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The Railplug: Development of a New Ignitor for Internal Combustion Engines

Annual Report

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Railplug Project

The goal of the railplug project is to commercialize this miniaturized railgun as an engine technology as rapidly as possible. To improve the technology transfer process, a board of industrial advisors was established. A list of representatives is included at the end of this annual report. The Railplug External Advisory Board (REAB) met in Austin on March 17-18, 1991 to discuss the project plan. A list of comments from the REAB is included at the end of this progress report, along with our written response to those comments. An alternate 'first' meeting with some representatives of the REAB was held on July 9, 1991. This meeting was attended by most of the board members who were unable to attend the first meeting. The second meeting of the REAB was held in Toronto, Canada, on October 10, 1991. A list of the board members comments from this meeting is included at the end of this report, along with our written response to those comments. These meetings have proven to be most useful in assuring that this project is conducted as efficiently as possible.

The railplug project is essentially divided into three main tasks: I) Railplug System Development, II) Application of Railplugs to Engines, and III) Railplug Durability. The status of each of these tasks is described below.

I. Railplug System Development

Railplug system development is subdivided into two categories: power supply development and ignitor development. In addition to these two categories, there is also a significant amount of work in progress to standardize the evaluation techniques used to measure railplug system performance. These issues are described below.

I.a. Power Supply

The railplug requires a high voltage spike to break down the gap between the rails followed by some sustained voltage to drive the arc down the rails. Two power supplies have been developed that fulfill these requirements, a parallel circuit supply and a series injection circuit. The parallel circuit utilizes a high voltage (~20 kV) ignition coil in parallel with relatively low voltage (<350 V) capacitors to supply the breakdown and follow-on energies to the plug. The capacitors are charged off of line voltage while an automotive battery and opening switch provide the input to the ignition coil. This circuit is simple, inexpensive, and reliable, but has the drawback of requiring a high voltage diode to isolate the low voltage capacitors from the high voltage impulse. This diode is not really a single element, but rather consists of many diodes serially connected to achieve a high standoff voltage. It has a limited average current rating, which means that high rep rates (>~20 Hz) are not attainable. The diode also consumes significant amounts of energy. The series injection circuit eliminates the need for the diode because the high voltage and low voltage parts of the circuit are connected serially with the railplug. The difficulty with this circuit is that the coil that is used to generate the high voltage breakdown spike must be rated to carry high currents through its secondary winding. This requirement precludes the use of ordinary ignition coils. A first generation, proof of principle series injection circuit was built using a readily available pulse transformer that is capable of carrying high average currents; however, later systems will require a special transformer more suited to our system needs.

Both of these power supplies have consistently discharged railplugs at pressures up to 500 psig.

I.b. Railplug Design

Two types of railplug geometries have been investigated over the course of the contract, coaxial railplugs and parallel railplugs. These designations refer to the geometry of the electrodes or rails.

Parallel railplugs, in which the arc moves out of the plug between two parallel rails, proved to be difficult to fabricate. There are several reasons for this. First, the ceramic insulator that encapsulates the rails and shields the back end of the plug from high combustion temperatures was difficult to make due to its brittle nature and non-axisymmetric geometry. Secondly, at elevated pressures it was very hard to prevent the plug from breaking down at the external connection rather than in the bore. Also, it was difficult to accurately drill the long, small holes through the breech plug insulator that captures the rails and maintains them in alignment. Finally, the welded initiation point that controls where the spark will break down could not be made consistently from one plug to the next.

For these reasons, it was decided to develop a coaxial geometry plug, in spite of the fact that a coaxial plug may suffer slightly in performance. This is because the inductance gradient (L') that is proportional to the driving force on the plasma is typically lower in a coaxial geometry than in a similarly sized parallel one (about 0.22 μH/m for the coax vs. 0.30 μH/m for the parallel). However, the consistency with which the coaxial plug can be fabricated outweighs this drawback and recommends it for evaluation. All of the problems cited above in the construction of parallel plugs are eliminated in the coaxial geometry. To date, the plugs have been made with both a low cost, low temperature plastic insulator for non-engine evaluation and a high temperature Torlon insulator for use in the engine. The design is disassemblable to allow for non-destructive inspection of the electrodes. Champion Spark Plug Company is also building a prototype coaxial geometry railplug. The Champion railplugs will be made in both a 12 mm design for use as a cold-start ignitor in the Volkswagon IDI diesel and a 14 mm design that may be used in the combustion bomb or a variety of spark ignition engines. The first of these is expected to be delivered around November 1.

Both the coaxial and parallel geometry railplugs have been successfully fired at elevated pressures (up to 500 psi), high rep rates (> 20 Hz), and in an engine environment. The co-axial plugs will remain the primary choice for engine and combustion bomb studies, but parallel plugs will continue to be made on a selected basis for specific investigations.

I.c. Railplug System (Test and Evaluation)

We are currently developing standardized tests to use in the evaluation of different railplug and power supply configurations. This sequence of tests is designed to evaluate railplug performance before the plug is tested in an engine, thereby reducing the amount of time spent performing the more complicated and costly engine tests. In these preliminary evaluation tests, we plan to characterize plasma velocity, penetration, and impulse. While not all of the evaluation tests have been refined, the combustion bomb has been built and used extensively as an evaluation tool. Preliminary railplug testing has been performed resulting in a technical paper (appended).

