**“Railplug Ignition System for Enhanced Engine Performance and
Reduced Maintenance”
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ABSTRACT

During the first two years of this project, four experimental subtasks were to have begun but only one of these was to have been completed. Additionally, six modeling subtasks were scheduled to begin, five of which were to have been completed. We are on schedule for all but two of these 10 subtasks.

The experimental tasks are on schedule. A second round of durability tests has been developed and testing has begun. It is too early to draw conclusions from this second round of durability testing. The test engine has been moved to a new dyno with superior controls. The baseline tests have been repeated, revealing that the engine is somewhat more dilution tolerant than originally concluded. Railplug testing has begun, but it is too early to draw any conclusions from these tests. A new railplug design was generated. It is a hybrid between the coax and parallel designs that we refer to as the semi-parallel railplug.

Development of a model for the railplug ignition process was scheduled for completion during the fourth 6-month period. This task consists of three elements. First, a railplug circuit model was developed and validated during the third 6 months. Second, an analytical model was developed for the effects of geometric and circuit parameters on the Lorentz force. From this model, it was concluded that thermal expansion is important to the performance of railplugs. Thermal expansion and other physical effects are incorporated in the numerical model that is the third element of Task 2.2. Although significant progress was made on this last model, unforeseen numerical problems were encountered due to the unusual nature of the boundary conditions for the electromagnetic force. We expect to find a solution to this problem in the near future.

We delayed the development of a 3D model for the ignition process until near the end of the project because of the computational time requirements. We can learn most of the important lessons from the 2D model. Delay of this subtask will not affect the timely completion of the project.

Progress has also been made in the technology transfer task. A third paper on the ignition process has been drafted. It will be submitted to a journal in the near future. Also, we have begun discussion with Stitt Spark Plug Company regarding commercialization of the railplug. Stitt makes spark plugs for large bore natural gas engines, and for other applications.

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1. INTRODUCTION

The US Department of Energy established the Advanced Natural Gas Reciprocating Engine (ANGRE) program to improve large-bore stationary natural gas engines. The goals of the ANGRE program are to increase fuel efficiency to 50%, decrease emissions of the oxides of nitrogen (NO_x) by a factor of 10, and decrease maintenance costs by 10%. Achievement of the efficiency and NO_x goals of the program will require use of higher boost pressures and leaner air/fuel ratios. Both factors increase the demands upon the ignition system, whereas the ignition systems currently in use – for the present gas densities at ignition and mixture strengths – often fail to meet customer expectations for performance and durability. The ignition systems currently in use are derived from automotive applications and are not designed or optimized for the higher load, leaner conditions of large natural gas engines. There is, therefore, an acute need for a more robust ignition system for big natural gas engines offering longer igniter life and better ignition characteristics.

Via the ANGRE program, DOE funded a project at The University of Texas (UT) that consists of two simultaneous tasks. The experimental task is the development of a railplug and driver-electronics system designed around the unique requirements of stationary natural gas engines. Two sequential numerical tasks are also included in this project. First, we are expanding our prior model of spark ignition from a 2D transient simulation to a 3D transient version, incorporating both plasma and flame chemistry for methane/air mixtures (the typical natural gas is more than 90% methane), and including the dynamics of the electronics circuit. This model will be useful as a new design tool for conventional spark plugs, optimizing the driver-electronics for spark plugs, and understanding ignition system dynamics and demands not only for current large bore natural gas engines, but also for future engines with higher boost pressures and air/fuel ratios. The second numerical task combines the improved spark plug model with a railplug model, to serve as an optimization design tool for development of railplugs for large bore natural gas engines.

An Executive Summary for the fourth 6-month period is provided in Section 2. The tasks are presented in Section 3. Details on the progress of each of the tasks during the fourth 6-month period are provided in Section 4. Conclusions that may be drawn from the work during this period are provided in Section 5.

2. EXECUTIVE SUMMARY

During the first two years of this project, four experimental subtasks were to have begun but only one of these was to have been completed. Additionally, six modeling subtasks were scheduled to begin, five of which were to have been completed. We are on schedule for all but two of these 10 subtasks. Each of the tasks is discussed below.

Experimental Task 1.1, development of new railplug designs, was completed on schedule, but we will generate additional railplug designs as we learn more throughout the course of this project. A new design, the semi-parallel railplug, was developed during the fourth 6-month period. This design is discussed later in this Executive Summary.

