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CRADA Final Report
for
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ENGINE SYSTEM ELECTRONICS FOR HIGH-TEMPERATURE AND HIGH-VOLTAGE ELECTRONICS, MATERIALS, AND COMPONENTS FOR UNDER-HOOD APPLICATIONS

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CONTENTS

ABSTRACT

A cooperative research and development agreement (CRADA) between General Motors AC Rochester (GM-ACR) and Martin Marietta Energy Systems (Energy Systems) to develop engine systems electronics suitable for high-temperature and high-voltage under-hood applications has been completed. The objective of the CRADA was to improve the performance and/or reliability of automotive ignition systems. This was accomplished by identifying common failure modes of ignition system components and developing cost- effective improvements to appropriate manufacturing procedures. Development of test hardware and new manufacturing techniques was also pursued during the project.

Contributions to the CRADA were made by AC Rochester, Packard Electric, and Delco Remy divisions of General Motors on spark plugs, secondary ignition wiring, and ignition coils respectively, with assistance from Energy Systems. During the project, organizational changes at General Motors resulted in combining the aforementioned organizations into Delphi Automotive Systems.

1. CRADA OBJECTIVES

This cooperative research and development agreement (CRADA) between General Motors AC Rochester (GM-ACR) and Martin Marietta Energy Systems (Energy Systems) was to develop engine systems electronics suitable for high temperature and/or high-voltage under-hood applications. Technically correct, cost-effective engine management is essential for meeting future performance requirements of internal combustion engines. Development of supporting technologies for under-hood applications is pivotal to advanced engines and thus the competitiveness of the U.S. automobile industry. To achieve the goals of this project, the following tasks were to be completed as specified in the original Statement of Work:

1. Identify common failure modes of ignition system components and develop cost-effective improvements to appropriate manufacturing procedures.
2. Develop test hardware and procedures that will reveal substandard components and materials before they are installed in automobiles.
3. Develop new ignition system concepts for future automotive application.

This project involved three divisions of GM, each having expertise in different aspects of the automotive ignition system. AC Rochester in Flint, Michigan, provided spark plug expertise; Packard Electric in Warren, Ohio, provided secondary ignition wiring system expertise; and Delco Remy in Anderson, Indiana, provided ignition coil expertise. Energy Systems in Oak Ridge, Tennessee, supported all the work done by the three participating divisions of GM.

2. MEETING CRADA OBJECTIVES

As mentioned earlier, this CRADA had three main goals that were defined in the statement of work. The first goal was to identify common failure modes of ignition system components and develop cost-effective improvements to appropriate manufacturing procedures. This was accomplished primarily through studies of ignition coil failure modes with Delco Remy. While the present manufacturing techniques produce very good coils, the effort in this project was to reduce coil failure rates to lower levels than presently achievable. The studies resulted in identifying the root cause of some coil failure modes followed by recommendations on how to improve the manufacturing process.

The second main goal of this CRADA was to develop test hardware and procedures that would reveal substandard components and materials before they are installed in automobiles. During the project, it was agreed that this goal should include developing test hardware to determine the performance of the entire ignition system. An ignition system is normally designed to deliver energy to a spark plug, which, in turn, ignites the fuel/air mixture in the combustion chamber. The quantity and profile of energy delivered to the spark gap are critical to the combustion process and very difficult to measure accurately. In this CRADA, an energy delivery measurement system was developed that has 1% repeatability and the ability to accurately display the energy delivery profile in time. This hardware can be used by the industrial partner to optimize ignition system designs without spending numerous hours on an engine test stand.

The third goal of this project was to develop new ignition system concepts for future automotive applications. To achieve this goal, a new process for manufacturing spark plug insulators was investigated. Referred to as the gel-cast process, this new approach was anticipated to yield insulators of higher dielectric strength that would allow for the development of smaller spark plugs. Another advantage of this approach is that parts would be cast in a near net shape and would require very little additional grinding.

3. BENEFITS TO DEFENSE PROGRAMS

The U.S. Department of Energy (DOE) has been interested in encapsulation of high-voltage coils for a number of years. As in the automotive industry, DOE has studied the manufacture of robust and reliable electric coils and has maintained an interest in the area. Encapsulation of other devices likewise remains a concern of DOE. In addition to high-voltage materials interest, theoretical modeling of high-voltage systems is also a skill that must be maintained by DOE.