II. Application of Railplugs to an Engine Environment

There are several applications for which the railplug is currently being considered for use as an ignition source. The specific engine applications which will be evaluated at UT include 1) use as a cold starting device for indirect injection diesel engines and 2) replacement of spark plugs in dilute homogenious charge (DHC) 4-stroke spark ignition engines. Several other applications have been identified and will be pursued as funding permits. UT researchers are currently working on cooperative efforts with industry to pursue these applications. These applications include methanol fueled engines (in cold weather conditions), direct injection 2-stroke engines, and gas turbine engines.

The status of the lean burn and diesel cold start evaluation efforts is provided below.

II.a. Dilute Homogeneous Charge SI Engine

Initial testing of the railplug system was performed in a single cylinder research engine. Based upon input from the external advisory board, subsequent testing is scheduled to be performed in a production-type automotive engine. Results from the preliminary testing in the research engine and the status of the production engine set-up are discussed below.

A single cylinder Cooperative Fuels Research (CFR) engine was used to compare the performance of railplugs to a spark plug and to a surface discharge ignitor. The coefficient of variation of the indicated mean effective pressure (COV of imep) was used as an indicator of performance. The COV of imep was calculated from 40 engine cycles. For near stoichiometric operation, the peak cylinder pressures were aligned at 17 degrees ATDC (which roughly corresponds to MBT timing). For lean operation, it is not possible to have both MBT timing and matched imep, so the imep's were matched, as shown in the table of engine operating conditions below.

CFR Engine Parameters

	Spark Plug		Railplug	
RPM	1000		1000	
r_c	7.5:1		7.5:1	
E_{ign} (J) [1]	~0.08		~5	
vol. eff. (%)	54		54	
ϕ	0.81	1.04	0.81	1.05
θ_{ign} (BTDC)	34	26	34	5
imep (kPa)	440	562	440	559
COV	~25	1.5	3.2	1.3
$\theta_{peak\ pres}$ (ATDC)	17	17	6	17

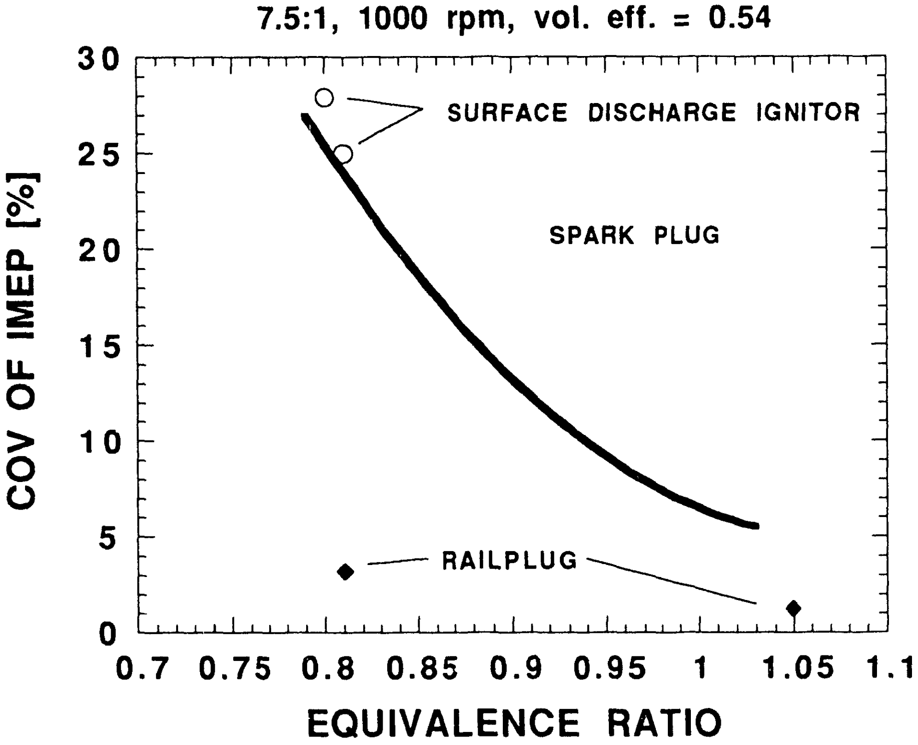
1 energy delivered to the plug is reported.

The figure presented below shows the trend of COV of imep vs. equivalence ratio using the spark plug as an ignition source. Also shown on this graph are two data points using the railplug and two data points using the surface discharge ignitor as an ignition source. These results indicate that the railplug was successful in extending the lean operating limit in the CFR engine. Additionally, the fact that use of the surface discharge ignitor did not improve the COV over that with a spark plug suggests that the amount of energy delivered to the plug is less important than the method of energy deposition (i.e. the fact that the railplug provides kinetic energy to the combustion chamber is advantageous). For lean operating conditions, comparisons of pressure-crankangle traces between spark plug and railplug ignition show the faster burn time associated with the railplug ignitor. This was also true, although to a lesser extent, for the near-stoichiometric mixture.

