TP 13021E

DEVELOPMENT OF ALL-CERAMIC GLOW PLUGS FOR HEAVY-DUTY ENGINES
Phase II

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The Electrofuel Manufacturing Company Limited
21 Hanna Avenue, Toronto, Ontario M6K 1W8

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Development of All-Ceramic Glow Plugs for Heavt-Duty Engines

Phase II

by

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The Electrofuel Manufacturing Company Limited

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16. Abstract

This report details the development work done in Phase II of a project to develop all-ceramic glow plugs for heavy-duty diesel engines. This phase focussed on increasing the operational voltage ratings of the proof-of-concept plugs developed in Phase I in order to meet all commercial expectations in terms of performance, reliability/durability, and economic manufacture. The work involved optimization of the material composition to meet design specifications, development of manufacturing process and fabrication of plugs, and bench and engine tests. The all-ceramic glow plugs rated at 12 V were shown to outperform conventional 24 V plugs. The development of the 24 V all-ceramic plug was only partially successful; however, it was deemed that the performance of the 12 V plugs superseded its need.

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16. Résumé

Ce rapport décrit les travaux de la deuxième phase d'un projet ayant pour objet la mise au point de bougies incandescentes entièrement en céramique pour moteurs diesels de poids lourds. Il s'agissait plus particulièrement d'adapter la bougie de validation de principe, mise au point lors de la phase antérieure, à des tensions plus élevées, en vue de satisfaire aux exigences commerciales de rendement, de fiabilité, de durabilité et de coût de revient. Les travaux ont porté sur l'optimisation des caractéristiques du composite céramique-céramique et sur le perfectionnement des procédés de fabrication afin de satisfaire aux nouvelles exigences techniques, puis sur la fabrication des prototypes et leur essai au banc et sur moteur. Les bougies incandescentes en composite céramique-céramique pour applications de 12 V mises au point dans cette deuxième phase se sont avérées plus performantes que les bougies de type classique 24 V. La version destinée aux applications de 24 V n'a été qu'une réussite partielle. Toutefois, compte tenu de la performance de la version 12 V, la version 24 V a été jugé superflue.

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Summary

This project was implemented with the support of the Transportation Development Centre of Transport Canada to develop 12 V and 24 V versions of the proof-of-concept all-ceramic glow plug developed in Phase I. While the original all-ceramic glow plug showed improved durability and performance at 6 V, there was a need to meet the requirements of higher voltage plugs that met commercial expectations in terms of performance, reliability/durability, and economic manufacture.

After the development of specifications for the higher voltage plugs, the main work involved the optimization of the material composition to meet the new design requirements, and the improvement of the manufacturing process to achieve more stringent tolerances. Work was performed in the following areas:

- Material composition: silicon nitride, molybdenum disilicide, sintering aids
- Multilayer casing process: mould, injection pressure of slurries, deposition time, drying time
- Sintering process: time/temperature cycle, atmosphere, etc.
- Electrode brazing process: brazing material, temperature, environment

Once the glow plugs were manufactured, the following tests were performed:

- Mechanical and electrical performance tests
- Bench and engine tests

As the tests were completed, the plug redesign and manufacture along with retests became an iterative process to the conclusion of the project.

The final design of the 12 V all-ceramic plug performed in a far superior manner compared to the conventional 24 V glow plug. The original need for a 24 V design was based on the retrofit market for engines fitted with a 24 V system. It was concluded that it is better to reduce the supply voltage to 12 V and use the all-ceramic glow plug because of its superior performance in terms of substantially quicker cold starts, enhanced combustion characteristics, and the inherent stability and durability of the all-ceramic material.

Sommaire

Ce projet, appuyé par le Centre de développement des transports de Transports Canada, avait pour objet d'adapter la bougie incandescente de validation de principe, entièrement en céramique, mise au point lors d'une phase antérieure, pour les applications de 12 V et de 24 V. La version originale, destinée à des applications de 6 V, s'est avérée plus durable et plus performante que les bougies incandescentes 6 V de type classique. Mais il fallait mettre au point des versions de cette bougie pour des applications de tension plus élevée, pouvant satisfaire aux exigences commerciales de rendement, de fiabilité, de durabilité et de coût de revient.

Après la définition des spécifications techniques des bougies destinées aux applications de 12 V et de 24 V, les travaux ont porté essentiellement sur l'optimisation des caractéristiques du composite céramique-céramique et sur le perfectionnement des procédés de fabrication pour satisfaire aux nouvelles exigences. Ils concernaient plus précisément ce qui suit :

- Composition du matériau : nitrure de silicium, disiliciure de molybdène, adjuvants de frittage.
- Revêtement multicouche : moule, pression d'injection de la pâte, temps de dépôt, temps de séchage.
- Frittage : cycles de temps/température, atmosphère, etc.
- Brasage des électrodes : matériau de brasage, température, atmosphère.

Les nouveaux prototypes ont été soumis, dès après leur fabrication, aux essais suivants :

- essais mécaniques et électriques;
- essais en laboratoire et sur moteur.

Les chercheurs ont suivi dans ce projet une démarche itérative, c'est-à-dire qu'ils utilisaient les résultats des essais pour perfectionner le concept et les procédés de fabrication, la nouvelle version étant chaque fois soumise à nouveau aux essais.

La performance de la nouvelle bougie incandescente entièrement en céramique mise au point pour les applications de 12 V était de loin supérieure à celle des bougies incandescentes classiques de 24 V. Au départ, la mise au point d'une version 24 V avait également été envisagée, pour remplacer les bougies de type classique dans les moteurs existants fonctionnant avec des bougies 24 V. Or, il semble préférable de réduire plutôt la tension d'alimentation à 12 V et d'utiliser la bougie incandescente en composite céramique-céramique 12 V, compte tenu de la supériorité de cette dernière du point de vue du temps de réponse pour l'allumage à froid, de la tenue à la combustion, de la stabilité et de la durée de vie utile.

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1. Introduction

The Electrofuel Manufacturing Company has been developing an all-ceramic glow plug for diesel engine applications for a number of years. The Phase 1 laboratory scale "proof of concept" program was supported by Transport Canada. Glow plug development using the laboratory scale program has shown very promising results. These glow plugs were tested by Detroit Diesel Engine and Advanced Engine Technology, Ottawa and were found to have an excellent performance. Electrofuel has received two patents in this field. A schematic of the "Proof of Concept" Electrofuel All-Ceramic Glow Plug is shown in Figure 1.

