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Development of New Iridium Alloy for Spark Plug Electrodes

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ABSTRACT

From the view of suppressing the global warming and environmental pollution, responding to the regulation of fuel consumption and exhaust gases along with lengthening the maintenance interval, are becoming more demanded. The development of a high-performance, long life spark plug has become essential in response to these demands. While improve performance (high ignitability and low required voltage), the discharge part of the spark plug needs to be reduced in size. But, in the past this has been difficult because of the limitations of platinum alloys in terms of wear. It has been difficult to achieve both smaller discharge parts and longer life.

To dramatically improve wear resistance, we researched materials that are both resistant to oxidation and have a high melting point. This research resulted in our development of a new iridium alloy.

Through this development we have been able to produce an iridium spark plug that surpasses the conventional platinum technology. The new iridium spark plug is now being used in high volume vehicle production.

This paper is divided into the following three parts and describes the development of the new generation of iridium spark plugs.

Chapter 1: Introduction
    The need for smaller electrode diameter and longer life spark plugs and related issues
Chapter 2: Development of Electrode Materials
    History of the development of the new iridium alloy
Chapter 3: Application in Spark Plugs
    1. High-performance and maintenance free spark plugs
    2. Super high-performance spark plugs

CHAPTER 1

INTRODUCTION

. Today, more sophistication is being demanded of the essential requirements of engines in terms of performance, which are "high power" and "low fuel consumption".

At the same time, a closer eye is being kept on global environmental problems than in the past, and "lower emissions" are becoming essential.(1)

To achieve these tasks, the number of engine-related components is increasing, and the space in which such components can be loaded is severely restricted.

In response to these social and technical trends, we expect that in the future spark plugs, which are placed in the combustion chamber, must be able to withstand more severe conditions. That is, they must be able to withstand leaner combustion, higher pressure, stronger swirling, and large quantities of EGR. This in turn will increase the required voltage and worsen the ignitability environment.(2)

Also, from the stance of better mountability, engine components are required to be as "maintenance free" as possible.(3)

It is known that the reduction in size of spark plug electrode is the most basic and effective means of responding to high performance.(4)

However, a reduction in size also substantially reduces wear resistance. It has been extremely difficult to both reduce size and maintain wear resistance.

The release of the platinum plugs in 1982 greatly improved performance and wear resistance compared to that in nickel alloy plugs of the past. However, we regarded that there is a limit to their usefulness in the engines of the future, and continued the research. Therefore, to come up with an ultimate spark plug which satisfies the engine requirements completely, we embarked on establishing a long-life technology higher than that of platinum.