Experimental Task 1.2, durability testing, was begun but was not scheduled for completion during the first 2 years. Using a Design of Experiments approach for parallel railplugs, we completed the first round of durability testing during the third 6-month period and began a second round during the fourth 6-month period. From the initial round of durability experiments, it was concluded that the rail separation should be as small as practical and that three interactions are important: voltage and rail separation, capacitance and rail separation, and voltage and capacitance (energy). The parameters to be examined in the second set of durability experiments are rail diameter and length, void space, inductance, capacitance, charging voltage, and resistance between the capacitor and inductor.

Experimental Task 1.3, setup of the test engine, was completed on schedule. Although some conclusions were drawn from the initial experiments, it was found that the dyno controller was inadequate. The engine was moved to another dyno during the fourth 6-month period. Use of the improved control system revealed that the test engine is somewhat more dilution tolerant than was concluded from the initial experiments. Tests using railplugs have begun but data is not yet available.

Subtask 1.4, experimental railplug optimization, began 4 months into this period. We generated a hybrid design: the semi-parallel railplug. This is a coax with a ceramic tube – with a narrow channel cut completely through along its length – covering the center rail. This tube is a tight fit to both the center rail and the body, thereby allowing superior heat transfer compared to the coax. This design is also amenable to mass production. Additionally, it minimizes the mass that must be accelerated out of the railplug, like a true parallel. Finally, our decision to focus on the semi-parallel design allows us to focus our modeling efforts on a single option rather than two.

Experimental Task 1.5, tech transfer, was begun by submitting two technical papers for publication during the third 6-month period. One of these was published during the fourth 6-month period. A third paper, an extensive review of the spark ignition process including the new knowledge gained from the present study, was begun during the fourth 6-month period. Additionally, the University of Texas began discussions with Stitt Spark Plug Company regarding rights to mass production of railplugs for large bore stationary natural gas engines.

Subtask 2.1.a, development of appropriate chemical kinetics mechanisms for the ignition process, was completed during the first year of the project.

We delayed Subtask 2.1.b, development of a 3D model for the ignition process, until near the end of the project because of the computational time requirements. We can learn most of the important lessons from the 2D model. Delay of this subtask will not affect the timely completion of the project.

Subtasks 2.1.c and 2.1.d, development and validation, respectively, of a model for the dynamic response of the ignition circuit, were both completed – and important conclusions were drawn – during the third 6-month period. Additional validations of this model were planned for the fourth 6-month period, including breakdown, arc, and higher gas densities. Also, a model for a CD ignition circuit is planned for development and validation. Unfortunately, problems developed with both the current and voltage probes during the fourth 6-month period. However, these additional validations are not essential to the timely completion of the overall project.

Task 2.2, development of a model for the railplug ignition process, was scheduled for completion during the fourth 6-month period. This task consists of three elements. First, a railplug circuit model was developed and validated during the third 6 months. Second, an analytical model was developed for the effects of geometric and circuit parameters on the Lorentz force. From this model, it was concluded that thermal expansion is important to the performance of railplugs. Thermal expansion and other physical effects are incorporated in the numerical model that is the third element of Task 2.2. Although significant progress was made on this last model, unforeseen numerical problems were encountered due to the unusual nature of the boundary conditions for the electromagnetic force. We expect to find a solution to this problem in the near future.

Subtask 2.3 consists of using the models, in combination with the experimental data (Subtask 1.4), to optimize the design of the railplug. Although the numerical model is not yet complete, valuable conclusions regarding the optimization of the railplug system were generated from the circuit and analytical railplug models. These conclusions were enumerated in the progress report from the third 6 months. Open issues, to be addressed via the numerical model and experiments, are:

- (1) Is the rate of current rise or the peak current more important? That is, from the durability perspective, is it more important to get the arc to move early in the discharge or to get it to move as far as possible? This issue relates to the design of the electrical circuit.
- (2) To maximize the effects of thermal expansion on arc movement, what is the optimum design/volume of the void space? This issue relates to the railplug geometry.