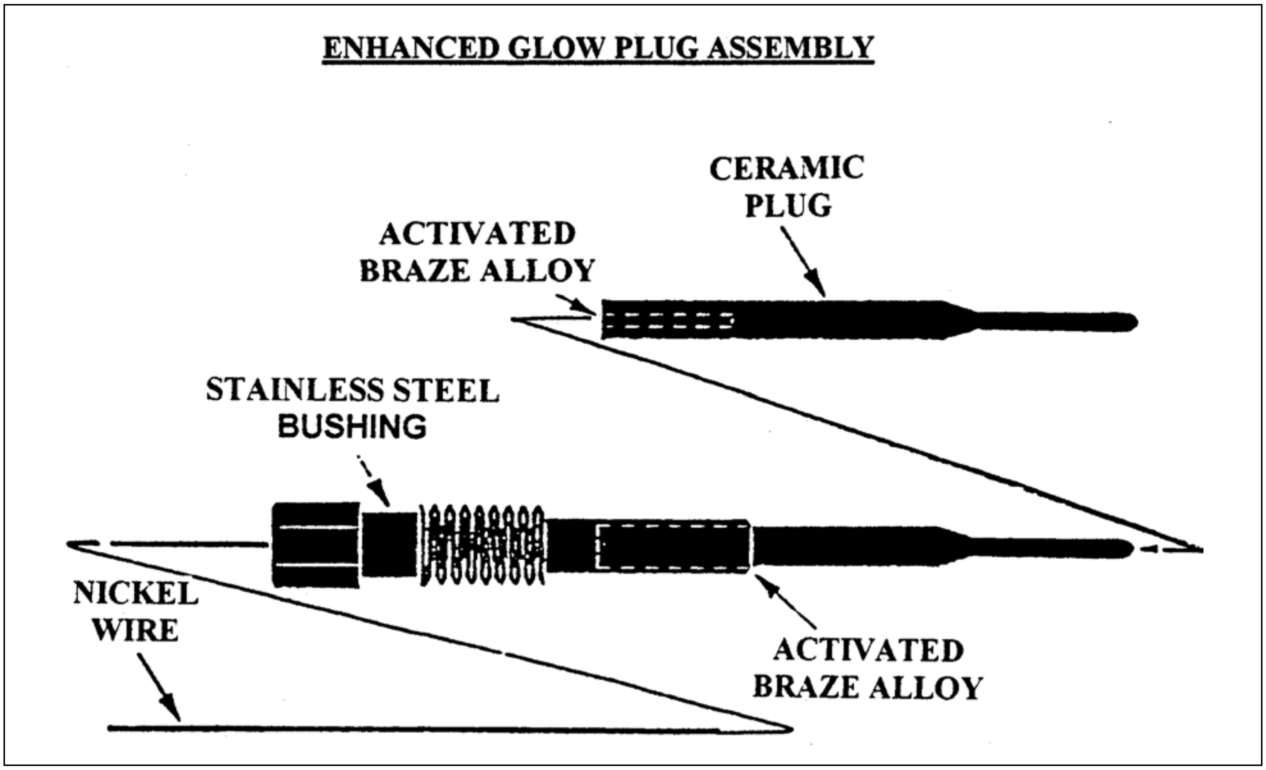

FIGURE 1: A Schematic of Electrofuel's All-ceramic Glow Plug

Electrofuel's all-ceramic glow plug is designed to replace traditional metal heater-based glow plugs. Traditional glow plugs are pencil shaped and consist of a tubular heater element (metal/nichrome wire) embedded in magnesia powder inside a metal sheath. These metal glow plugs suffer from problems relating to high corrosion rates, short life, slow response time and low operating temperatures; in addition they cannot meet the newer more stringent engine specifications. Recently, ceramic/metal glow plugs were commercialized with somewhat improved performance over the metallic glow plugs. In ceramic/metal glow plugs the metallic sheath has been replaced by a ceramic sheath into which a tungsten coil is embedded to serve as the metallic-heating element. Most of the problems relating to the metallic glow plug, such as brittleness of the metallic heating element at elevated temperatures, inherent incompatibility of the metal/ceramic interface and poor thermal conductivity remains

Electrofuel's all-ceramic glow plug does not contain any metallic wires as the heating element. The ceramic itself is the heating element and thus the ceramic glow plug can attain much higher temperatures than conventional glow plugs. The response time of such a glow plug is also very fast because the heater itself is the surface of the glow plug, and there is no necessity for the heat to travel through an insulating layer. All-ceramic glow plugs will have much lower corrosion rates than metallic glow plugs because ceramic is an inert material. Electrofuel glow plugs offer a number of advantages over the existing glow plugs:

Cold Starting: EF ceramic glow plugs operate at significantly higher temperatures and require less time to reach a given temperature level than presently used glow plugs. This allows for a quicker start and improved engine performance.

Energy Saving: Use of EF ceramic glow plugs led to an enhanced combustion process as observed with increased cylinder firing during a given period of time, smoothing of the engine speed trace, and a noticeable reduction in overall engine noise.

Major Environmental Benefits: Diesel engines are known to cause some air pollution, including particulate emissions. Use of the EF ceramic glow plug, leads to a higher temperature operation resulting in significant environmental benefits. Preliminary analysis showed that the higher operating temperature of ceramic glow plugs leads to improvement in engine firing which in turn leads to a significant drop in particulate emission. In addition, a drop in NO_x contents was observed.

Low power: The glow plug uses very low power (60 watts) to reach ignition temperature; consequently it can be used with low-performing batteries.

Warpage and Dimensional Stability: Electrofuel's ceramic glow plugs have exceptional dimensional stability. One of the major problems with metal glow plugs is warpage. After repeated cycling, metal glow plugs deform. Removal of these metal glow plugs for replacement or repairs is very difficult. At times the engine has to be taken apart in order to access the warped metallic glow plug. The EF glow plug poses no such problems.

Continuous Operation: Ceramic tips in EF glow plugs are very stable in the presence of hot gases (virtually no corrosion). Thus, unlike the metallic glow plug, the EF ceramic glow plug can be operated continuously. Continuous operation results in improved combustion in diesel engines.

Long Life: All these properties (low corrosion, dimensional stability, resistance to thermal shock, etc.) will lead to longer life for the EF glow plugs in diesel engine operations.

2. Background

Glow plugs have traditionally been used as an aid to compression ignition in Indirect Injection (IDI) Diesel Engines. In recent years they have also been used as an ignition source for alcohol-fueled Direct Injection (DI) diesel engines and as an aid to cold starting unconventionally fuelled DI diesels.

In the last 15 years much attention has been focused on the potential use of alcohols as fuels. This interest was originally motivated by the need to develop alternatives to petroleum based fuel. Today, however, the environmental qualities of alcohols are the most important motivation. In diesel engines, methanol and ethanol have been shown to reduce emissions of nitrogen oxides and dramatically reduce particulate emissions. Companies currently producing methanol-fueled Direct Injection Diesel engines include Detroit Diesel Corporation (DDC), Caterpillar, Cummins, Deutz, MAN and Volvo.

One problem encountered in the development of alcohol-fueled diesel engines has been the poor ignition quality of the fuel. At low engine speeds and loads alcohol fuels will not auto-ignite with conventional diesel compression ratios. As a result, the engine cannot operate under these conditions without some kind of ignition aid. Surface ignition, using a glow plug in the combustion chamber has been used to overcome this problem.

