26). On the engine side of the aspiration plate, the intake port is 1.99 in^2 cross-sectional area (29% larger than A26) and the exhaust ports are 1.75 in^2 cross-sectional area (14% larger than A26).

Below is an event summary (Figure 3-1- Figure 3-4) for one aspiration cycle of this aspiration plate. The aspiration cycle begins with the roton uncovering the exhaust port.

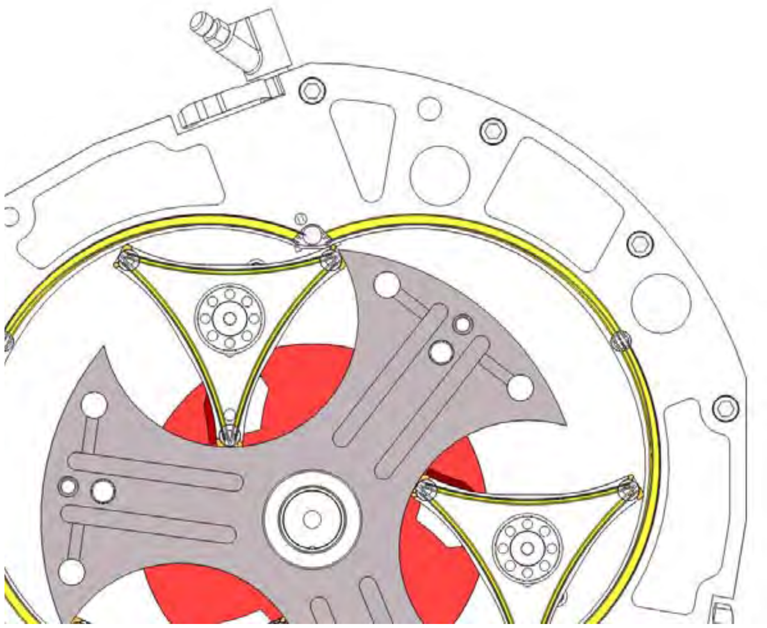

Figure 3-1. Illustration. Exhaust port opens at 96° after TDC.

Exhaust gases begin to exit the working volume through the exhaust port.

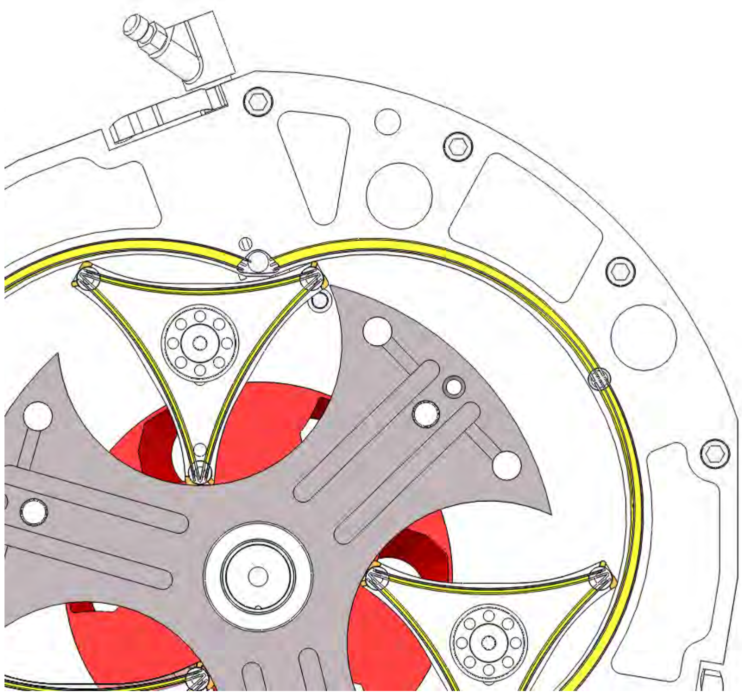

Figure 3-2. Illustration. Dead volume is opened to main volume at 106° after TDC.

Fresh charge is introduced to the working volume through the intake port, displacing exhaust gases through the exhaust port.