4. WORK ACCOMPLISHED*

4.1 SPARK PLUG CERAMIC STUDY

During this project, one area of work was to study the dielectric breakdown mechanism(s) in ceramics so as to build stronger insulators for spark plugs used in future down-sized and multivalve engines. After touring the ACR spark plug factory in Flint, Michigan, and studying previous work on the ceramic manufacturing process, work to determine the root cause of spark plug insulator failures began.

Preliminary examinations were conducted on six insulators sent to Energy Systems by ACR. The insulators had been fired to densify the ceramic but had not been glazed. In each case there were one or more pin-hole-type defects that were formed by arc-through when the insulators were subjected to a 25-kV potential during "proof testing."

All six insulators were examined (in the areas of the arc-throughs) by X-ray computerized tomography (CT). The X-ray beam passed radially through each sample as it was moved linearly through the beam. After each pass, the sample was rotated a few degrees about the long axis. Approximately 20 CT slices, at 0.25-mm increments along the long axis, were taken at each arc-through location to trace the path of the pin holes as they traversed through the wall of the insulator. The toroidal-shaped scans were somewhat difficult to interpret because of what appeared to be a generally porous microstructure that tended to obscure any features associated with the pin holes. However, by careful examination, one can identify the relevant indications. The images show that in each case the arc traveled in a tortuous path, with only a portion of the length of the hole being shown in each CT scan. There were few indications of high-density particles in the insulators that might, for example, have resulted from contamination by a metal during processing. There was no evidence of cracking in the CT scans, but rather what appears to be linear indications made up of aligned pores. These preliminary examinations suggest that the arc-throughs occur at these linear groups of pores.

To learn more about the insulators, we sliced two with a thin diamond-grit saw to remove toroidal-shaped sections containing an arc-through pore. The sections were 3 and 5 mm in thickness, with the thinner piece taken from the tip region of the insulator and the thicker piece taken from the body of the insulator. After slicing, the sections were reexamined by CT to ensure that no additional defects had been introduced during cutting. Within the sensitivity of that technique, no additional defects were found.

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*This Section contains Protected CRADA Information

The sections were examined ultrasonically using a 75-MHz focused transducer. This technique was able to image both the general porosity in the samples as well as portions of the arc-through holes. Again, any linear indications appeared to be from linear arrays of pores instead of cracks. The most striking feature in the section from the tip was the apparently radial orientation of the internal structure of the ceramic. This type of pattern is not typical in other ceramic materials and is attributed to the fabrication process. The radial pattern was not as noticeable in the ultrasonic images of the sample from the body of the insulator. Most noticeable in this sample were broad bands of what was interpreted as very fine porosity, smaller than the resolution limit of the technique and transducer used.

Work continued on spark plug failure analysis using X-ray CT, ultrasonic inspection, and scanning electron microscopy (SEM). In the case of the SEM studies, the insulators that failed during high-voltage testing as well as those that failed during the engine scuff test have been examined. Over 50 SEM images were produced, and the appropriate people from ACR were enlisted to analyze the results. A report containing glossy copies of the micrographs was provided to ACR.

Three spark plugs from different manufacturers were also sectioned to reveal the reasons that different electrical models exist for each type of spark plug. The physical differences were obvious and helpful in identifying the elements of a spark plug that affect performance.

ACR supplied failed spark plugs to Energy Systems along with information describing their manufacture. Continued support was also provided pertaining to the test methods and common failure modes of spark plugs in general and insulators in particular. Analysis of new data was continuously supported by ACR.

Representatives from ACR traveled to Oak Ridge to review the work that had been done to improve spark plug ceramic high-voltage tolerance. CT scans and ultrasonic test results were presented, and plans to measure dielectric strength of different ceramic formulations were discussed. ACR also provided Energy Systems with green ceramic spark plug bodies to be studied in an effort to identify the manufacturing step that introduces the most common flaws.

The concept of gel-casting spark plug insulator bodies was suggested and has a number of advantages that include potentially increased dielectric strength. To test dielectric performance, gel-cast test parts were fabricated in a tubular shape that allows high-voltage electrodes to apply high electric fields to the sample ceramic while maintaining large surface paths between electrodes. This approach tends to eliminate the problem of surface arcing seen when dielectric tests are performed on small, disc-shaped samples.

Spark plug ceramic studies continued, with Energy Systems producing their own ceramic test pieces from material supplied by the industrial partner. Aqueous mixtures of the alumina, clay, calcium carbonate, and talc have been used to cast simple shapes as well as spark plug insulators. Those parts have been compared to others made with finer alumina powder to determine the effects of alumina particle size on dielectric properties. Additional samples have also been formed using a gel-cast process to determine the viability of this alternate approach to forming spark plug bodies.