3. EXPERIMENTAL AND NUMERICAL TASKS

The tasks and timelines that were incorporated in the proposal for this project are provided in Figure 1. The vertical dash-dot line highlights the first 24 months of the project. The beginning of each task is an open circle and the end is a filled circle. Vertical arrows show subtasks that feed into other subtasks. Lines that are linked (bold) feed each other throughout the duration of both. Three subtasks from the initial 18 months were extended into the fourth 6-month period (Subtasks 1.1, 2.1.b, and 2.1d). None of these three will affect the progress toward the overall project objectives. Subtask 1.1 is shown to be continuing even though we generated new railplug designs on schedule, because we will continue to improve the designs as we learn more throughout the course of the project. We have deferred Subtask 2.1b to near the end of the project because of the computational demands of the 3D simulations, whereas we can learn almost all of the needed lessons from 2D simulations. Finally, we have attracted two undergraduates who will acquire additional data to validate the model for the dynamics of the electrical circuits, but this additional validation will only verify rather than improve the model. Only one subtask was scheduled for completion during the fourth 6-month period: Subtask 2.2, completion of the railplug ignition model. We have encountered unforeseen numerical problems with this model, as discussed in Section 4. Progress on each of the tasks is discussed in Section 4.

Figure 1. Tasks and timelines. The vertical dash-dot line highlights the first 24 months of the project.

4. RESULTS AND DISCUSSION

Progress on each of the experimental and numerical tasks that were scheduled for the fourth 6-months of this project is discussed in the following two subsections.

4.A. Experimental Tasks

The experimental tasks scheduled for the fourth 6-months of the project were to: 1) continue the durability tests, 2) continue the engine tests, 3) begin optimizing the railplug, and 4) continue technology transfer.

A second round of durability tests were planned, and the testing began during the fourth 6-month period. As for the first round of durability tests, these were focussed upon parallel railplugs. The test matrix is provided in Table 1. The geometric variables for parallel railplugs to be examined in the second round are the rail diameter, rail length, and length of the void space before the initiation gap. The circuit parameters to be varied are the capacitance and inductance of the follow-on circuit, the voltage to which the capacitor is charged, and the resistance between the capacitor and inductor (this is a new circuit parameter).

Table 1. Design of Experiments Variables for Second Round of Durability Testing

	Rail diameter (mm)	Void length (mm)	Rail length (mm)	Charging voltage (V)	Inductance (μ H)	Capacitance (μ F)	Resistance (Ω)
Min.	2	0	5	100	0	100	0
Max.	5	2.5	10	250	100	800	1

The second experimental task was to continue the engine tests. However, as noted in our third 6-month progress report, the dyno that we were originally using had a controller problem. Therefore, much of the recent period was expended in moving the engine and test instrumentation to a new dyno. This transfer was completed during this period; everything is up and running again. The baseline data (conventional spark plug) were repeated, as shown in Figure 2. The improved dyno control system allowed us to maintain the desired conditions more accurately. As illustrated in Figure 2, this revealed that the engine is more tolerant of dilution than was concluded from the initial data. The Lean Stability Limit is encountered at an equivalence ratio of about 0.65 at a full load IMEP of about 3.5 bar. However, improvements in the dilution tolerance due to improved ignition should still be obvious. Tests with railplugs began during this period but no data are available at this time.

Figure 2. Baseline engine data; 1300 rpm, full load, MBT ignition timing.

Subtask 1.4, experimental railplug optimization, began 4 months into this period. As noted in prior progress reports, parallel railplugs have superior performance than coaxial designs due to an inherently greater electromagnetic effect. Also, it is easier to transfer heat away from the electrodes in a parallel design since, for the coax design, the center rail is exposed only to gases for much of the active length. The only difficulty with parallel designs is that they lack the axi-symmetric attributes that make the coax more suitable for mass production. Therefore, we have generated a hybrid design: the semi-parallel railplug. This is a coax with a ceramic tube – with a narrow channel cut completely through along its length – covering the center rail, as illustrated in Figure 3. This tube is a tight fit to both the center rail and the body, thereby allowing superior heat transfer compared to the coax. This design is also amenable to mass production. Additionally, it minimizes the mass that must be accelerated out of the railplug, like a true parallel. Finally, our decision to focus on the semi-parallel design allows us to focus our modeling efforts on a single option rather than two.

Figure 3. Semi-parallel railplug.

We also made progress on Subtask 1.5, technology transfer, during the fourth 6-month period. The tech transfer task was begun during the third 6-month period by submitting two technical papers for publication during the third 6-month period (Bhat et al., 2003a, 2003b). One of these was published during the fourth 6-month period (Bhat et al., 2003a). A third paper (Seers et al., 2003), an extensive review of the spark ignition process including the new knowledge gained from the present study, was begun during the fourth 6-month period. Additionally, the University of Texas began discussions with Stitt Spark Plug Company regarding rights to mass production of railplugs for large bore stationary natural gas engines. Stitt manufactures a variety of spark plugs for this application.