Glow plugs aid compression ignition of fuel sprays by providing a localized hot surface on which combustion can begin at the required time, even if the air temperature in the combustion chamber is not high enough to cause auto-ignition of the fuel at that point in the cycle. Methanol is well suited to this ignition technique because it has a relatively low surface ignition temperature. Glow plugs can also be used to assist cold starting in conventionally quelled DI diesel engines. Trucks, buses, military equipment, ferries, tugboats, construction equipment, mining and logging machinery, and locomotives require extended periods idling in order to avoid cold starting. The use of glow plugs in these engines would reduce their emissions, lower the noise/emissions nuisance factor, and decrease fuel costs by eliminating the need for extended idling.

Present Status of the Glow Plugs

Traditional glow plugs are pencil-shaped and consist of a tubular heater element (metal/nichrome wire) embedded in magnesia powder inside a metal sheath. These metal glow plugs suffer from problems relating to high corrosion rates, short life, slow response time and low operating temperatures and cannot meet the newer, more stringent engine specifications.

A number of companies such as Kyocera, Bosch and Nippondenso have been active in this area of development, and one manufacturer has recently commercialized a ceramic/metal glow plug, which has a somewhat improved performance over the metallic glow plug. In this plug, the metallic sheath has been replaced by a ceramic sheath into which a tungsten coil is embedded as the metallic-heating element. Most of the problems relating to the metallic glow plug, such as brittleness of the metallic heating element at elevated temperatures, inherent incompatibility of the metal/ceramic interface and poor thermal conductivity remains.

3. Objectives

The objectives of this project fit into three categories:

- Environmental
- Diesel engine performance
- Commercial.

3.1 Environmental Objectives

The first environmental objective of this project is to produce a glow plug that will allow diesel engines to start quickly under all conditions, enabling them to be turned off when not in use. Currently diesel engines are left on in cold conditions, when not in use, due to the difficulties involved during start-up.

Wide-scale use of reliable efficient glow plugs would result in a substantial saving in the world's limited supply of fossil fuels. It would also dramatically reduce the amount of air pollutants. The problems associated with air pollutants are magnified in colder climates due to the generally more sensitive ecosystems. It is in these colder climates where these glow plugs will have their greatest environmental effect.

The second objective is to produce long-life glow plugs that are not consumed as quickly as conventional glow plugs, and thus produce less solid waste. The Electrofuel glow plug is made of non-toxic environmentally benign materials.

3.2 Diesel Engine Performance Objectives

Diesel engines have many advantages over their gasoline counterparts, such as lower fuel costs and longer lives, but one crucial disadvantage is the longer start-up time in cold conditions. This disadvantage is major problem in emergency situations, and is unacceptable for ambulances, fire trucks and military vehicles.

An objective of the Electrofuel glow plug development is to reduce the start-up time from one or two minutes to one or two seconds.

Conventional glow plugs have a short life span and frequently need replacement. The Electrofuel glow plug has a substantially greater life span and will need to be replaced less frequently, thus improving the overall reliability of the diesel engine.

3.3 Commercialization Objectives

Most diesel engines are equipped with conventional glow plugs. In general these glow plugs are screwed into the precombustion chamber with a standard threaded connector.

In order to facilitate the anticipated commercialization of the Electrofuel glow plug, it has been designed with the same size and connector as conventional glow plugs. Conversion from conventional glow plug to the Electrofuel glow plug will not require any modification to the diesel engine, nor will it require new expertise or new tools.

The Electrofuel glow plug has also been designed to use relatively inexpensive materials and production techniques in order to ensure that it will not only be the environmental and performance choice for glow plug users, but will also be competitively priced.

4. Development of All-Ceramic Glow Plug

4.1 Specifications:

Evaluation of the performance requirements of glow plugs for most of the applications relates to the specifications listed in Table 1.

Table 1
GLOW PLUG SPECIFICATIONS

CHARACTERISTICS	SPECIFICATIONS
Response time	2-5 seconds at an initial power of 150 W
After glow time	≥ 2 minutes after peak temperature is achieved
Peak Temperature	For 24 V system ≥ 1 000°C; Glow plug will be exposed to in-cylinder gas temperatures up to 1 850°C and a spike voltage of 38 VDC
Corrosion Characteristics	Must withstand exposure to salts and other cleaning agents as well as methanol and ethanol fuels
Electrical Connectors	Must be able to withstand a static force of 111 N without loosening, distorting , or affecting the operation of the device when applied ♦ in the direction of engagement and disengagement ♦ at the end of connector perpendicular to the line of engagement and disengagement
Flexural Strength	≥ 80 Kgf/mm^2
Glow Plug Life	Must exceed 100 000 cycles of 60 second on and 60 second off
Fracture Toughness	≥ 5 MPa√m
Tensile Strength	≥ 750 MPa
Thermal Shock Characteristics	≥ 1 200°C
Mechanical Shock Load	≥ 40 g's
Erosion Resistance	Glow plug must be insensitive to orientation with respect to fuel spray direction.
Electromagnetic Interference (EMI)	Must meet EMI MIL-STD-461B requirements for electromagnetic emission and susceptibility for control of EMI

4.2 Glow Plug Fabrication

4.2.1 Sintering and Microstructure

The sintering of glow plugs as done in a gas pressure-sintering furnace in nitrogen or argon atmosphere. Glow plugs were sintered at temperatures ranging between 1 700°C – 1 950°C at pressure up to 5 Mpa. Prepared samples were studied using Secondary Electron Microscopy for microstructure. For the best glow plug performance the silicon nitride and molybdenum disilicide phases are homogeneously distributed. These are shown in Figures 2 and 3, taken at respective magnifications of x100 and x600. However, improper slurry mixing and/or sintering can lead to development of large grains, which can lead to catastrophic failure of the glow plugs during operations. A typical example is shown in Figure 4.

4.2.2 Bench Test

In the laboratory, various ceramic glow plugs were fabricated and cycled using a power-supply. The heating and cooling cycles were done in air and typically 100 cycles signified an initial test. Additionally, hot glow plugs were plunged into cold water and tested for thermal shock.

The bench tests were followed by engine tests at Detroit Diesel Corporation (DDC), where the glow plugs were tested in operating diesel engines.

4.2.3 Composition Optimization

Extensive composition optimization was carried out to produce glow plugs capable of operating at 12 V and 24 V. The 24 V glow plugs needed extreme precision and were difficult to achieve using standard hand-crafted laboratory procedures.