While these results do not necessarily prove the railplug to be a superior ignitor, they do show promise. The CFR has been extremely useful to date as a tool for both railplug development and for assessing our data acquisition capabilities. We have identified several problems with our current data acquisition system and have taken the steps necessary to purchase the correct equipment. We plan to use this new data acquisition system for production engine testing.

We are currently working to set-up our production engine test facility for railplug evaluation. A General Motors 2.2 liter 4 cylinder engine has been chosen for testing purposes and we have been working closely with GM powertrain engineers on our test plan. GM has been extremely helpful in providing both hardware and information to support this test plan. This test cell is scheduled to be operable in January, 1992, which should coincide with a more optimized railplug design.

In addition to testing the railplug in the GM 2.2 liter engine, we are currently working to test a railplug in an optically accessible engine (OAE). This OAE uses a cylinder head from the GM 2.2 liter engine and will be useful in diagnosing the effect of the railplug on flame growth in the cylinder.



II.b. IDI Diesel (Cold Start)

For this application, Volkswagen of America has donated a 1992 production model 1.6 liter IDI diesel engine. We received the engine in September of 1991 and are currently working to complete the instrumentation. Champion Spark Plugs is building a coaxial railplug for this engine. The current plan is to install the railplug in the threaded glow plug hole of one cylinder of this engine. All four exhaust ports will be instrumented with thermocouples to monitor the exhaust gas temperatures during the starting transient. Exhaust gas temperature histories from the three non-railplug cylinders will be compared with that of the railplug cylinder. This test plan represents a simple and cost-effective means for demonstrating superior cold start capabilities when using railplugs. This engine will be ready for testing in the November 1991 time frame.

III. Durability

At this point in the project, not enough information on railplug discharge characteristics is known to begin a meaningful durability assessment. We have found, as expected, that the electrode erosion is a strong function of the energy delivered to the rails. Champion Spark Plugs has indicated that they will pursue the durability issue in an engine environment when the railplug system is sufficiently developed. In the mean time, Champion is working on an electrode test experiment to evaluate electrode erosion from high energy level discharges typical of the railplug.

RAILPLUG EXTERNAL ADVISORY BOARD

COMMENTS
October 10, 1991

1. **Try to find average plasma velocity using simple techniques, rather than attempting to characterize velocity profile within the railplug bore . (e.g., use an ion probe or shadowgraphy at muzzle to measure time of flight of plasma).**

   This comment is in response to the difficulties encountered in trying to obtain velocity profiles in the bore of the plug. We understand the board's concern, but feel that we are not ready to throw in the towel on obtaining in-bore velocity information. The techniques that have been tried to date have not been fully tested, and further, it is not clear that single-point external measurements are necessarily easier (ion probe measurements have failed to date; external fiber optic measurements are only successful if the arc exits; elevated pressure testing is problematic for any probe measurement). Our feeling is that with a little more effort we can obtain the more detailed information about the velocity profile in the bore.

   Schlieron and shadowgraphy studies will of course continue to be a vital research tool.
2. **Use design of experiments techniques to aggressively manage parameter space.**

   The gist of the advisory board's suggestion was not so much that we adhere to a particular design of experiment technique (e.g., Taguchi methods), as we simply be smart about which experiments are performed and the conclucsions drawn from them. We agree. The board expressed concern that without proper planning we may be spread too thin. The example of Sugimoto, et al, in the SAE paper "Toyota Air-Mix Type Two-Hole Injector for 4-Valve Engines" was cited as a very good example of intelligent methodology.
3. **Move applications to back burner.**

   The board members present suggested performing more fundamental research with railplugs before trying to apply the technology to specific engines. We agree and are focusing our effort in this direction.
4. **Focus on energy reduction to improve electrode durability.**

   Again, we agree and will learn more about this issue as we focus on the fundamental parameters.
5. **Value of diesel cold start model to railplug advancement/commercialization is unclear.**

   While it is true that this work does not directly impact railplug commercialization, it does not consume much effort and is part of a student's doctoral dissertation. Further discussions of this model will be limited to parties interested in the topic.
6. **Continue to evaluate tradeoffs between the coaxial and parallel geometry plugs.**

   This comment emerged from the belief by some members that it may be pre-mature to discard the parallel design in favor of the co-ax, especially inasmuch as the co-ax drives a larger volume of gas at lower L'. We agree that the tradeoffs between the two designs have not yet been fully evaluated and will adress this issue in our fundamental plug studies.