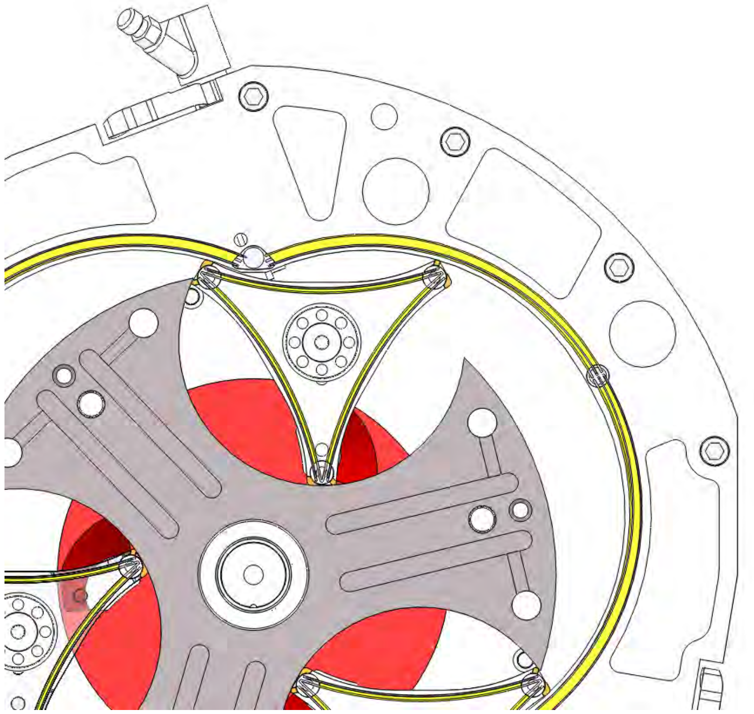

Figure 3-3. Illustration. Exhaust port closes at 135° after TDC.

The intake port is still open, allowing the working volume to be pressurized.

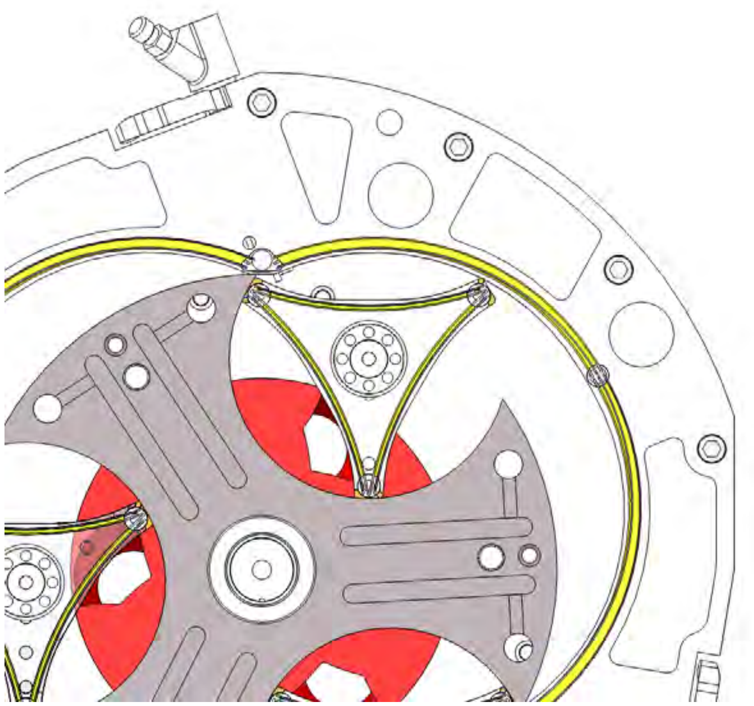

Figure 3-4. Illustration. Intake port closes at 140° after TDC and compression process begins.

Once both the intake and exhaust ports are covered, the working volume is sealed and compression of the fresh charge begins.

3.2 Testing and Evaluation

The third aspiration plate was assembled into the GEN2.5B prototype and compression tested. Typical results are shown in Figure 3-5. These results show that the intake charge is boosted above atmospheric pressure; the pressure trace for the trailing volume shows compression beginning at approximately 15 psi. This aspiration plate also produced increased compression pressure with respect to both the first and second aspiration plates.