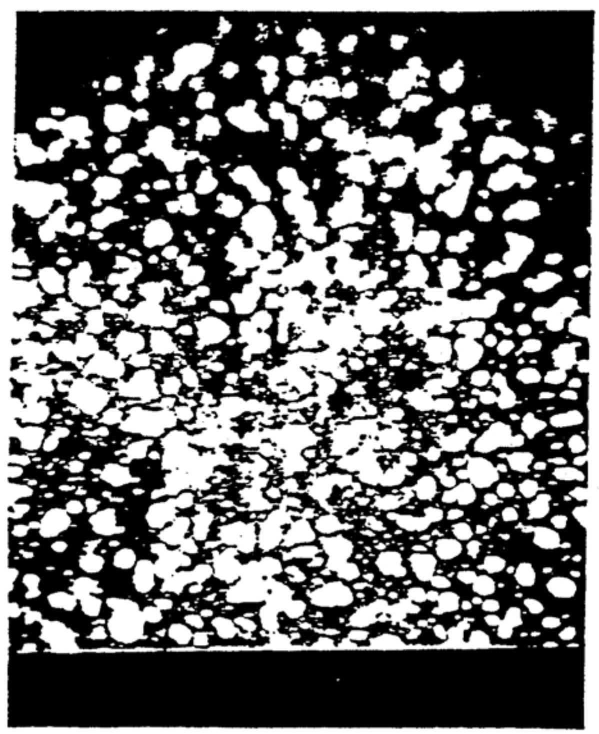

FIGURE 2: SEM Micrograph of ceramic composite conducting layer (Magnification X100)

FIGURE 3: SEM Micrograph of ceramic composite conducting layer (Magnification X600)

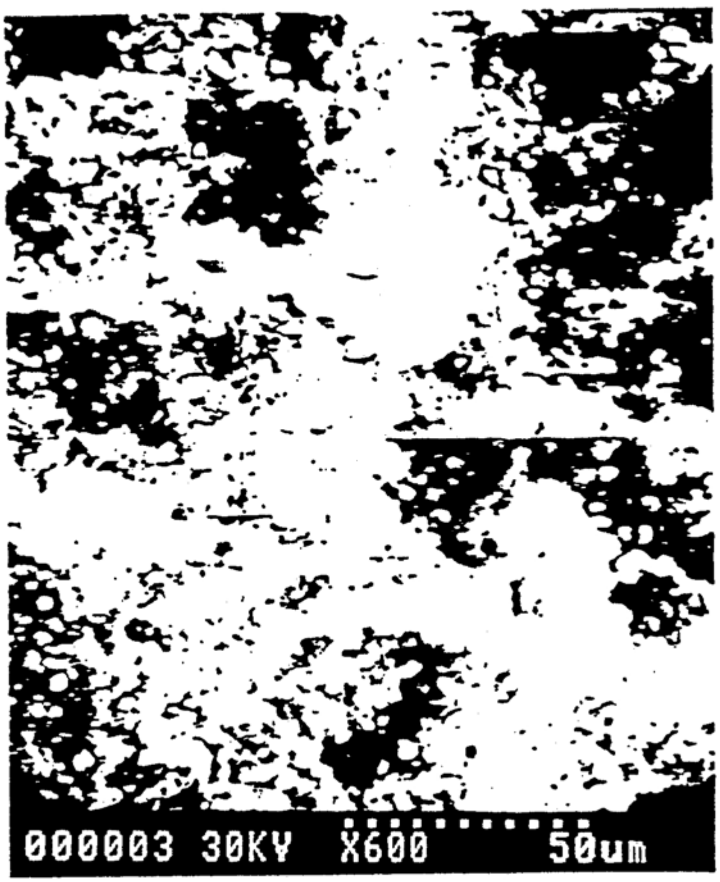

FIGURE 4: SEM Micrograph of ceramic composite conducting layer (Magnification X600)

4.3 Engine Tests at DDC

4.3.1 Performance of Glow Plug

Electrofuel glow plugs were tested at Detroit Diesel Engine test facility using an 8V-71T LHR model 7 083-7 391 engine.

Some performance data is shown in Figures 5-8. Figure 5 shows that the Electrofuel all-ceramic glow plug showed rapid response time as a function of applied voltage. The test was done on a glow plug that was designed for operations up to 12V. This glow plug shows the response time of better than 5 seconds. While operating this plug at 16V, the temperature rose very rapidly until the thermocouple wire failed. The normal operating temperature of 950°C reached in less than three seconds.

Figure 6 compares the performance of Electrofuel's all-ceramic glow plugs with conventional glow plugs, all of them operating at 12V. The all-ceramic glow plugs achieved 2 000°F in less than six seconds while the other glow plugs did not achieve even 1 400°F after twenty-four seconds. The all-ceramic glow plug operating at 12V even out performed the high technology plug operating at 24V, as illustrated in Figure 7.

In addition to improving cold start performance, all-ceramic glow plugs have shown a potential for enhanced combustion during the expansion process and may offer part load fuel economy benefits as shown in Figure 8.

The cold start performance of the all-ceramic glow plug as compared to the presently used glow plug is shown in Table 2. The data was generated after soaking the 8V-71T LHR model 7 083-7 391 engine for 20 hours at -25°F. The results are derived from data shown in Figures 6 and 7

4.3.2 Failure Analysis

An analysis of Electrofuel's glow plug, which failed after limited cycling, was performed jointly by Electrofuel and DDC.

The conclusions drawn were utilized by Electrofuel to improve the processing technology.

Figure 9 shows a photograph of a glow plug failed at 20V operation. Other glow plugs failed when a 12V potential was applied. Molten material that cam e out of the tip was analyzed to be silicon and sulphur. Techniques used for further analysis included part X-ray, optical microscopy and SEM analysis with EDAX. Whole part X-ray revealed some porosity inside the plug beneath the brazed area. The glow plug was sectioned lengthwise by keeping it in a threaded device made specially for positioning the plug over the diamond saw. An internal crack about 3 mm long and about 1 mm from the tip was seen (Figure 10). Si, Al, S, C, O and Mo were detected in the inner layer by EDAX. Overlap of the S and Mo peaks was resolved by going to higher energy levels.

In addition, fairly large pores (up to 500 micron) were observed in the outer silicon nitride layer that requires high structural integrity. This was due to problems with MCP process. These problems were assessed and improvements in the MCP process were introduced.

Other undesirable facets revealed by SEM were interconnected porosity (Figure 11) and unsintered particles of silicon nitride and molybdenum disilicide (Figure 12). This indicated poor process control and powder mixing. These issues were addressed and improvements were made. However, a detailed quality control of process parameters will be undertaken during the development of the manufacturing process.