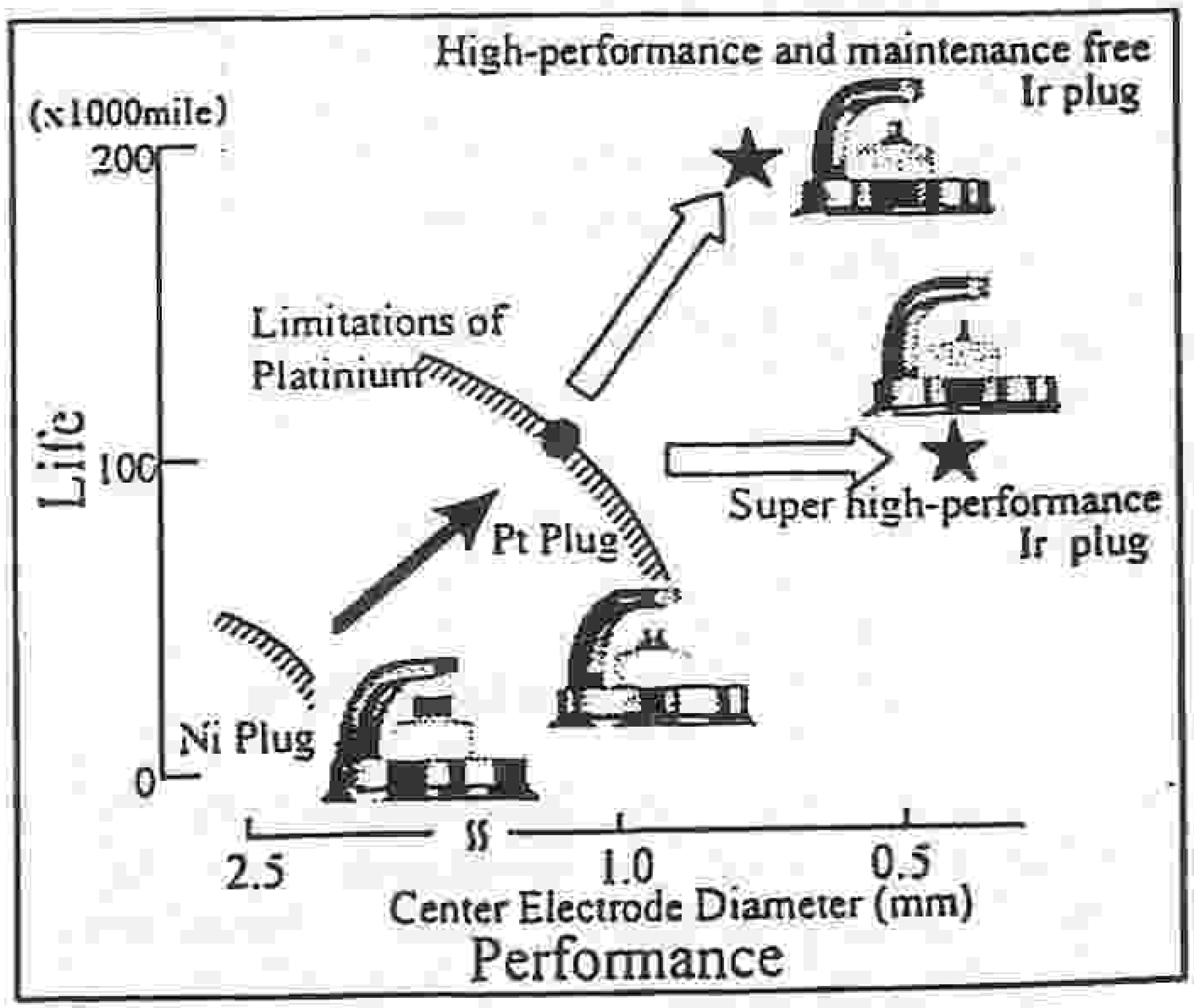


Fig.1 The "Next-Generation Spark Plug" Development Target

Now: before explaining the history of this development, this hapter will outline the effects of reducing the electrode iameter in the discharge part, that most affects spark plug roperties.

LECTRODE DIAMETER AND REQUIRED VOLTAGE

The required voltage is affected by various factors. he main such factors are:
① gap length, ②electrode shape, ③gas density, ④gas and lectrode temperature, and ⑤gas type. The factors that are elated to spark plugs are the gap length and the electrode hape. If the gap is shortened, the voltage decreases. But, as xplained later, ignitability deteriorates when this happens, and herefore the gap length is becoming longer and longer.
n the other hand, making the electrode smaller leads to lower oltage and higher ignitability at the same time.
hat is, the smaller the electrode, the more the centralized is he electric potential around the electrode tip. The required oltage can be reduced because the level of the electric field is nade stronger and local insulation breaks down easily.

Figure 2 shows the effects of electrode size on a spark plug sing a conventional nickel electrode. It is very clear that the maller the electrode, the lower the required voltage.