Development of the gel-cast spark plug insulator continued with the discovery that trapped gas bubbles were the biggest problem because they result in voids that are cosmetically unacceptable and degrade the dielectric performance of the finished part. Hardware improvements were developed that allowed the gel-cast liquid to be poured under vacuum and greatly reduce the likelihood of bubble formation. Proper support of the green state insulator was also an engineering issue that needed improvement so that the parts did not warp during the sintering process.

The most significant advancement in overall quality of the gel-cast insulator resulted from a modified procedure by which to fill the mold. The technique uses the central mold insert as a fill tube so that the mold will fill from the bottom without having to evacuate the air from the mold with a vacuum pump. This greatly improved the manufacturing aspect of the process by reducing gas bubbles trapped in the mold. The improvements resulted in fewer cosmetic flaws and a likely improvement in dielectric strength. To determine actual dielectric strength, sintered gel-cast spark plug bodies would have to undergo CAT scans, ultrasonic imaging, and high-voltage breakdown testing. These procedures had not been completed at the time funding was exhausted.

High-voltage test apparatus necessary for studying ceramic insulator performance was assembled in Oak Ridge. The system has the ability to apply 100 KV to a ceramic sample under test to determine the dielectric strength of the sample. The test apparatus is completely enclosed and shielded for personnel safety and for reduction of electromagnetic interference that is generated during high-voltage breakdowns.

4.2 ENERGY DELIVERY MEASUREMENT

4.2.1 Ignition System Model Development

Another area of work in this CRADA was to optimize the secondary ignition wiring system for energy delivery in a cost-effective manner. To do this, it was necessary to develop analytical models and measurement systems that could predict the energy delivered by the high-voltage cable and components of an ignition system. The initial focus was on gas breakdowns and the corresponding theoretical understanding necessary to assess energy delivery. Understanding of gas breakdown was also a necessary preliminary step in developing predictive models for dielectric breakdown of cables and components, particularly in the area of interface seals.

Development of a computer model to simulate typical ignition system performance was accomplished with input from the industrial partner. The most challenging aspect of the model was to determine a realistic representation of the spark gap. Concurrent with the literature search on the subject, all known elements of the ignition system were programmed into the computer model.

The original computer model developed for this project contained only the basic elements of the ignition system and was refined as the project progressed. The spark gap in the model was simulated with a capacitor and a switch until a more realistic model of the spark gap was developed.

Concurrent with the computer modeling effort, an energy delivery measurement system was configured in the laboratory using actual automotive ignition system parts. The performance of the energy delivery test hardware was compared to that of the computer model under development. Instrumentation necessary to verify correct operation of the system was also configured. The system ultimately provided an early indication of how well the model correlated to actual ignition system performance. As the project progressed, more elaborate experimental systems were used with enhanced instrumentation. This allowed for the study of fast ignition system characteristics in the nanosecond time range.

Packard Electric continually furnished information to Energy Systems necessary to model an actual automotive ignition system presently in use. Packard Electric also provided guidance to Energy Systems on materials issues and the importance of understanding the ignition system environment so that accurate models could be developed.

4.2.2 Development of an Energy Delivery Measurement System

Hardware necessary to study energy delivery of an ignition system was assembled; it included a vacuum chamber with a variable gap spark plug. The vacuum chamber allowed different gases and pressures to be combined with various spark gap lengths to determine interactions of the variables. Refinements to the vacuum chamber to eliminate all sharp edges that concentrate the electric field and produce undesirable streamers and arcs was an important aspect of the project. The energy delivery test apparatus was used to verify the computer model of the ignition system and help improve the understanding of factors that affect the repeatability of present energy delivery test systems.

A vacuum chamber was constructed for spark plug simulation and tested with an automotive ignition coil driven by a high-voltage pulse generator. The frequency response of the coil was such that the coil did not provide sufficient voltage stepup of the applied pulse and was replaced with a capacitive discharge system that provided adequate voltage to break down the test gap in the chamber. Once operational, voltage, current, and impedance variations during gap breakdown were observed. Data were obtained with a high-impedance spark plug wire in series between the capacitor and the spark gap. An actual automotive ignition system was used to apply high voltage to the test chamber and provided waveforms that were ultimately compared to the computer model of the ignition system.