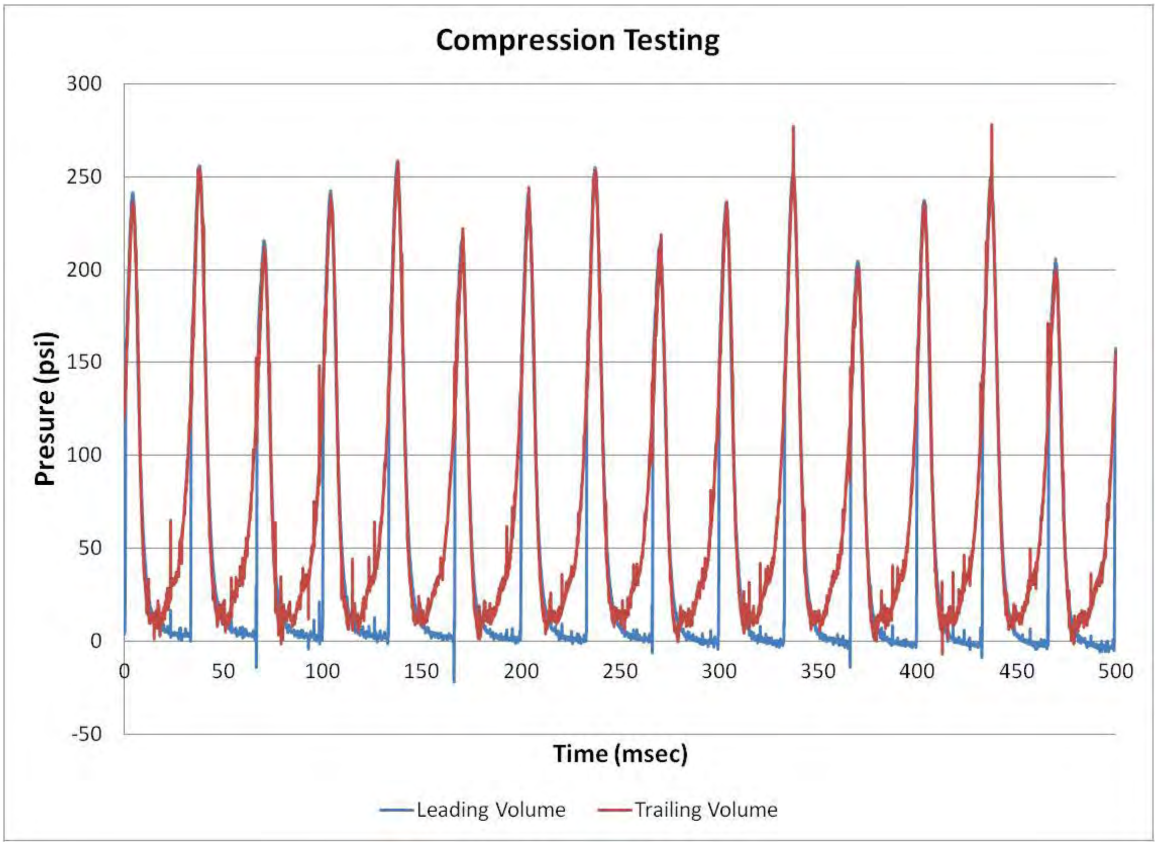

Figure 3-5. Graph. Typical compression testing results for the third aspiration plate.

Combustion testing was also performed with this plate assembled in the GEN2.5B prototype. Typical results are shown in Figure 3-6. The results are consistent with the compression testing results. As in previous testing, the air/fuel ratio was purposely limited to a very lean calibration. For this round of testing, the fuel injection system has been upgraded to achieve 12,000 psi fuel injection pressure. The combustion is more consistent; however, one of the roton faces is not achieving compression pressures as high as the other two. Therefore, the achieved combustion pressure is also lower. In fact, combustion is likely not being achieved on that roton face.