In attendance at the meeting:

Board Members
- Rick Anderson (Ford)
- Tom Asmus (Chrysler)
- Norris Bassit (AC Delco)
- Dan Tribble (Champion Spark Plug)

Railplug Investigators
- Richard Faidley
- Mark Koeroghlian
- Ron Matthews
- Steve Nichols

Commercialization Reps
- James Hamann (CTDT)
- Dale Mosier (RAI)

RAILPLUG EXTERNAL ADVISORY BOARD

COMMENTS
April 12, 1991

PROGRAMMATIC

- Apply DOE (Taguchi) techniques to manage parameter space.
- Early collaboration with industrial users
- Ensure DOE buy in to REAB suggestions
- Ensure CES/CEM coordination (Formalized Structure)
- Utilize Maxwell (labs) information where applicable
- Task priorities
    1) Bomb/Optical and Jet Analysis
    2) Real Engines ASAP
    3) Real Optical Engine Studies
    4) Address Enabling Issues for Commercialization
    5) DHC Performance
        Light Load/High EGR
        WOT Knock Suppression-Low priority
    6) et. al. Analytical Tasks

COMMERCIALIZATION

- Target applications
    Low volume applications, easiest (e.g. aircraft)
    Automotive application, hardest
    IDI Diesel Volume Rapidly Diminishing
- Seek applications having lowest cost sensitivity
    - Aircraft
    - Natural gas engines

TECHNICAL

Aggressively pursue:

- Performance at pressure extremes, eg. 5-500 psia
- Materials durability (focus on applications where durability is not an issue)
- EMI control
- Electrical energy efficiency
- Focus analysis on jet fluid mechanics (not global)
- Definition of design goals - parameter space

RESPONSE TO SUGGESTIONS FROM THE FIRST MEETING OF THE RAILPLUG EXTERNAL ADVISORY BOARD

PROGRAMMATIC

1) Design of experiments to manage the parameter space.

The research team agrees that we face a significant problem in controlling the parameter space. This parameter space is divided into two parts: railplug system development and specific application development, as discussed in the following paragraphs. Initial testing of railplug designs will be performed to evaluate railplug performance while further testing will be performed to evaluate the railplug's effectiveness in a particular application. By performing initial railplug performance testing before trying them out in an engine, we hope to reduce the amount of time spent testing erroneous railplug designs in the engine environment.

To support railplug system development, we are currently developing a railplug system test and evaluation procedure. This procedure is designed to quantify railplug performance in a systematic manner. One test has been developed to evaluate plasma velocity while another test will evaluate penetration. A test that is more specific to the SI engine application has been designed to evaluate heat release in the combustion bomb. Preliminary work has shown that results in the bomb can be correlated to results in the CFR engine. We plan to create a database which can be used to correlate the various measured parameters with design changes (see attached figure). That is, plasma exit velocity, plume penetration, and heat release rate in the bomb - for pressures encountered in SI and diesel engines - will be correlated against both the railplug geometry parameters (e.g., aspect ratio, rail diameter, coax or parallel, etc.) and electronics parameters (capacitance, voltage, inductance, energy delivered, etc.). It is believed that this procedure will allow us to rapidly identify the correct directions for future modifications of both the railplugs and the electronics.

For specific application development, the project team must select the most promising applications and limit research and development to select topics and select operating conditions. Due to our previous commitments, we must continue experiments in the CFR. However, we plan to finish these experiments this semester by focusing this study. Specifically, we will examine lean operation for only a single compression ratio, engine speed, engine load combination and with only one candidate railplug and one electronics package. We will also explore knock inhibition, but only using one standard test, comparing spark plug knock characteristics with those of a single candidate railplug with a single electronics package. We will then focus our attention on only two particular applications: DHC SI engines and diesel cold start. The initial diesel cold start investigation will consist solely of examining the cold start temperature limit of a production IDI diesel. If successful, the results of this study should open the possibility for additional financial support for both IDI and DI cold start applications. Lean burn provides an opportunity to develop the railplug as an enabling technology for an application that has previously received significant effort. We will limit this study by focusing only upon three speed/load combinations for a production SI engine.

2) Early collaboration with industrial users

We also perceive this is an issue of paramount importance, and have since the outset of this project, before we even acquired funding. Our charge from the Department of Energy is to commercialize this technology as soon as possible. We recognize that we must get industry involved as soon as possible to achieve this objective. In fact, the first meeting of this Railplug External Advisory Board (REAB) not only served as part of the review of our research plans but also as an early step in the commercialization of the technology. We plan to work closely with the members of the REAB and other commercial and industrial firms both in the research and development stages. It is our hope that members of the REAB will help us not only by reviewing and guiding the research and development of the railplug but also by supporting, aiding, and guiding the commercialization efforts. If we are missing an opportunity to collaborate with industry, please do not hesitate to call to our attention how we may do so. As we develop systems with which we are comfortable for a particular application we plan to aggressively pursue commercialization potential. Additionally, we plan to include potential commercialization partners as early in the process as possible. Our present plan is discussed in the following paragraphs. However, we are still uncertain about the most fruitful means of assuring industry collaboration, and **hope that you will come prepared to discuss this issue at the next meeting of the REAB**.

As for the SI engine application, we will disseminate the results of our single cylinder "mock" production engine (see Task Priorities #2) as soon as they become available. We believe that FTP emissions testing is a task more suited to the automakers. We are already working closely with Ron Nitschke of our Advisory Board on this project, but would like to work more closely with Tom Asmus and Rick Anderson to improve the potential for commercialization for the gasoline engine application. We also hope that these results are sufficiently promising that Don McCaw, a new member of the REAB from John Deere, will help us pursue the gas engine research that could lead to commercialization.