On the basis of these analyses, further investigations were undertaken in the following areas:

- Pre-mixing of raw materials
- Improvements in sintering and overall process control to eliminate sulphur and carbon contamination
- Investigation of MCP process and alternative cold isostatic pressing technology to improve green body manufacturing
- Improvement in brazing of the ceramic body to the metal housing

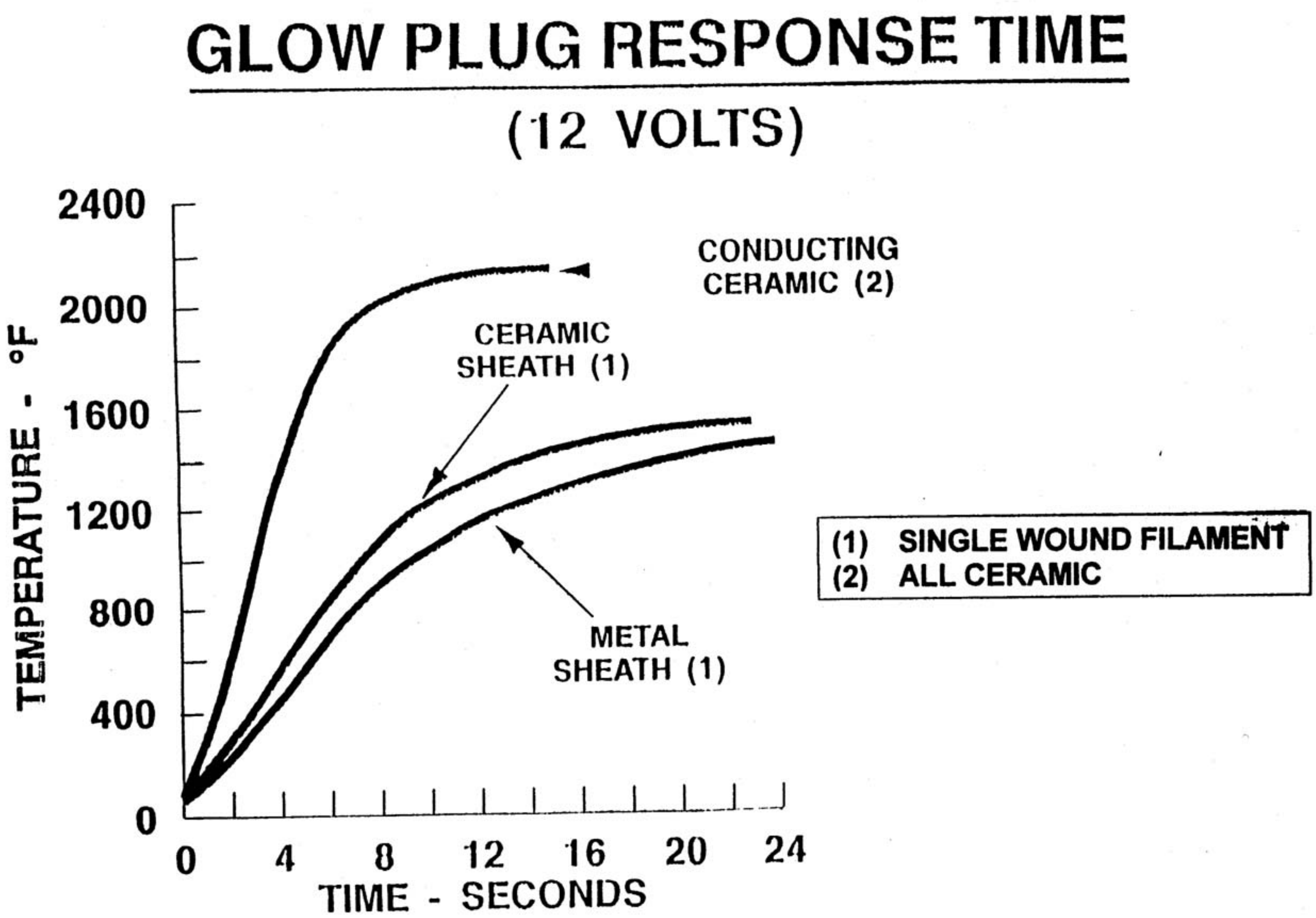

FIGURE 5: Performance of all ceramic glow plug
DDC Engine Testing

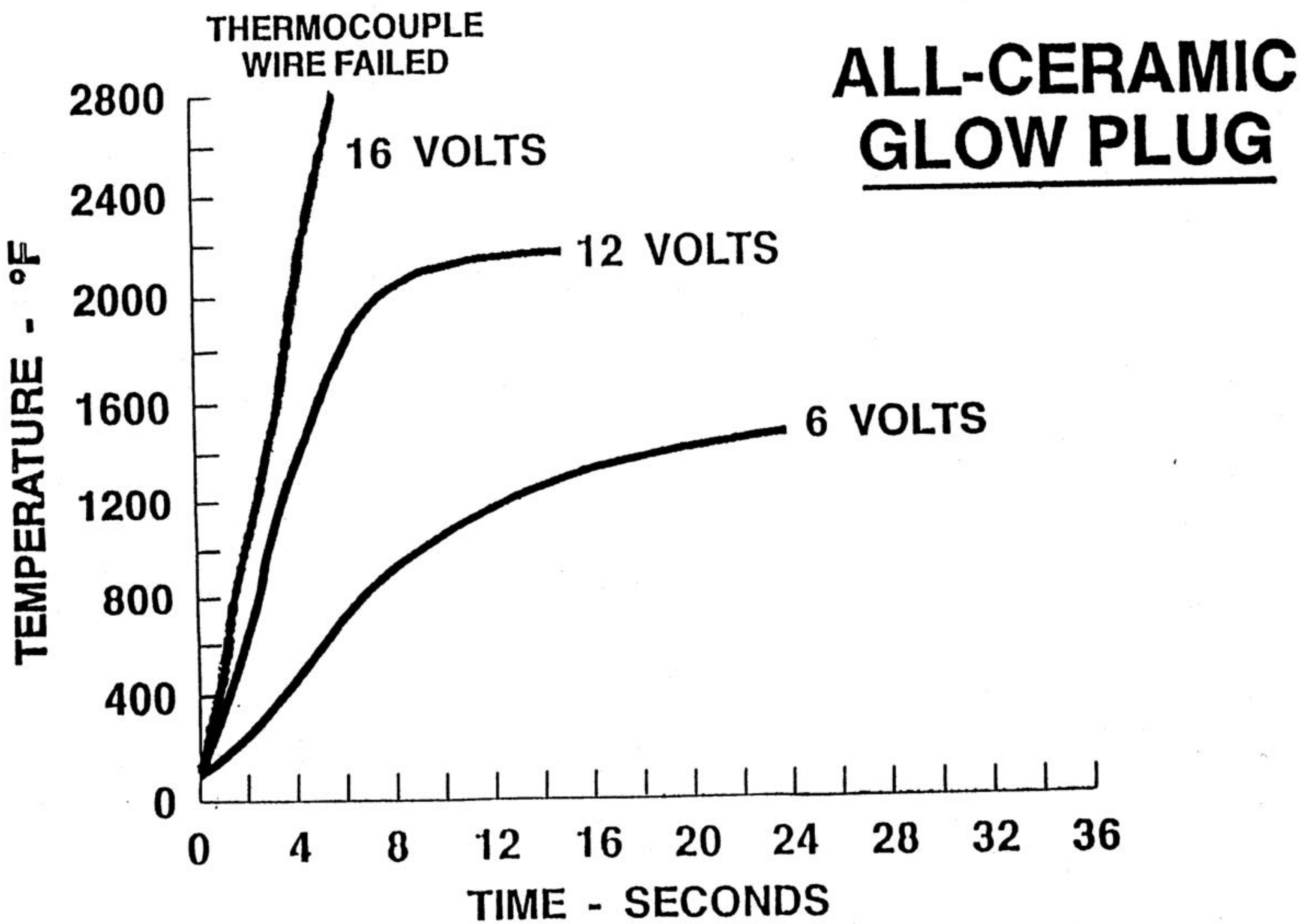

FIGURE 6: Response Time Ceramic glow plug vs. Conventional DDC Engine Testing

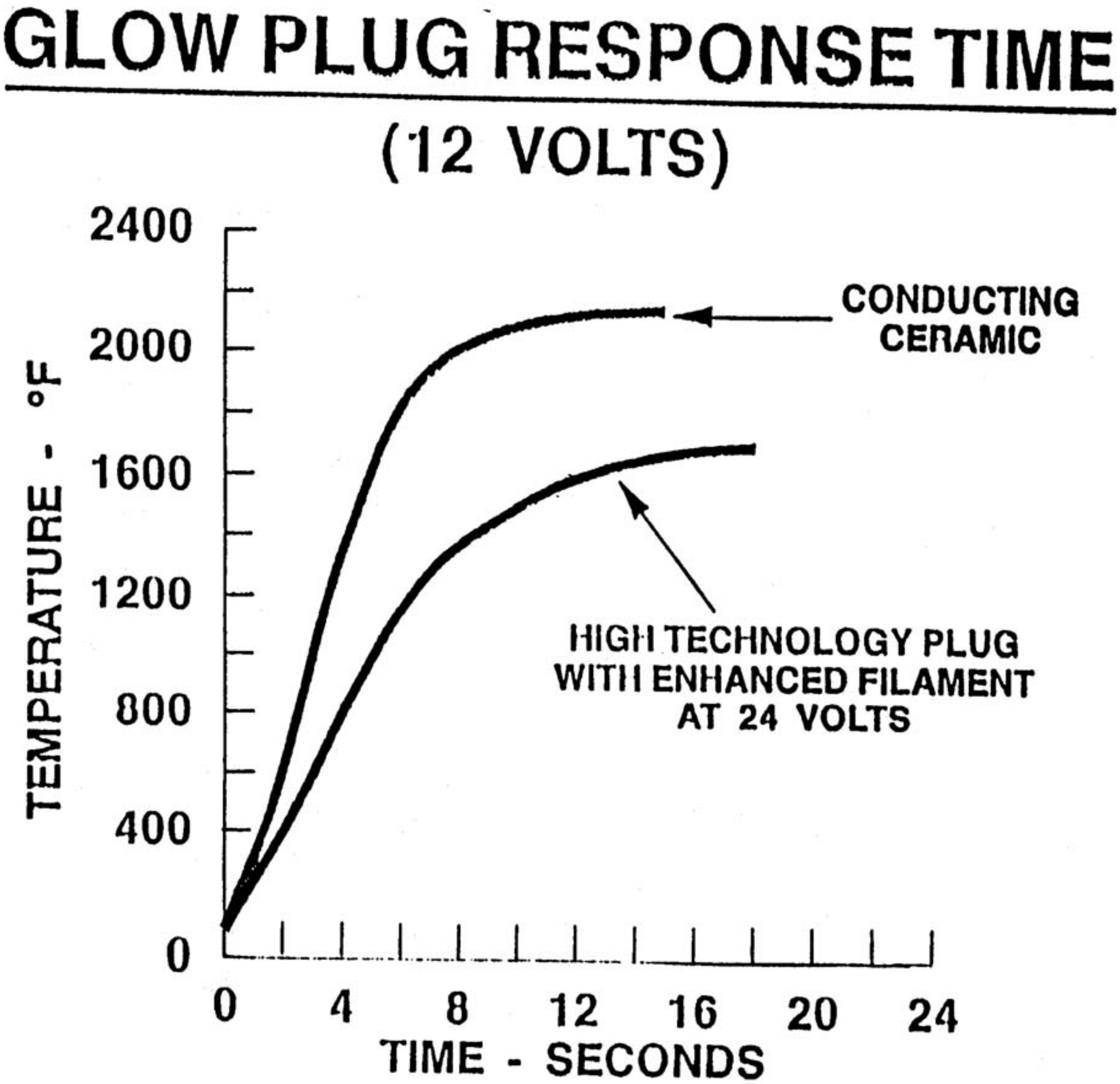

FIGURE 7: Response Time Ceramic glow plug vs Conventional DDC Engine Testing