In an effort to further stabilize the energy delivery measurement, the test chamber was backfilled with dry nitrogen and illuminated with a small ultraviolet light to provide initiating electrons necessary for breakdown. It was shown that breakdown events of interest occurred in the nanosecond time regime, so instrumentation issues were significant.

At this stage of development, the energy delivery measurement system used a slowly rising direct current (dc) power source to reduce the uncertainty of voltage and free electron timing, necessary for breakdown to occur. The next generation of the energy delivery measurement system replaced the dc source with an actual automotive ignition system that provided very fast voltage rise times. Changing the power source to an automotive ignition system reduced the repeatability of the energy delivery measurement to some extent because of the uncertainty of voltage and free electron timing coincidence.

In an effort to enhance repeatability while using an ignition system, an alternate light source was used to provide an intense photonic source of electrons in the gap prior to breakdown, thus improving breakdown repeatability. This was accomplished by pretriggering a powerful Xenon strobe light focused on the spark gap microseconds before the high voltage was applied to the gap. The high-intensity light provided initiating electrons for the breakdown and stabilized the performance of the spark gap, thereby improving the repeatability of the energy delivery measurement. Best system performance using the coil and strobe was achieved with a nitrogen shield gas surrounding the gap at a pressure of 2 atm.

When the Statement of Work was written for this project, it was believed that electrode performance was the sole source of variation in the energy delivery measurement. With that understanding, electrode developments were used as project milestones in more than one case. Since then, it was determined that electrodes were only a part of the source of energy measurement variation and that other spark gap parameters were also important. While Packard Electric completed testing on electrodes according to the milestones, they also agreed in writing to expand their effort to include duplicating spark gap improvements developed by Energy Systems.

The newly developed energy delivery measurement hardware was then used to measure the performance of four different wire samples supplied by the industrial partner. The results of the tests verified that resistive wires have greater loss than inductive wires, thereby delivering more energy to the spark gap. Details of the recorded energy delivery profiles indicated that greater energy delivery is observed with inductive wires because of longer glow phase current and approximately the same glow phase voltage. These measurements were made possible only by the stabilized energy delivery measurement hardware developed in this project.

The original motivation to develop an energy delivery measurement system was to assess the performance of various ignition wiring systems without a dynamometer test. The industrial partner has now suggested that the energy delivery measurement hardware could also be used to assess the performance of coils and spark plugs and is communicating internally to coordinate this effort.

A report of possible invention was written on the energy delivery measurement system developed in Oak Ridge for this project. The energy delivery measurement system may prove to be a valuable tool in assessing the performance of new ignition systems for GM and others; however, this application is beyond the original project goal of measuring the performance difference of ignition system wires.

4.3 COIL ENCAPSULATION STUDIES

During an initial meeting with representatives from Delco Remy to discuss issues of interest to them, they indicated that reducing the failure rates of coils to lower levels than presently achievable would be highly desirable. The existing coil failures were known to be electrical in nature and were thought to be brought on by mechanical flaws. The coils presently in production are completely encapsulated in an epoxy material, so a team of polymer specialists from Energy Systems was assembled to work with representatives from Delco Remy on manufacturing issues.

The polymer specialists from Energy Systems visited the Delco Remy plant in Anderson, Indiana, to discuss manufacturing issues pertaining to ignition coils and to tour the manufacturing facility. It was pointed out that the present encapsulation material was supplied to Delco Remy by Dexter Hysol, who was not part of the CRADA agreement and had no obligation to share manufacturing information on encapsulation formulation. For that reason, Delco Remy personnel acted as a communication conduit between Energy Systems and Dexter Hysol.

Various encapsulation issues were studied with Delco Remy, and tests to measure the time required to pump down and out-gas coil assemblies prior to encapsulation were performed. The data were shared between Energy Systems and Delco Remy and were helpful in determining ways to improve the encapsulation process. Encapsulation formulation issues were also addressed which required the cooperation of Dexter Hysol. As planned, Delco Remy provided all necessary support in this effort.

Representatives from Delco Remy and Dexter Hysol visited Oak Ridge for a complete review of the initial work on coil encapsulation issues. Dexter Hysol, the sole supplier of coil encapsulant to Delco Remy, has historically provided outstanding technical support for their product and was very interested in the work done on the subject by Energy Systems. During the review, Energy Systems personnel presented CT scans of Delco coils which revealed internal areas of probable failure. Numerous additional data were presented and nondestructive testing was recommended for assessing future changes made to the coil encapsulant. Energy Systems agreed to continue to provide assistance to Delco Remy in any area that would improve ignition coil reliability, and Delco Remy supplied additional ignition coils in various stages of completion to Energy Systems for analysis.