We have received an IDI diesel from Volkswagen for our initial cold start studies. They supplied this engine due to their interest in railplugs as cold start aids. Thus, we believe that if the initial cold starts tests show promise, then we will be able to work with VW to enhance the potential for commercialization of railplugs for this application. We also hope that these results will show sufficient promise that Jim Sibley of our Board will work with us on the DI application, with eventual commercialization in mind.

We would like to perform some testing of the railplug as a cold start ignitor for alcohol fueled SI engines, however initial work in this area is probably more well suited to the combustion bomb testing. If the bomb results look favorable, we would like to explore the opportunity to perform some additional development testing with an industrial partner. We hope that our results will show sufficient potential that Scott Jorgensen, and possibly other members of our board, will become sufficiently enthusiastic that they will guide us on further alcohol fuel studies with the goal of commercialization.

We have applied for funding to explore the application of railplugs for high altitude relight of aircraft gas turbines. Because of our interest in this area, we have invited Randy Williams to be a member of the REAB, so that we can then pursue commercialization for this application as rapidly as possible.

In summary, we are now working with industry on several potential applications because we believe that this should enhance prospects for commercialization. As importantly, at least as we perceive it, we are relying on the members of our Advisory Board to aid us in commercializing this technology, if it proves promising/successful in their particular area of expertise. Again, if we are missing an opportunity to collaborate with industry, please do not hesitate to call to our attention how we may do so. **Your feedback on this topic will be genuinely appreciated.**

3) Ensure DOE Cooperation

The Department of Energy (DOE) has designated the funding for the railplug project as a "Special Grant." As such, we have broad latitude to accomplish our primary objective: research, development, and commercialization of the railplug technology. We are including

DOE in the distribution of this correspondence to assist in communications with DOE. Thus, DOE cooperation has already been assured.

4) Ensure CES/CEM coordination

From their comments, it is clear that the members of the REAB have experience in coordinating (or trying to coordinate) projects between organizations. Such coordination requires effort and attention even when the two organizations are part of one institution. We will have our share of potential problems, but we have several advantages in the coordination of CES and CEM. First, the division of responsibility between CES and CEM is based on technical expertise. Second, both centers are firmly committed to the success of the project because the top level management of both centers serve as principal investigators. Third, both CES and CEM have a full-time project engineer whose sole responsibilities involve this project and these two project engineers are in daily contact. Furthermore, during the early stages of the program, <u>all</u> project personnel meet on a weekly basis. As we are getting further into the research effort, we are finding that as the project progresses, the staff is less concerned about center affiliation and more concerned with technical progress and project success. To further assure CES/CEM coordination, three meetings are held each week. CEM has weekly staff meetings to discuss the railplug system development, while CES has weekly staff meetings to discuss progress concerning specific railplug applications. Then the Principle Investigators and Project Engineers meet weekly to discuss program issues and the technical staff from both CEM and CES attend these meetings as necessary. All parties meet together monthly.

We will continue to monitor the CES/CEM coordination and look forward to your continued feedback and suggestions on our coordination efforts.

5) Utilize Maxwell (labs) information where applicable

Just as CES is responsible for maintaining a current survey of relevant literature on engines and combustion, CEM is responsible for surveying the state of the art in pulsed power technology and electromagnetic guns. Commercial information as well as open literature sources (including pulsed power conferences, EML conferences, etc.) are included. Capacitor energy storage technology developed at Maxwell Labs is presently used in CEM laboratories, although the scale is substantially larger than required for the railplug project. We are currently using a Maxwell Labs triggered spark gap on one of the railplug power supply designs. We would appreciate more specific suggestions in this area if we are omitting additional opportunities to take advantage of Maxwell technology or other existing technologies.

6) Task priorities

PRIORITY 1 - Bomb/Optical and Jet Analysis

We agree that this task should receive the top priority. Here it should be noted that our first report on this project (presented at the Fuels and Lubes conference during which the next meeting of the REAB has been scheduled) presents the results of our initial studies in the bomb. Preliminary studies in the bomb are essential to the system development task that is currently in progress. CEM is working to develop an instrumented railplug, while the combustion bomb continues to be used as the primary development tool for CES. One piece of information that we would like to obtain from the combustion bomb experiments is the relative importance of mass and velocity on the plume characteristics. For a given amount of energy input to the railplug, we can change the plug geometry to increase or decrease the mass. We believe that in some applications, maximizing the plasma velocity will be more important than maximizing the plasma mass. We plan to use the combustion bomb to explore the limiting cases. As noted above, we plan to use the bomb to quantify the effects of the various railplug geometry parameters (e.g., aspect ratio, rail diameter, coax or parallel, etc.) and electronics parameters (capacitance, voltage, inductance, energy delivered, etc.) on the plasma exit velocity, plume penetration, and heat release rate for pressures encountered in SI and diesel engines It is believed that this procedure will allow us to rapidly identify the correct directions for future modifications of both the railplugs and the electronics.

Janet Ellzey is leading the modeling effort which will begin with the jet simulation for the combustion bomb. This modeling effort should be helpful in exploring these mass vs. velocity tradeoffs. This modeling effort is progressing well, as will be discussed at the next meeting of the REAB.