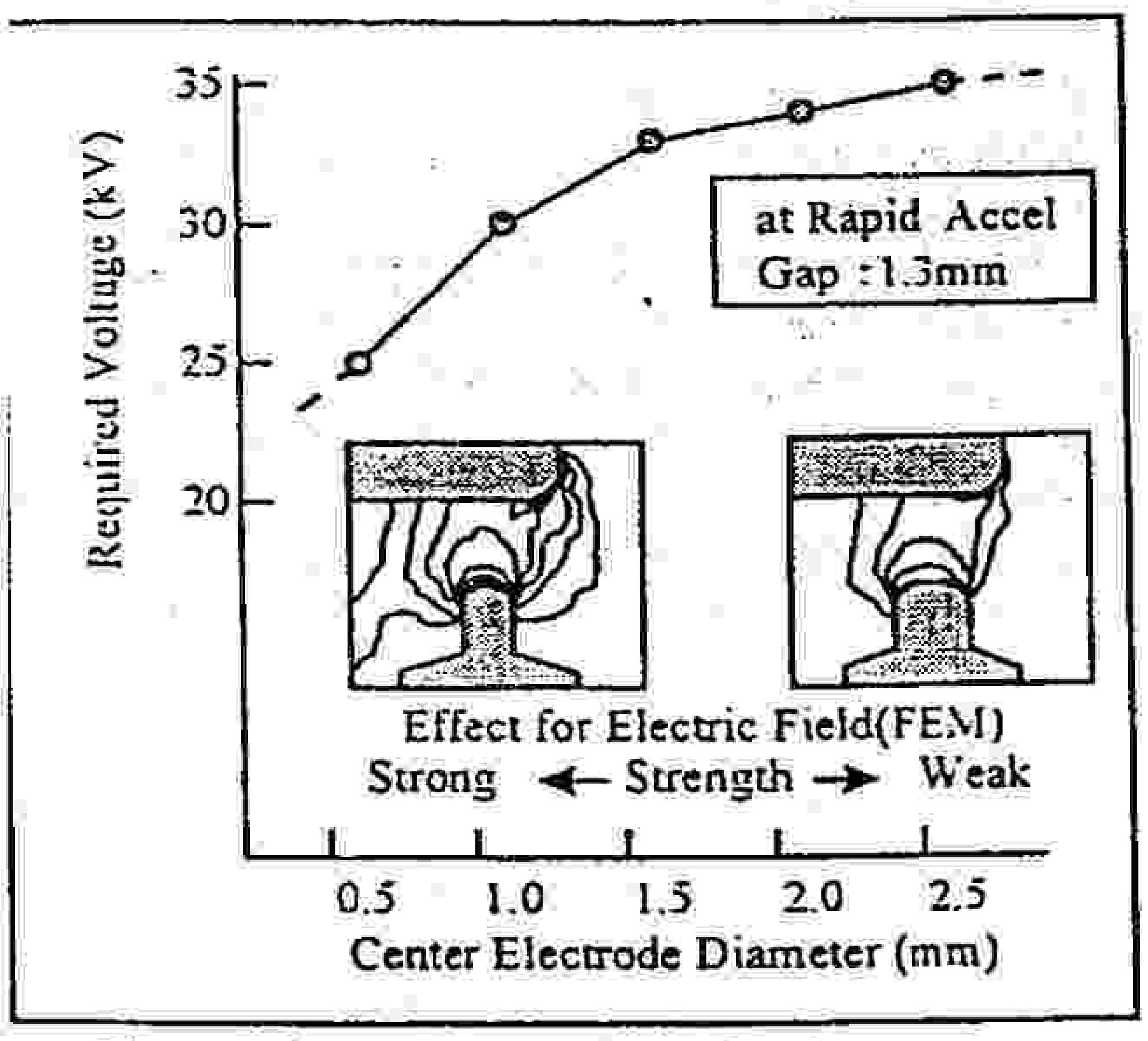


Fig.2 Effect of Center Electrode Diameter on Required Voltage

ELECTRODE DIAMETER AND IGNITABILITY

The electrode makes a quenching action to absorb the heat energy of spark flame nucleus. To minimize this quenching action and increase the ignitability , a smaller electrode (less contact area between the electrode and the spark nucleus) is the most effective process. Smaller electrode can put the energy provided from the ignition coil for the growth of spark flame nucleus. without any loss. Given the spark flame nucleus larger than a certain size. the flame propagation can continue even after being quenched by the electrode. preventing the misfire.

Figure 3 shows the effects of reducing the electrode size. Because ignitability performance deteriorates as the gas mix is made leaner, to evaluate plug ignitability we determined the maximum air to fuel ratio at which ignitability still occurred.