Additional experiments confirmed that material separations within coils occurred because of insufficient mechanical strengths of materials and excessive internal pressures generated during the curing process. Material separations reduce the dielectric strength of the coil and increase the probability that premature coil failures will occur because of localized high-voltage breakdown. Several techniques to increase the internal strength of the coil were considered and were reviewed with Delco Remy at another program review.

Three possible replacement ignition coil insulation samples were selected for further test and evaluation. One of the considerations was the dielectric strength of the candidates, which requires high-voltage breakdown measurements to be performed. To do this, a high-voltage test fixture was fabricated that allowed spherical electrodes to be positioned on each side of the sample under test while located in an environmental chamber. Voltage breakdown tests were performed at a constant humidity and constant temperature to ensure repeatable results. Mechanical property tests of the samples were also performed to determine wicking, strength, and coefficients of thermal expansion. Viable replacement candidates also demonstrated compatibility with the existing coil design and had sufficient mechanical and dielectric strength to insulate adjacent layers in the coil.

Several replacement ignition coil insulator candidates were judged likely to improve the reliability of the final coil assembly. Sufficient quantities of the three most promising candidate insulators were procured and used to manufacture a statistically significant number of ignition coils. The industrial partner provided assistance in designing a test for replacement coil insulating material and scheduled manufacturing time for a prototype run. The industrial partner also performed testing on the manufacturing line to determine the effects of coil winding tension on final coil performance.

Three potential replacement ignition coil insulator samples were selected for use in the manufacture of prototype coils. However, one of the samples selected proved to be too flexible for use in the automatic coil winding machine, so prototype coils were manufactured using the two remaining samples. Prototype coils were wound, cut, and encapsulated using standard manufacturing techniques and were subjected to accelerated life tests. Preliminary destructive tests, performed on a limited number of units, suggested that prototype coils were significantly stronger than standard coils. This was encouraging because premature coil failures had been linked to mechanical weakness.

Once the accelerated life tests were completed, Delco Remy had to assess the costs and benefits associated with implementing any changes to the manufacturing process based on information gained in this project.

5. REPORT OF POSSIBLE INVENTION

During this CRADA, work performed by Energy Systems on improving energy delivery measurements was considered unique; so a patent disclosure was written and submitted to the Office of Technology Transfer (OTT). On December 5, 1995, OTT issued a letter to the inventors stating that Invention Disclosure ESID No. 1774-XC, S-83,831, "Energy Delivery System Using an Automotive Ignition Coil for Spark Plug Evaluation," had been reviewed and may have commercial potential. The letter also stated that OTT will be responsible for working with the inventors to eventually develop a commercialization strategy.

6. COMMERCIALIZATION POSSIBILITIES

As mentioned in the previous section, an "Energy Delivery Test Measurement System Using an Automotive Ignition Coil for Spark Plug Evaluation" may have commercial possibilities and will be pursued by the OTT. In addition to the work on measuring energy delivery, a significant effort during this CRADA was made on gel-casting ceramic parts and improving encapsulation systems. The commercialization of gel-casting parts is an ongoing effort of the Metals and Ceramics Division at Oak Ridge National Laboratory, and this project has helped develop gel-casting techniques. Improving encapsulated systems has added to the experience of the Y-12 Development Division, which has enhanced their ability to develop products for the DOE Defense Programs.

7. FUTURE COLLABORATION

During this CRADA, representatives from Delco Remy specifically asked how the services of the Oak Ridge complex could be employed in the future to solve other technical problems. The Work For Others (WFO) program was described to them as a possibility.

8. CONCLUSIONS

This CRADA between Martin Marietta Energy Systems and General Motors Corporation was planned as a 3 year project to benefit both parties. The Statement of Work (SOW) included a general description of work to be accomplished and a specific list of milestones assigned to Energy Systems and GM. To achieve everything listed in the SOW, all aspects of the ignition system had to be addressed. This required the involvement of Packard Electric, Delco Remy, and AC Rochester divisions of GM.

As the project progressed, milestones were met in a timely fashion, and information was shared between Energy Systems and GM as appropriate. By the conclusion of the project, each participating division of GM had gained valuable information about their manufacturing process or product test methods. Energy Systems also acquired knowledge useful in carrying out the DOE Defense Programs mission. The project was indeed beneficial to both parties, as planned.

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