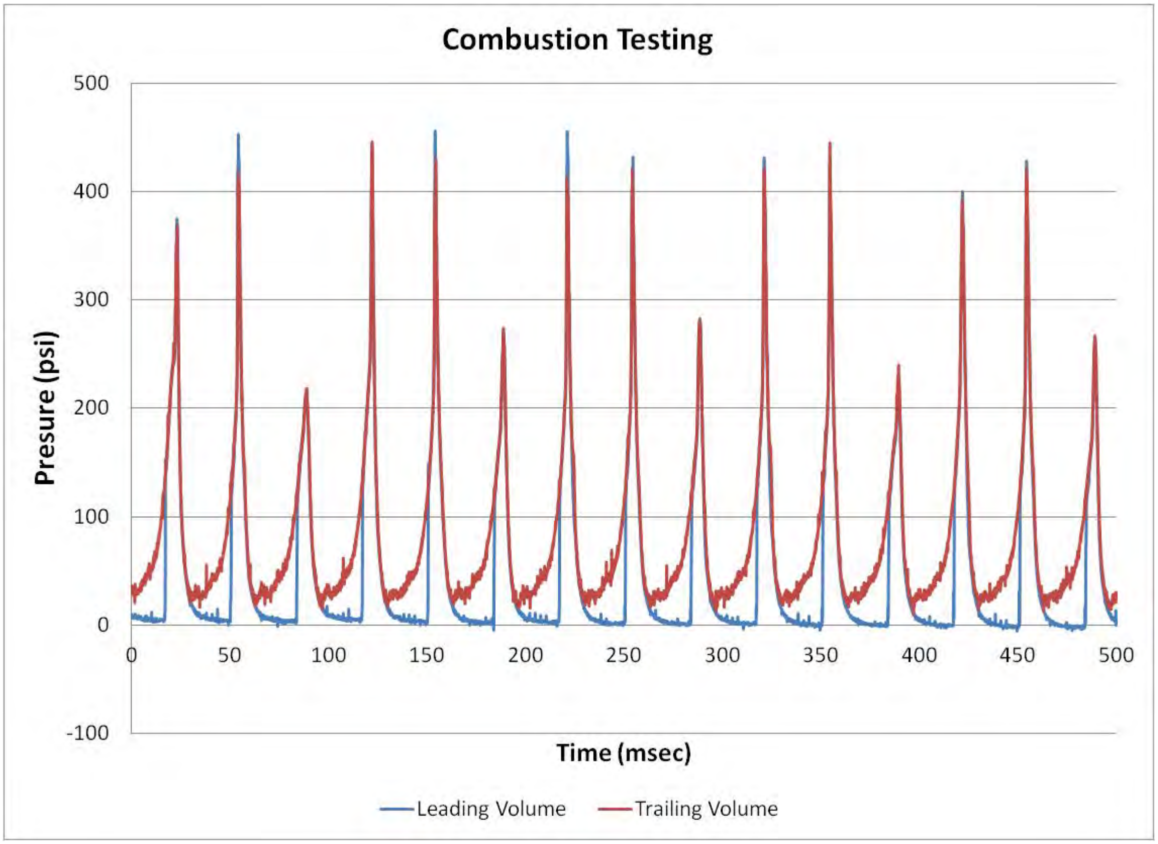

Figure 3-6. Graph. Typical combustion testing results for third aspiration plate.

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Chapter 4 – Results and Conclusions

The development of an aspiration plate with optimal port geometry has been addressed in the project. Both non-boosted and boosted port geometry were evaluated in the first and second aspiration plate designs. Based on the results of compression testing and combustion testing, the boosted design was selected for optimization in the third aspiration plate design.

4.1 Results

The first aspiration plate design exhibited essentially equivalent performance compared to the original aspiration plate in the GEN2.5B prototype. The second design produced approximately equivalent compression pressures; however, the ability to pressurize (boost) the intake charge air was demonstrated. Based on these results, the third aspiration plate was designed with increased port size and duration of opening to further increase the volumetric efficiency (the "breathing" efficiency) of the engine. The manifold-side port openings were also increased in diameter. The effectiveness of these modifications is evident in the increased intake pressure with respect to the second design.