We found that with a smaller electrode there was a substantial improvement in lean limit ignitability

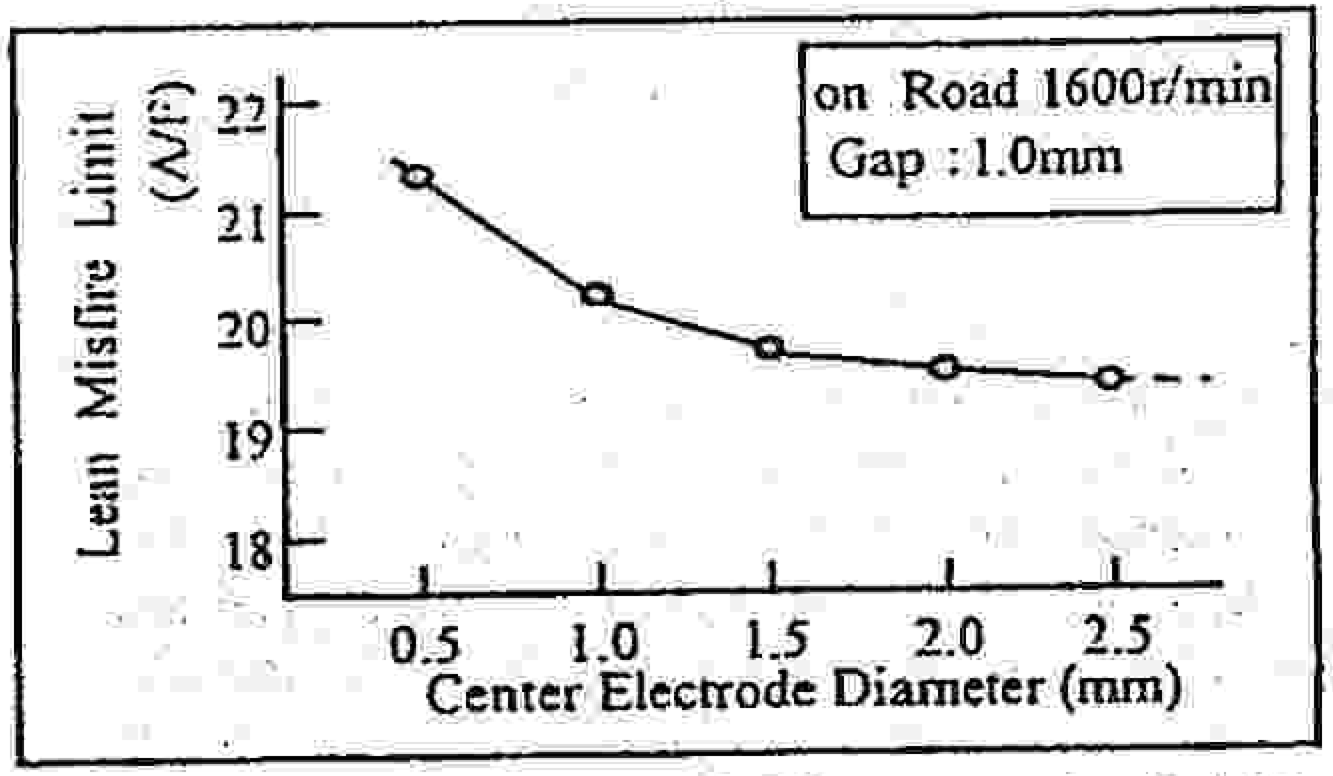


Fig.3 Effect of Center Electrode Diameter on Ignitability

ELECTRODE SIZE AND WEAR RESISTANCE

Reduction in size of an electrode contributes both to reducing the required voltage and improving ignitability performance. On the other hand, as shown in Figure 4, there is a rapid acceleration in wear as the electrode becomes smaller. This is because a smaller electrode, being exothermic by a concentration of spark energy and heat received from combustion gas, accelerates the wear by electrode temperature rising.

