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

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ABSTRACT

During the first 6 months of this project, four subtasks were scheduled. Two of these commenced earlier than originally proposed. The experimental task, development of new railplug designs, was completed on schedule. The three numerical subtasks were not completed on schedule. However, this is not expected to affect the capability to complete the overall project on schedule. Because we are early in the project, no results or conclusions were generated. Our progress included development of new railplug geometries, to be tested during the second 6 months of the project, and development of an initial 3D model. Progress was also made in development of the appropriate chemical kinetics and generation of a model for the ignition circuit.

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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 compression ratios and/or 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 ignitor 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 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.

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 6 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. Four subtasks were to have been both begun and completed during the first 6 months. Two of these subtasks began earlier than proposed (the open circles with the dashed horizontal lines leading to another open circle – where the one on the right was the originally-proposed task start schedule). Task 1.1, generation of new railplug designs, was completed on schedule; the horizontal dashed arrow simply indicates that we will continue developing new designs as we learn more throughout the course of the project. Subtasks 2.1.a-c were not completed on schedule. Progress on each of the tasks is discussed in Section 3.

Figure 1. Tasks and timelines. The vertical dash-dot line highlights the first 6 months of the project.

2. EXECUTIVE SUMMARY

During the first 6 months of this project, four subtasks were scheduled. Two of these commenced earlier than originally proposed. Our progress included development of new railplug geometries, to be tested during the second 6 months of the project, and development of an initial 3D model. Progress was also made in development of the appropriate chemical kinetics and generation of a model for the ignition circuit.

The experimental task was completed on schedule. New railplug designs were developed for both parallel and coaxial geometries. Railplugs were fabricated and ready for testing on schedule (during the second 6 months). There was no data scheduled for this task during the first 6 months.

The three numerical subtasks were not completed on schedule. However, this is not expected to affect the capability to complete the overall project on schedule. The first numerical task is development of reactions and corresponding rates that are appropriate when the gas temperature exceeds 5000 K, as occurs during the electrical energy deposition process. As the plasma cools, energy liberation occurs through reaction paths that are not incorporated in normal flame propagation chemistry. Development of this reaction mechanism is expected to be completed during the second 6-month period. The second numerical task was to convert our present two-dimensional spark ignition model into a three-dimensional model. A 3D numerical gridding scheme was generated, but no numerical runs were performed during the first 6-month period. This task must, logically, await the appropriate kinetics scheme. The final numerical task scheduled for completion during the first 6-month period was development of a model for the dynamic response of the ignition circuit. This model is essential for predicting the temperature history during electrical energy deposition. Significant progress was made in developing the ignition circuit model but it is not yet complete.

Because we are early in the project, no results were generated. It is too early to draw any conclusions from this project.

3. EXPERIMENTAL AND NUMERICAL TASKS

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

3.A. Experimental Tasks

The only experimental task scheduled for the first 6 months of the project was to generate new railplug designs. The need for this task is illustrated in Figure 2. Near the end of our prior railplug project, we operated a Champion 727 railplug in an engine to test durability. The test was run at 1000 rpm with a low load, MBT timing, and slightly lean ($AF=15.8$). We achieved 1,000,000 successful firings with 0.6 J delivered, approximately 50 times longer durability than a conventional spark plug with the same energy. However, 10^6 firings is insufficient, but we are convinced that we can do much better. Two failure modes were noted: blistering of the center electrode with > 1.0 J delivered, and center rail erosion near the initiation gap with 1.0 J or less delivered. This erosion is illustrated in Figure 2. We expected the large increase in the inductance gradient downstream of the initiation ring to accelerate the arc past the ring. Instead, the discontinuity held the arc on the downstream edge of the initiation gap. That is, there was a design flaw in the railplug used for most of our prior work – the arc did not move completely down the rails, so the energy was not spread along a large surface area but was, instead confined to $\sim 1/8''$ of the center rail.

Figure 2. The center rail of the 727 railplug eroded in the vicinity of the initiation gap.

There are two keys to durability: spreading the energy over a large surface area (arc movement) and effective heat transfer away from the center rail (insufficient heat transfer back up the center rail caused the blistering with higher energies, and also contributes to rail erosion). Making the arc move rapidly depends upon both the geometry and the electronics circuit (matching the circuit to the geometry).

Our prior railplug project was focussed upon the light-duty automotive application. This constrained us to coaxial designs for two reasons: the cost-sensitivity of the light-duty market, and the lack of “real estate” in plug bodies that are 14 mm or smaller. The 18 mm plugs used in stationary natural gas engines have a larger cross-sectional area, allowing design flexibility, and this market is much less cost-sensitive from the perspective of the cost of the ignition system and ignitors. Therefore, in the first 6 months of this project, we developed both coaxial and parallel railplug designs. The advantage of the parallel design is that the inductance gradient is higher. In turn, the increased inductance gradient yields increased plasma velocities. This is why railguns use parallel rail designs.

A generic parallel railplug is illustrated in Figure 3. The rail length, A, the rail separation, B, the spark initiation gap, C, and the rail diameter, D, were all varied for the initial designs. The values used for each dimension are provided in Table 1.

Figure 3. Parallel railplug, illustrating the dimensions that were varied for the initial designs.