4.B. Modeling Tasks

Only one subtask was scheduled for completion during the fourth 6-month period: Subtask 2.2, completion of the railplug ignition model.

Our initial model was analytical, developed to provide some insights into the relative importance of various design factors. This model only accounted for the effects of railplug geometric factors and electronic circuit factors on arc motion due to the Lorentz force. However, as illustrated in Figure 4, this model did not yield very good agreement with experimental data for a parallel railplug. The conclusion is that thermal expansion is important. Additionally, several assumptions were used in the development of the analytical model, and these assumptions can be removed once the model is more complete.

Figure 4. Comparison of measured arc motion with the predictions of an analytical model for a parallel railplug.

Therefore, we continued the development of a numerical model for railplug ignition during the fourth 6-month period. Figure 5 represents the computational domain. The following equations govern the physical and chemical processes in a railplug:

Mass conservation

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}) \quad (1)$$

Momentum conservation

$$\frac{\partial(\rho v_x)}{\partial t} = -\nabla \cdot (\rho v_x \vec{v}) - \frac{\partial}{\partial x} \left(P + \frac{1}{2\mu_0} B_z^2 \right) \quad (2)$$

$$\frac{\partial(\rho v_y)}{\partial t} = -\nabla \cdot (\rho v_y \vec{v}) - \frac{\partial}{\partial y} \left(P + \frac{1}{2\mu_0} B_z^2 \right) \quad (3)$$

Energy balance

$$\frac{\partial E}{\partial t} = -\nabla \cdot [(E + P)\vec{v}] - \nabla \cdot \vec{q} + \frac{j_x^2 + j_y^2}{\sigma} \quad (4)$$

Electromagnetic induction equation (applied only in the conducting – plasma - region)

Figure 5. Schematic of the railplug geometry for the numerical simulations (not to scale).

To close the system, the following constitutive relations are used:

$$E = e + \frac{1}{2} \rho (v_x^2 + v_y^2) \quad - \text{Energy per unit volume}$$

$$e = \frac{P}{\gamma - 1} \quad - \text{Internal energy per unit volume}$$

$$P = \rho R T \quad - \text{Equation of state}$$

$$j_x = \frac{1}{\mu_0} \frac{\partial B_z}{\partial y} \quad - \text{Current densities in x and y directions}$$

$$j_y = -\frac{1}{\mu_0} \frac{\partial B_z}{\partial x}$$

$$\vec{B} = \frac{\mu_0}{4\pi} \int_L \frac{Id\vec{l} \times \vec{r}_{QP}}{r_{QP}^3} \quad - \text{To calculate magnetic field at the rear of the plasma}$$

Above, the symbols μ_0 and σ represent the magnetic permeability and electrical conductivity, respectively.

For the gas dynamics equations, we have ‘insulated hard wall’ boundary conditions at $x=0$ and on the electrode surfaces. For the downstream, the outflow boundary conditions shown below were used.

$\frac{\partial \rho}{\partial x} = 0, \frac{\partial P}{\partial x} = 0$	$\frac{\partial \rho}{\partial x} = 0, \frac{\partial P}{\partial x} = 0$
$\text{at } x = 0 \quad v_x = 0, \frac{\partial \rho v_y}{\partial x} = 0$	$\text{at } x = L \quad v_x = 0, v_y = 0$
$\frac{\partial E}{\partial x} = 0$	$\frac{\partial E}{\partial x} = 0$

$\frac{\partial \rho}{\partial y} = 0, \frac{\partial P}{\partial y} = 0$
$\text{at } y = \pm d / 2 \quad \frac{\partial \rho v_x}{\partial y} = 0, v_y = 0$
$\frac{\partial E}{\partial y} = 0$

The electromagnetic induction equation is solved for the conducting region, $x_{pi} \leq x \leq x_{pf}$.

$\text{at } x = x_{pi} \quad B_z = B(y), \text{ as calculated using Biot-Savart's Law}$	$\text{at } x = x_{pf} \quad B_z = 0$
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$\text{at } y = \pm d / 2 \quad \frac{\partial B_z}{\partial y} = 0$
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It should be noted that the computations start shortly at the end of breakdown, when the system has attained local thermal equilibrium (the electron and gas temperatures are equal). The initial conditions, at this time (of the order of 50 ns after the spark has jumped the gap), consist of the initial temperature, pressure and plasma channel radius (model inputs).