PRIORITY 2 - Real Engines ASAP

Currently, there are two "real" engines that we plan to use for railplug development. These are the General Motors 2.2 liter SI engine and the Volkswagen 1.6 liter IDI diesel. These two engines provide a test bed for the proposed SI engine and diesel cold start development work. We are pursuing these two projects as rapidly as possible, as discussed below.

SI Engine: Based on input from the advisory board, we have revised our plans with respect to SI engine testing. We are currently working to set up a production engine test facility for the 2.2 liter engine. We received this engine from Ron Nitschke early this summer. Unfortunately, we found that it had a deep scratch in the number 3 cylinder wall. We are now waiting for delivery of a new engine. In the interim, we are acquiring the instrumentation for this test facility and plan to continue testing railplugs in our CFR engine. We recognize that the CFR results may be inconclusive with respect to overall system performance because the CFR is a slow burn engine. However, we feel that it is important that the railplug be tested in an engine environment as soon as possible. Also, this is the only convenient engine for testing effects on mechanical octane. Furthermore the CFR will provide valuable system operation experience. As of August, 1991, a prototype railplug and power supply were successfully used to provide ignition in the CFR engine, as will be discussed at the next meeting of the REAB. We plan to have finished the CFR tests by the time the 2.2 engine is operable.

We expect our production engine test facility to be completed by December 1991. We currently plan to operate the 2.2 liter engine as a single cylinder engine with respect to railplugs. This will reduce the initial prototype hardware requirements and the engine can be used later for further development work as a multicylinder engine. To reduce the amount of data required for system evaluation in the GM production engine, we will map a reduced set of data points chosen from the FTP cycle. Specifically, GM has provided three speed/imep engine operating conditions that are representative of the FTP cycle for the 2.2 liter engine. These points are normally used to assess bsfc over this driving cycle, but we believe that they can serve equally well for minimizing the parameter space for the production SI engine tests. In effect, these three points represent idle, road load, and high load. We will initially focus upon the idle condition.

CI Engine: The other real engine application we are currently plan to evaluate is the IDI diesel. The diesel engine application is discussed in more detail under the "commercialization" heading. We have been trying to acquire this engine from VW for several months, but they had a difficult time obtaining one to send to us because 1992 is its first production year. This engine was finally received on

September 13, 1991. We are beginning to install it in our environmental chamber. In the interim, we have continued our efforts on cold start modeling for the eventual DI diesel application, as will be discussed at the next meeting of the REAB.

PRIORITY 3 - Real Optical Engine Studies

The optical engine with the GM 2.2 liter head will be used to allow visualization of the railplug in an engine environment. We also plan to use this engine to evaluate the effect of railplug angle on engine performance. We have been waiting for delivery of the crankcase of this engine with the dyno for over a year. It is expected to arrive during the week of September 23 (and this time we believe that it has actually been shipped). As soon as it arrives, we will begin assembling the engine and hope to be acquiring data from this engine by December.

PRIORITY 4 - Address Enabling Issues for Commercialization

We agree with the REAB that success in commercialization will come more rapidly if we develop a railplug that enables a desired technology. This is part of the justification for focusing on DHC engines. We also plan to do some bomb experiments to show the potential of railplugs for methanol engines because railplugs could be an enabling technology for this application. However, we do have some questions about how to proceed after the bomb studies of methanol ignition, and **hope to get feedback from the REAB about the future direction for this application**.

PRIORITY 5 - DHC Performance

Light Load/High EGR

We assume that these applications are assigned a high priority for real engine experiments, although this came as Priority 5 on the overall list. Our plan is to examine three load/speed combinations using the 2.2 liter SI engine, with one of these operating points simulating idle. Initially, we will vary the equivalence ratio in the railplug-equipped cylinder from stoichiometric to very lean conditions. After these experiments are completed, we will perform similar experiments using high EGR. We are currently trying to determine how to run high EGR just to the railplug-equipped cylinder. **Your thoughts on this will be appreciated**.

WOT Knock Suppression-Low priority

We have also assigned this a low priority, and thus are not planning on devoting a significant number of manhours to it. The only knock tests we currently have planned are those to be done this Fall in the CFR. As stated previously, we plan to continue railplug tests in the CFR while waiting for our 2.2 liter engine to be operable so that we can at least continue testing in an engine - even if this particular engine is not characteristic of the current state of production engines. The knock tests are quite simple and thus can easily be fit into this framework. Also, we had previously developed the appropriate software and instrumentation for these knock tests, and we hate to have wasted this effort.

PRIORITY 6 - Other Analytical Tasks

Because of the low priority assigned to this modeling task in comparison to the jet plume modeling task by the REAB, we have focused our numerical work on jet modeling. After we are satisfied with the results of the jet model and have learned as much as we can from it, then we will pursue modeling railplugs in an engine via modification of KIVA.

COMMERCIALIZATION

• Target applications

Low volume applications easiest (e.g., aircraft), automotive application hardest

We agree with the REAB completely. Thus, as discussed under "cost sensitivity" below, we have a continuing effort to attract funding for investigations of these niche applications. Nevertheless, we will simultaneously continue to pursue the automotive application because our funding focused upon this and because this application yields the highest payoff if successful, even though that payoff may not be realized in the near term.