Table 1. Parallel Railplug Dimensions

	electrode diameter	initiation gap	rail length	rail separation
	mm/in	mm/in	mm/in	mm/in
min.	2.36/.093	.508/.020	3.81/.015	2.54/.10
max.	3.172/.125	1.54/.060	12.7/.50	2.54/.10

Versions of the coaxial railplug designs that were generated for Subtask 1.1 are illustrated in Figure 4. The variable parameters include the diameter of the center electrode (A), the spark initiation gap (B), the electrode spacing (B+C), the tapered length of the outer electrode (D), the length of the initiation ring (E), the effective rail length (F), and the void volume (G). Table 2 lists the dimensions for these initial coax designs.

Figure 4. Coax railplug, illustrating the dimensions that were varied for the initial designs.

Table 2. Coaxial Railplug Dimensions

	center electrode diameter	initiation gap	rail separation	taper length	initiation length	effective rail length	void length
	A	B	B+C	D	E	F	G
	mm/in	mm/in	mm/in	mm/in	mm/in	mm/in	mm/in
min.	2.36/.093	.254/.010	0.635/.025	2.54/.10	1.27/.05	3.81/.15	0
max.	2.80/.110	1.54/.060	2.16/.085	12.7/.50	3.81/.15	12.83/.505	6.1/.24

3.B. Numerical Tasks

Three numerical tasks were begun during the first 6 months of this project. Each is discussed below.

Subtask 2.1.a consists of generating the appropriate ignition kinetics, including rates and transport properties. If the arc phase of ignition is sufficiently long, the gas temperature will exceed 5000 K. A long arc phase will occur in the CD ignition systems that are used on many stationary natural gas engines, and most certainly in railplug ignition systems. Thus, in addition to conventional flame propagation reactions (1000 K to perhaps 5000 K), plasma chemistry is also needed to properly describe the ignition process. We originally proposed the following plasma chemistry:

DISSOCIATION (PLASMA) REACTIONS:

NITROGEN IONIZATION AND RELAXATION REACTIONS:

It is not possible to predict kernel formation and early flame growth by simulating electrical energy deposition followed by normal flame chemistry because the extremely high plasma temperatures will produce rates of chemical energy release that are physically unrealistic. The actual path at very high (plasma) temperature is not fuel oxidation but is, instead, complete fuel dissociation (RX 1). The oxygen and nitrogen in the air are also dissociated. Reactions 1-3 are all endothermic. However, if the plasma temperature exceeds ~10,000 K, These reactions are not sufficiently endothermic to limit the plasma temperatures to physically realistic values. In this case, inclusion of the nitrogen ionization reaction (RX 4) is essential. As the plasma cools below 6000 K, recombination reactions occur:

RECOMBINATION REACTIONS:

Reactions 5-8 liberate chemical energy via a path other than via normal flame chemistry. This path is not included in any other model, but is critical.

Reactions 1, 4, and 6 are not included in flame propagation chemistry. Therefore, development of the kinetics and transport properties for these reactions and species was the focus of Subtask 2.1.a. This subtask was not as straightforward as expected. Reaction 1 is a

global reaction that incorporates a series of sequential reactions. We planned to develop the rate coefficients for this global reaction from examination of the rates for the individual reactions. However, finding the rate data for the individual reactions, valid up to plasma temperatures, proved daunting. The only difficulty for Reaction 4 was obtaining the high temperature transport properties, but this was accomplished on schedule. Reaction 6 only occurs during pyrolysis and plasma reactions. Finding rate coefficients that are valid at temperatures above 5000 K proved more challenging than expected.

Subtask 2.1.b is conversion of our 2-dimensional spark ignition model into a 3D model. In fact, we did complete a 3D model in Fluent to examine some issues. However, to simulate the ignition process, we must use a numerical scheme called Flux Corrected Transport (FCT) to assure convergence for a reacting mixture with small time step demands. Our 2D spark ignition model was built using FCT. After completing our 3D Fluent code, we began converting our 2D FCT/Fortran code to 3D. However, this conversion was not completed by the end of the first 6 month period. The dimensions used for this initial 3D model are shown in Figure 5. These dimensions were used as convenient for the purposes of this initial exploration, and do not reflect the typical dimensions for the spark plugs used in stationary natural gas engines. The 3D Fluent gridding is illustrated in Figures 6a-f.

Subtask 2.1.c, development of a model for the electronics circuit, began ahead of schedule but was more time-consuming than originally expected. However, significant progress was made, and we expect this model to be complete within the near future.

Figure 5. Dimensions used for initial 3-D model for a spark plug. In this case, the spark gap is 2 mm. Use of cylindrical coordinates requires a pie-shaped ground electrode.

Figures 6a and b. 3D geometry for a spark plug center electrode, ground strap, insulator, and body.

Figures 6c and d. Fluent surface gridding for a spark plug center electrode, ground strap, insulator, and body.

Figures 6e and f. Fluent surface gridding for a spark plug center electrode, ground strap, insulator, and body.

4. RESULTS AND DISCUSSION

Only one subtask was completed during the first 6 months of the project. New railplug designs were developed. Railplugs were fabricated and ready for testing on schedule (during the second 6 months). There was no data scheduled for this task during the first 6 months.

5. CONCLUSIONS

Because no data were generated during the first 6 months of the project, it is too early to draw any conclusions from this project. Our progress included development of new railplug geometries, to be tested during the second 6 months of the project, and development of an initial 3D model. Progress was also made in development of the appropriate chemical kinetics and generation of a model for the ignition circuit.

REFERENCES

none