$\rho = \rho_\infty$
$\text{at } t = 0 \quad v_x = v_y = v_\infty = 0$
$T = T_{in}, P = P_{in}, r = r_{in}$

The assumptions in the mathematical model are:

- i- Two-dimensional geometry.
- ii- Negligible viscous effects.
- iii- Ideal gas behavior of fluid.

iv- Single fluid approximation to the plasma.

The preliminary computations used the following set of parameters and values as inputs.

$r_{electrode} = 1 \text{ mm}$	Electrode radius $r_{electrode}$, and electrode spacing d .
$d = 4.5 \text{ mm}$	
$L = 60 \text{ mm}$	Length of electrodes (since solution does not reach the end of the domain, this has no effect on the results).
$I = 40 \text{ A}$	Current (taken as constant).
$B = \mu_0 I'$	Magnetic field at the rear of the plasma with infinite rail height approximation.
$r_{in} = 0.25 \text{ mm}$	Initial value of the plasma channel radius.
$T_{in} = 8000 \text{ K}$	Initial temperature of the plasma channel.
$P_{in} = 1.82 \text{ MPa}$	Initial pressure of the plasma channel.
$T_{th} = 3500 \text{ K}$	Threshold temperature, computational cell approximated as electrically nonconducting below it.

The results for these simulations are illustrated in Figures 6-8. Figure 6 shows the temperature distributions at 30 μs and 50 μs . Figure 7 shows the corresponding velocities and Figure 8 shows the current densities. As is most obvious from Figure 8, the arc is not moving. This is the result of a numerical problem. Specifically, the boundary conditions for the electromagnetic induction equation must move with the arc (positions x_{pi} and x_{pf} change from one time step to the next). We have tried several techniques for imposing this moving boundary condition, but have not yet found a successful method. We anticipate finding a solution in the near future.

Figure 7. Axial velocity between the electrodes at $t=30\ \mu\text{s}$ (upper), and at $50\ \mu\text{s}$ (lower). Velocity in m/sec, and dimensions are in meters.

Figure 8. Ratio of the current density in the y-direction to the initial current between the electrodes at $t=30 \mu s$ (upper) and at $50 \mu s$ (lower). Dimensions are in meters.

Subtask 2.3 consists of using the models, in combination with the experimental data (Subtask 1.4), to optimize the design of the railplug. Although the numerical model is not yet

complete, valuable conclusions regarding the optimization of the railplug system were generated from the circuit and analytical railplug models. These conclusions were enumerated in the progress report from the third 6 months. Open issues, to be addressed via the numerical model and experiments, are:

- (1) Is the rate of current rise or the peak current more important? That is, from the durability perspective, is it more important to get the arc to move early in the discharge or to get it to move as far as possible? This issue relates to the design of the electrical circuit.
- (2) To maximize the effects of thermal expansion on arc movement, what is the optimum design/volume of the void space (illustrated in Figure 3)? This issue relates to the railplug geometry.

5. CONCLUSIONS

The experimental tasks are on schedule. A second round of durability tests has been developed and testing has begun. It is too early to draw conclusions from this second round of durability testing. The test engine has been moved to a new dyno with superior controls. The baseline tests have been repeated, revealing that the engine is somewhat more dilution tolerant than originally concluded. Railplug testing has begun, but it is too early to draw any conclusions from these tests. A new railplug design was generated. It is a hybrid between the coax and parallel designs that we refer to as the semi-parallel railplug.

Progress has also been made in the technology transfer task. A third paper on the ignition process has been drafted. It will be submitted to a journal in the near future. Also, we have begun discussions with Stitt Spark Plug Company regarding commercialization of the railplug. Stitt makes spark plugs for large bore natural gas engines, and for other applications.

Progress was made on the numerical model for the railplug ignition process. We encountered a problem with imposing the moving boundary condition for the electromagnetic inductance. We anticipate finding a solution to this difficulty in the near future.

The final task, not yet scheduled for completion, is the use of the railplug model together with experimental data, to optimize the design of the railplug. Although the numerical model is not yet complete, valuable conclusions regarding the optimization of the railplug system were generated from the circuit and analytical railplug models. These conclusions were enumerated in the progress report from the third 6 months. Open issues, to be addressed via the numerical model and experiments, are:

- (1) Is the rate of current rise or the peak current more important? That is, from the durability perspective, is it more important to get the arc to move early in the discharge or to get it to move as far as possible? This issue relates to the design of the electrical circuit.
- (2) To maximize the effects of thermal expansion on arc movement, what is the optimum design/volume of the void space? This issue relates to the railplug geometry.

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