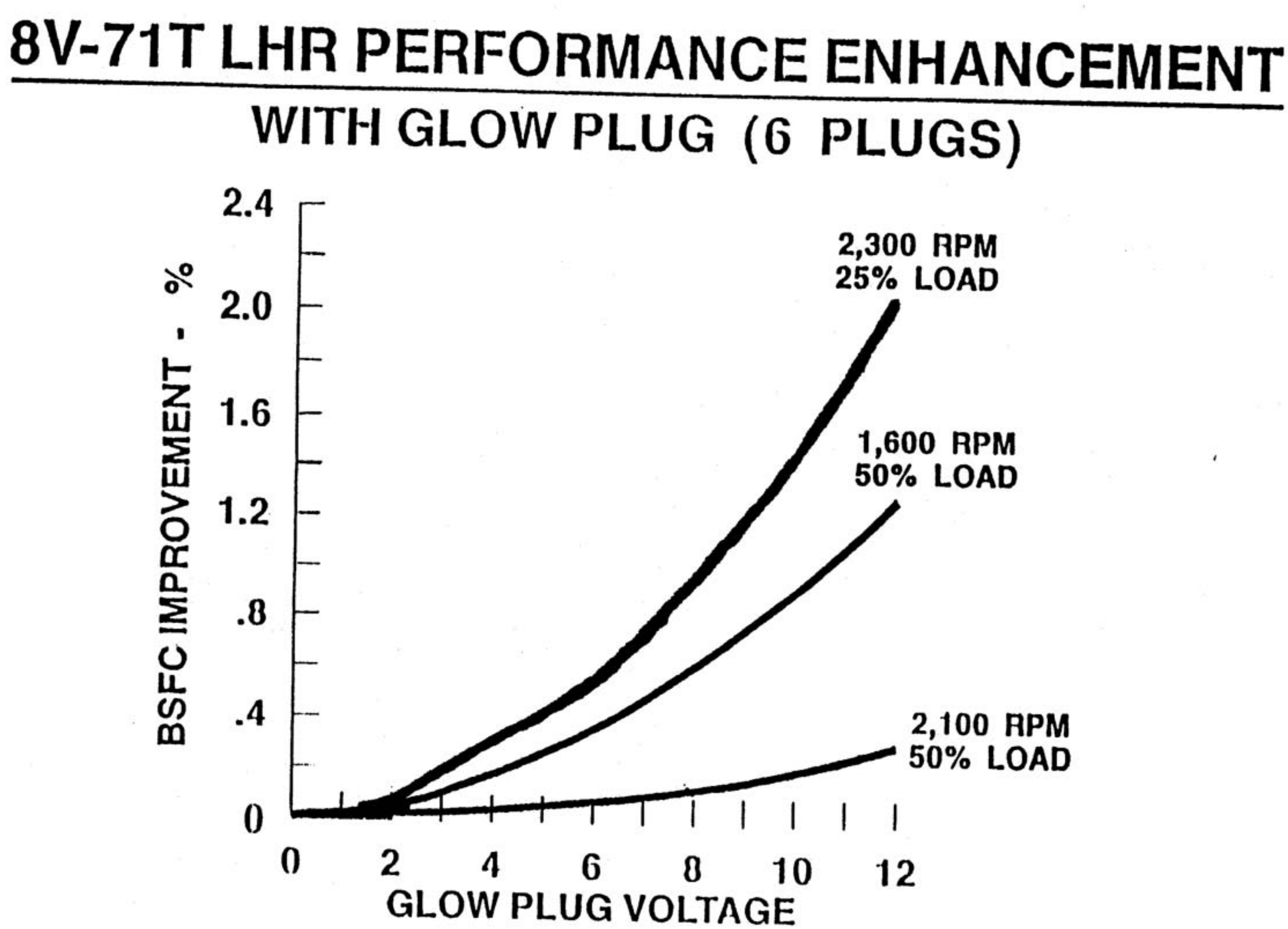

FIGURE 8: Engine Performance Enhancement with ceramic glow plug
DDC Engine Testing

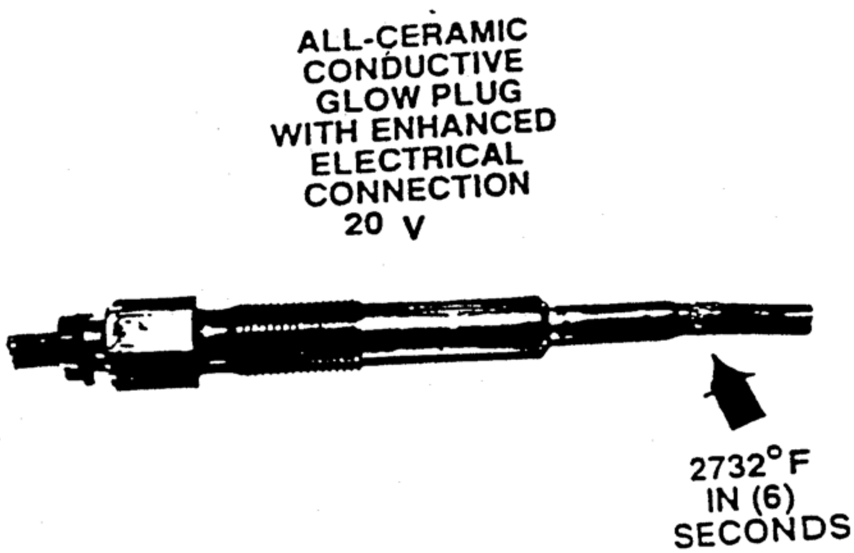

FIGURE 9: Photograph of all-ceramic glow plug after testing at 20 V

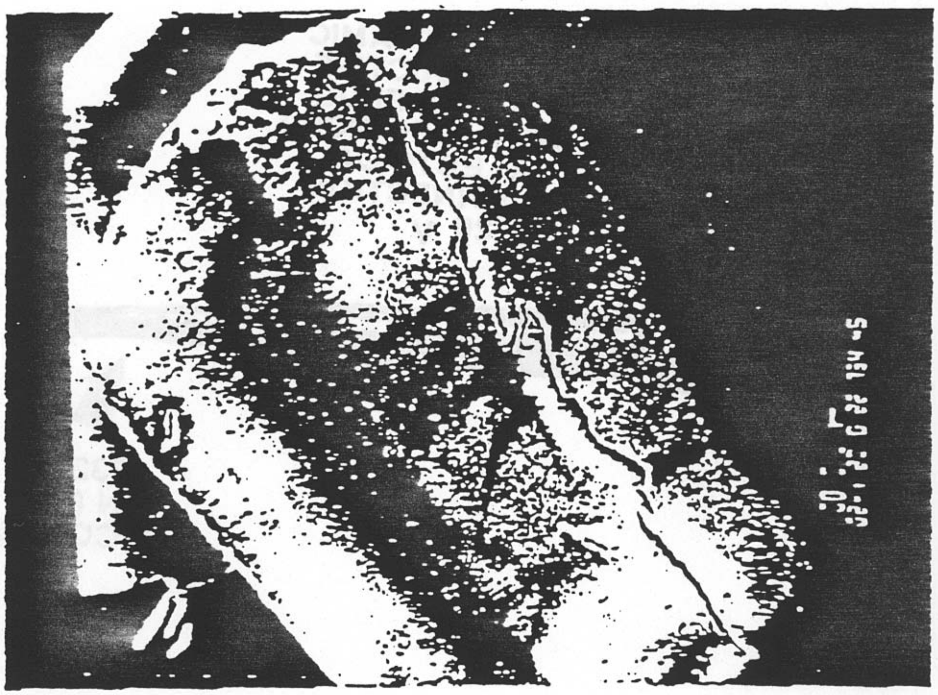

FIGURE 10: Scanning Electron Micrograph at 20 X showing crack and porosity

FIGURE 11: Scanning Electron Micrograph at 200 X
showing porosity cluster

FIGURE 12: Scanning Electron Micrograph at 1800 X showing unsintered silicon nitride particle

TABLE 2

COLD START

8V-71 T LHR MODEL 7083-7391 EQUIPPED WITH CONVENTIONAL METAL SHEATH GLOW PLUGS USED FOR BASELINE

PERFORMANCE COMPARISON AT -25°F AFTER 20 HOURS OF COLD SOAK

PLUG IDENTIFICATION	PRE-GLOW TIME (SECONDS)	VOLTAGE SUPPLY (VOLTS)	TIME TO 750 RPM (SECONDS)
PRODUCTION (P/N 25106758)	**38**	**24**	**50**
ALL CERAMIC PLUG	**20**	**6**	**24**
ALL CERAMIC PLUG	**6**	**12**	**9.5**

4.4 Design of Multi-Stationed Multilayer Casting Process (MCP) System

The results of the program were very promising; thus the company decided to investigate the possibility of improving the MCP process by using an automated multi-stationed MCP system. A conceptual design of such a system is provided in Figure 13.

A conceptual design of an automated machine to carryout the MCP process was completed. The machine will be constructed in the next phase of the program and used to produce glow plugs with higher precision than presently produced by handcrafted laboratory processes.