IDI Diesel Volume Rapidly Diminishing

We were interested to learn that the number of IDI diesels entering the market is rapidly diminishing in favor of the direct injection diesel. However, further discussions with Jim Sibley of Caterpillar resulted in the conclusion that we should simply modify our plan of using the IDI diesel to evaluate the railplug as a replacement for glow plugs, since this will yield insights about the cold start benefits of railplugs for both IDI and DI diesels. Thus, we are currently planning to perform preliminary cold start tests using a Volkswagen 4 cylinder IDI diesel. This preliminary testing will not include any emissions evaluation nor will we reduce the compression ratio as originally planned. Results of this preliminary testing will be provided to the members of the advisory board as well as to Volkswagen of America, who has donated the test engine. Here, it should be noted that there are still many IDI diesels in use in Europe and the orient, and both VW and Renault have expressed sincere interest in railplugs as cold start aids for their IDI diesels. Thus, based upon these discussions with manufacturers of IDI diesels, we now perceive the IDI diesel as a potential niche application that could lead to early commercialization. However, we will not expand the IDI tests unless we receive funding specifically for this from VW or Renault or another manufacturer. That is, we hope the IDI tests will lead to early commercialization and/or to additional funding for this application, but the primary goal of these tests is as an easy initial proof-of-concept for DI diesel cold start. As an additional indication that railplugs could be beneficial for DI diesel cold start, we have generated a DI diesel cold start model, and hope to use the model predictions to further demonstrate the potential of railplugs for the DI application. Of course, the difficulty with directly demonstrating railplugs in a DI diesel is the lack of an access port, such as a glow plug hole **Your thoughts on this plan of attack will be appreciated**.

• Seek applications having lowest cost sensitivity
- Aircraft

Although we agree that the aircraft industry is less sensitive to cost and durability, our present funding constrains us to the automotive market. However, we have been and will continue to pursue funding to develop railplugs for the aircraft gas turbine ignitor market. We expect to learn whether our proposal for this application has been awarded in late October. We have also had inquiries about use of the railplug as a detonator for bombs and are trying to pursue funding for this application. This application does ease the burden of having to develop a durable ignitor, since the ignitor gets blown up with the bomb and thus only has to fire one time. Energy is also not a consideration for this detonator application.

- Natural gas engines

All of our bomb work has been conducted using methane as the fuel. We plan to explore ignitability limits in the near future, again using the bomb. We hope that these results will show sufficient promise to interest Don McCaw, and possibly Jim Sibley, in the application of railplugs for gas engines. We also have tentative plans to turn the CFR into a gas engine and/or to generate a bomb that is large enough to simulate the combustion chamber in a typical gas engine. **We will appreciate feedback on future directions for research regarding this application**.

TECHNICAL

Aggressively pursue:

1) Performance at pressure extremes, e.g. 5-500 psia

This work is planned as part of the railplug system development process. To date railplugs have been fired at pressures up to 450 psig in an inert atmosphere. It should be noted that testing has not yet been performed above 450 psig due to limitations in CEM's pressure vessel design. CES plans to have completed these studies of pressure effects by the time of the next meeting of the REAB. However, we have had some recent instrumentation problems and are uncertain that we can repair the instruments and acquire the data before our next meeting. If we can acquire these data, we will present the results at the next meeting of the REAB.

2) Materials durability (focus on applications where durability is not an issue)

We plan to address durability issues as soon as possible with early work performed outside of an engine environment. Up to this point we have used a variety of rail materials including copper, nickel, brass, tungsten, and stainless steel. The tungsten rails have held up the best, however, the copper rails have also worked fairly well. As soon as we develop a plug that will yield repeatable results, we will perform some preliminary durability testing. We are pursuing applications where durability is not as much of an issue as it is in the SI engine automotive market. For example, we have had some inquiries from both the army and navy concerning the use of railplugs for bomb detonation. We also have submitted a proposal for funding in the area of jet engine relight, which also does not require as much durability. Use of the railplug as a starting device in diesel engines is another application where durability is less of an issue.

3) EMI control

We recognize the need to limit EMI. We are gaining experience with railplug EMI emissions in the CFR engine lab that will help us in designing the production engine experiments. We are evaluating SAE standards J551 and J1816 for EMI performance levels. Also, Norris Bassett of AC Delco has provided further information on this topic. We will report on progress in this area at a future meeting of the REAB.

4) Electrical energy efficiency

We recognize that the power required from the engine to drive the railplug is of primary concern, especially for the SI engine application. We are pursuing a preliminary investigation of the overall energy conversion process now. We need to know the optimum plasma quantity, temperature, and kinetic energy for the ignition process for a given application as well as the sensitivity of ignition to these variables before we can reach any definite conclusions about the power requirements. We do not currently know how much energy will be required for successful railplug ignition, and expect that it will depend upon the application. Thus, our present electronics package has necessarily been designed to be as flexible as possible. Within this framework, designing for electrical energy efficiency is not possible. As a result, the early applications of railplugs in combustion systems (the bombs, the optical access engine, the CFR, or the production engines) may use significantly more stored energy than necessary. Our goal in the early experiments will be to gain experience in the ignition process and to establish operating parameters. Once we have determined the delivered energy requirements for a given application, an electronics package can then be designed specifically for that application. The design of this application-specific electronics package will include energy efficiency considerations. Our goal for the SI engine is a delivered energy of 500 millijoules at idle. If the electrical system efficiency is 50%, the electrical energy consumption from the engine will then be essentially the same as that for current ignition systems.