Combustion testing of the three aspiration plate designs was also conducted. Combustion testing of the first two aspiration plate designs was conducted at approximately 3000 psi injection pressure due to problems with the injection system. These issues were resolved prior to combustion testing of the third aspiration plate design, and that testing was conducted at approximately 12,000 psi injection pressure. Combustion was inconsistent for the first and second aspiration plate designs. The combustion was improved, but still inconsistent for the third aspiration plate design.

The inconsistent combustion results are due primarily to lack of calibration data for the fuel injection system. The flush mount fuel injectors developed for this prototype are modified production fuel injector nozzles. They have had material added by welding, machined to contour, and small holes produced by the EDM process. As a result of these modifications, pertinent performance parameters of these nozzles need to be characterized. To move forward with combustion testing, the fuel flow rate of the flush-mount fuel injector nozzles needs to be characterized as a function of pressure and injector-on time. Due to the welding operation, the pintle to body interface has been altered. Even though every attempt has been made to ensure that any change was minimal, the movement of the pintle, which opens the injector for fuel to flow, has been altered. The delay time between command-to-open and actual opening also needs to be characterized.

4.2 Conclusions

This project evaluated induction and exhaust performance of three aspiration plate designs to develop optimal inlet and exhaust port geometry for the Legacy GEN2.5 prototype engine. The resulting aspiration plate design will optimize the induction and exhaust for the GEN2.5 Legacy engine prototype, allowing for development and commercialization efforts to continue.

Development of optimized port configuration for the aspiration plate has been accomplished. The aspiration plate configuration resulting from this study is particular to the configuration of the GEN2.5B. However, insight has been gained into the design criteria for optimized aspiration of the Legacy engine in general that may be applied to other configurations as they are developed for various applications. Areas requiring further research and development have been identified as described in the following section of this report.

Chapter 5 – Further Research

5.1 Overview

The development of an optimized aspiration plate design, completed during this project, allows for the further research required for the continuing development of the Legacy engine. These identified technical challenges represent only the most difficult issues that must be addressed. Numerous other challenges exist but are typical of challenges that must be addressed in any internal combustion engine development program.

5.2 Supplemental Ideas

Key areas of required research and development include:

- Combustion Optimization
  - Combustion optimization is the key to the increased efficiency predicted by our modeling and simulation. The unique geometry of the Legacy engine provides the opportunity to optimize the combustion processes and gain additional efficiencies beyond what is possible in a conventional engine. Additionally, the combustion chamber is divided into two separate volumes as illustrated in Figure 2-13 on page13. Fuel is injected into the leading volume and as the engine rotates air is forced from the trailing volume into the leading volume creating high turbulence and improved mixing. Improved mixing will result in improved combustion and lower emissions.
- Thermal management
  - Increased cooling demands are integral with unparalleled power density and high power to volume ratios. Providing the required cooling for such a compact engine design is an extreme challenge that requires an innovative approach to both the cooling system and the various materials in the engine.
- Subsystem Development
  - Controls
    - The prototype engine control system used thus far is fairly simple. It is capable of controlling the fuel injection parameters at single operating points. The injection timing and duration are real-time user inputs to the control software. For continued development of the Legacy engine, a more production-like control system must be developed that calculates and changes the control parameters based on sensor inputs.
  - Fuel injection
    - While the flush-mount fuel injector nozzle was successfully developed and demonstrated on this project, further development in combustion optimization requires research and development of the fuel injection system. Particularly, emissions compliance for compression ignition

engines depends heavily on optimizing the injection parameters (timing, duration, pressure, orifice size, etc.).

5.3 Conclusions

Successful completion of research and development in the listed areas will lead to validation of the predicted improvements in efficiency and will provide the foundation necessary for continued development and eventual commercialization of the Legacy engine.

The commercial Legacy engine would provide the marketplace with a more efficient diesel engine. The benefits of Legacy's efficiency would be the reduction in Greenhouse Gas emissions as well as the demand for oil. In a broader sense, it could reduce the United States' dependency on foreign oil, provide a technological advantage in a critical market, and lead to the creation of "green" jobs. The core technology and its deployment uses existing infrastructure which will reduce the cost and time of implementation into the marketplace.