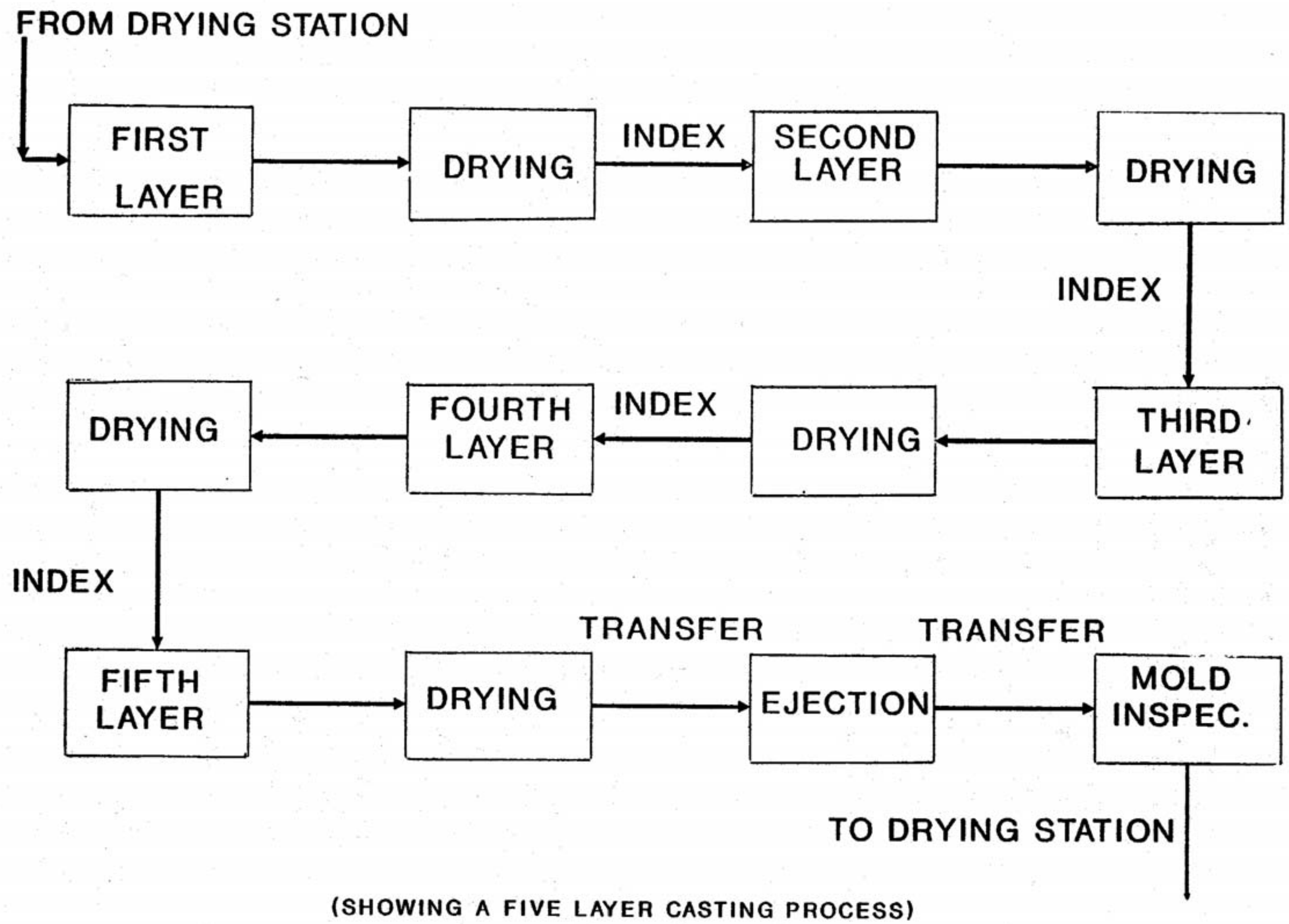

FIGURE 13: A Schematic Showing Various Process Steps in the MCP System

5. Results and Discussions

The company undertook the following experimental program to develop improved glow plugs. In order to increase the operating voltage of the glow plugs a number of iterative experiments were performed in the following areas:

- Material composition: silicon nitride, molybdenum disilicide, sintering aids
- Multilayer Casting Process (MCP)
- Casting process: mould, pressure of injection of slurries, time of deposition (thickness of layers), and drying time
- Sintering process: time/temperature cycle, atmosphere, etc.
- Electrodes and brazing process: brazing material, temperature and environment of brazing, etc.

Each of these areas was thoroughly studied. Samples were evaluated in-house for:

- heating rate and temperature
- leak rate
- other mechanical and electrical performance factors

A number of optimized samples were then given to DDC for testing in test engines.

Due to limitations imposed by the material composition it was not possible to achieve the 24 V operation in these glow plugs. The resistivity of the silicon nitride molybdenum disilicide composition changed rapidly as the ratio of the two major components was altered. In order to operate these glow plugs at a higher voltage it was essential to increase the resistance of the resistive layer to reduce the current being drawn by the glow plug. Excessive current will lead to overheating of the glow plug tip and can lead to catastrophic failure. A number of attempts to develop such a layer were not successful. The two possible ways to increase the resistance of the layer are to increase the resistivity of the composition or to make the cross-section of the layer very small. The resistivity of the composition could not be increased gradually due to a sharp gradient in the composition vs. resistivity curve for the molybdenum disilicide/silicon nitride composition. There was a limit to which the thickness of the layer could be reduced without causing manufacturing problems (warping, pinholes, inhomogeneity, etc.).

Further investigations are needed to develop glow plugs that can successfully operate at 24V.

Further investigation into the need for 24V glow plugs raises an important issue. Why do we need 24V glow plugs? The reason was to retrofit existing engines which are operating at 24V. But the performance results on Electrofuel all-ceramic glow plugs show that even operating these plugs at 12 V can lead to a far superior performance in terms of response time and temperature of operation so that we may not need 24V glow plugs. For retrofitting in the 24V applications, the circuit must be modified to drop the voltage from 24V to 12V. Even after dropping the voltage of operation the performance of the engine is expected to improve by using Electrofuel's all-ceramic glow plugs.

6. Conclusions

The overall program showed that ceramic glow plugs could become an important factor in diesel engines. The company developed a glow plug with superior performance.

Initial experiments to develop 24V glow plug were partially successful. However, the all-ceramic glow plugs operating at only 12V outperformed conventional glow plugs operating at 24V, thus the need for development 24V all-ceramic glow plug was not deemed essential.

Process parameters were further evaluated under this program to reduce the failure rate of glow plugs due to presence of porosity, unsintered particles and non-homogenous mixing. Further improvements in this area will be made during the development of the manufacturing technology, quality control and quality assurance procedures.

A preliminary design for the automated MCP process was developed. This concept will be further evaluated during development of the manufacturing technology.

The program shows great promise and has the potential to become a viable business venture if the manufacturing technology can be developed to produce a large number of glow plugs with minimum rejections, and the present program has shown the feasibility of this invention.

We recommend the following for the next phase of development:

a) Complete the customization and design of the automated MCP process.

b) Improve the joining between the ceramic and metal.

c) Produce glow plugs using the prototype MCP equipment and test in engines.

d) Produce both 12 V and 24 V glow plugs using the MCP equipment, for precise and accurate control.