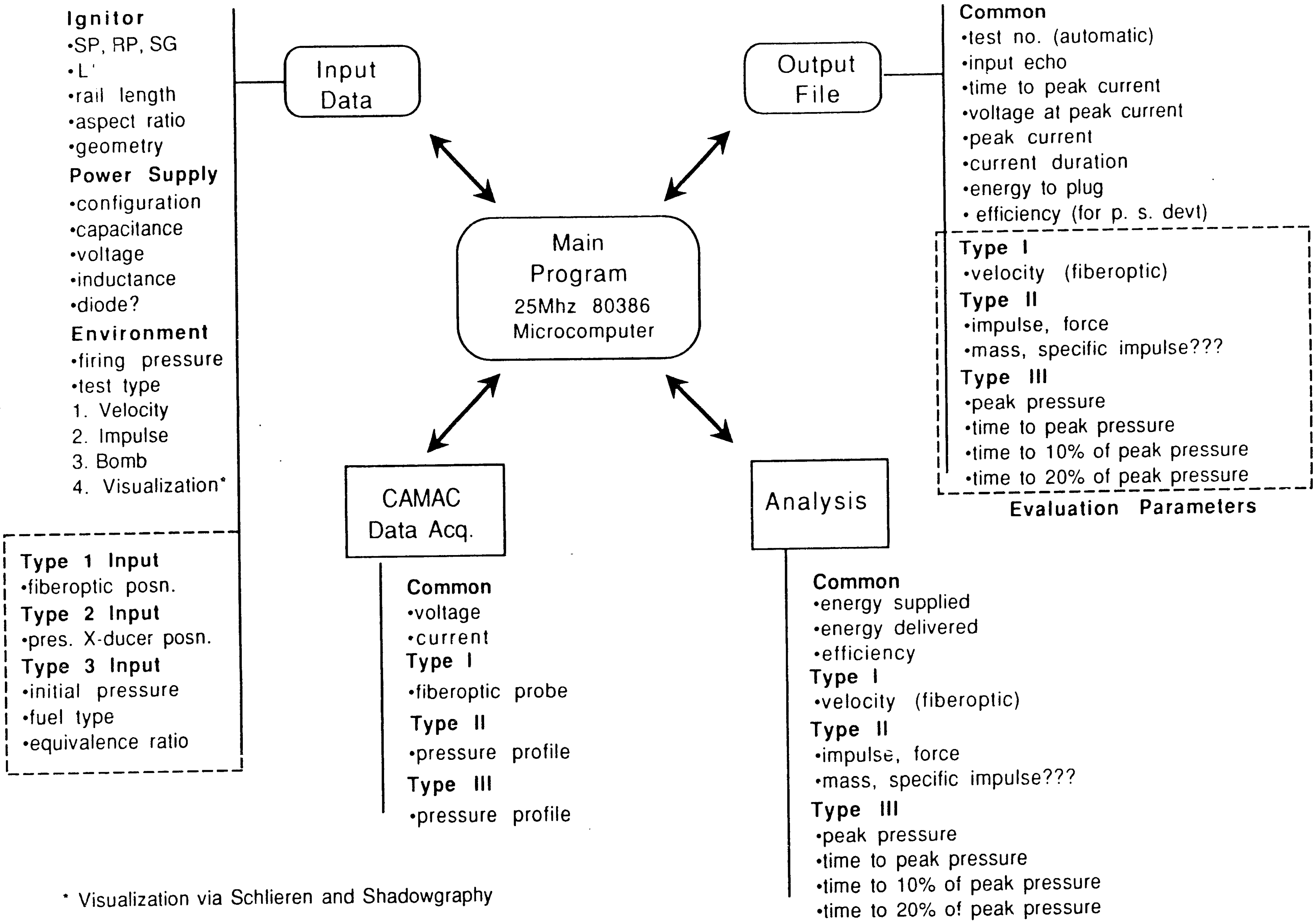
5) Focus analysis on jet fluid mechanics (not global)

As noted previously, we have incorporated this recommendation into our program. Janet Ellzey is leading the modeling effort which is now focused upon the jet simulation for the combustion bomb. After we are satisfied with the results of the jet model and have learned as much as we can from it, then we will pursue modeling railplugs in an engine via modification of KIVA.

6) Definition of design goals - parameter space

Much of the above discussion addresses this issue. We have taken the suggestions of the REAB seriously and we believe that we have successfully shrunk the parameter space via design of the experiments. We have developed a plan to allow us to more rapidly develop optimum railplug geometries and electronics packages. We have also significantly decreased the parameter space for the engine applications by focusing the experiments on a very limited number of operating conditions.

PC Based Data Acquisition and Analysis Program for Railplug Evaluation



* Visualization via Schlieren and Shadowgraphy

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