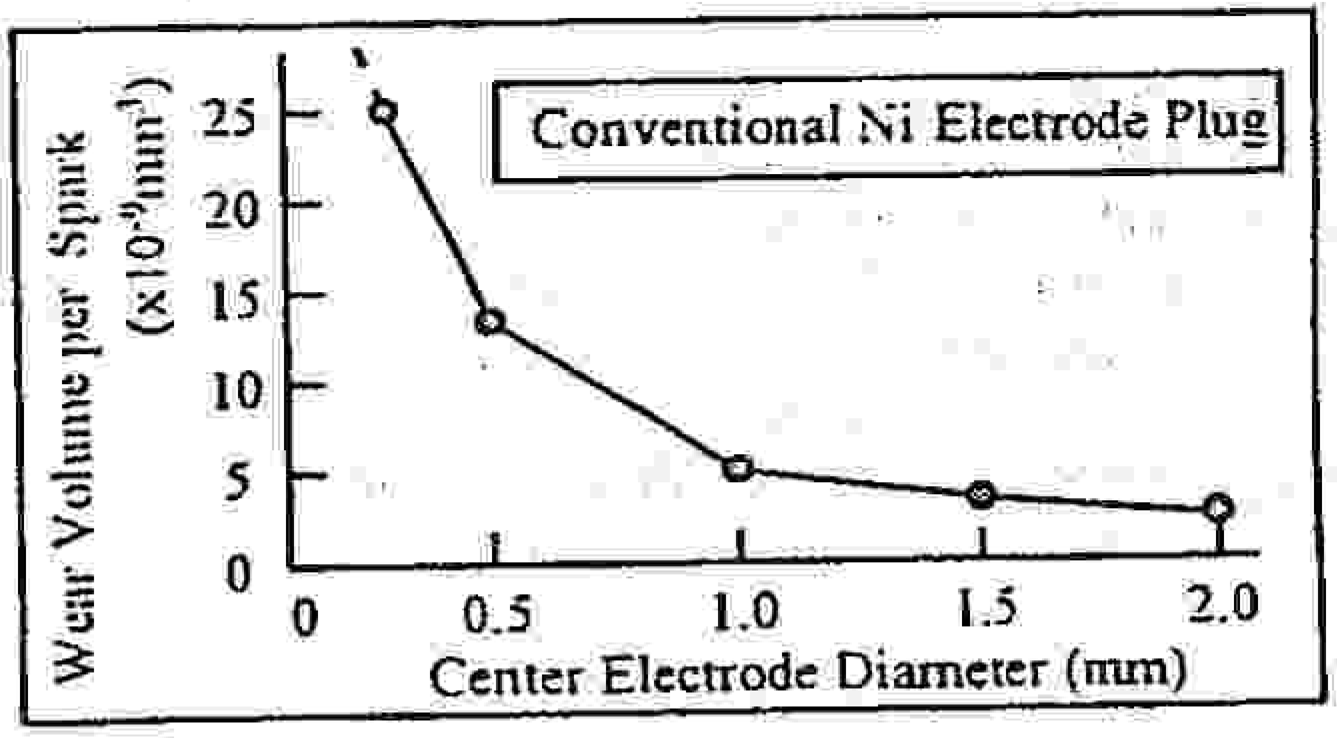


Fig.4 Effect of Center Electrode Diameter on Wear Volume (Field Test)

Let us now explain the mechanism that results in electrode wear. Electrode wear is affected by the following two factors.

(1) SPARKING WEAR

An electrode suffers wear whenever there is a discharge. The discharge caused by the ignition system in internal combustion engines is generally a combined discharge. It can be separated into the discharge resulting from the Capacitive component in the sparking circuit system, and the discharge resulting from the Inductive component.,

A Capacitive discharge is an electric discharge deposited in floating capacitive component formed in the space of ignition spiral, and between plug cable and engine. It has a very high energy density, and is characterized by high current flowing for a short time. This causes local temperatures of some thousands of degrees on the electrode, and wear because of melting and splashing.

On the other hand, in Inductive discharge, which occurs after the capacitive discharge, an electromagnetic energy deposited in secondary spiral of ignition coil is released. As the cations in the gas collide with the negative electrode(center electrode), with high kinetic energy, they throw out the atom on the surface of negative electrode. Although the current of inductive discharge is as small as few mA, they are kept for several mSEC which enlarges the wearing.
(The mechanism of sparking wear is shown in Figure 5.)

Therefore, use of a material with a high melting point is required to improve the sparking wear resistance.

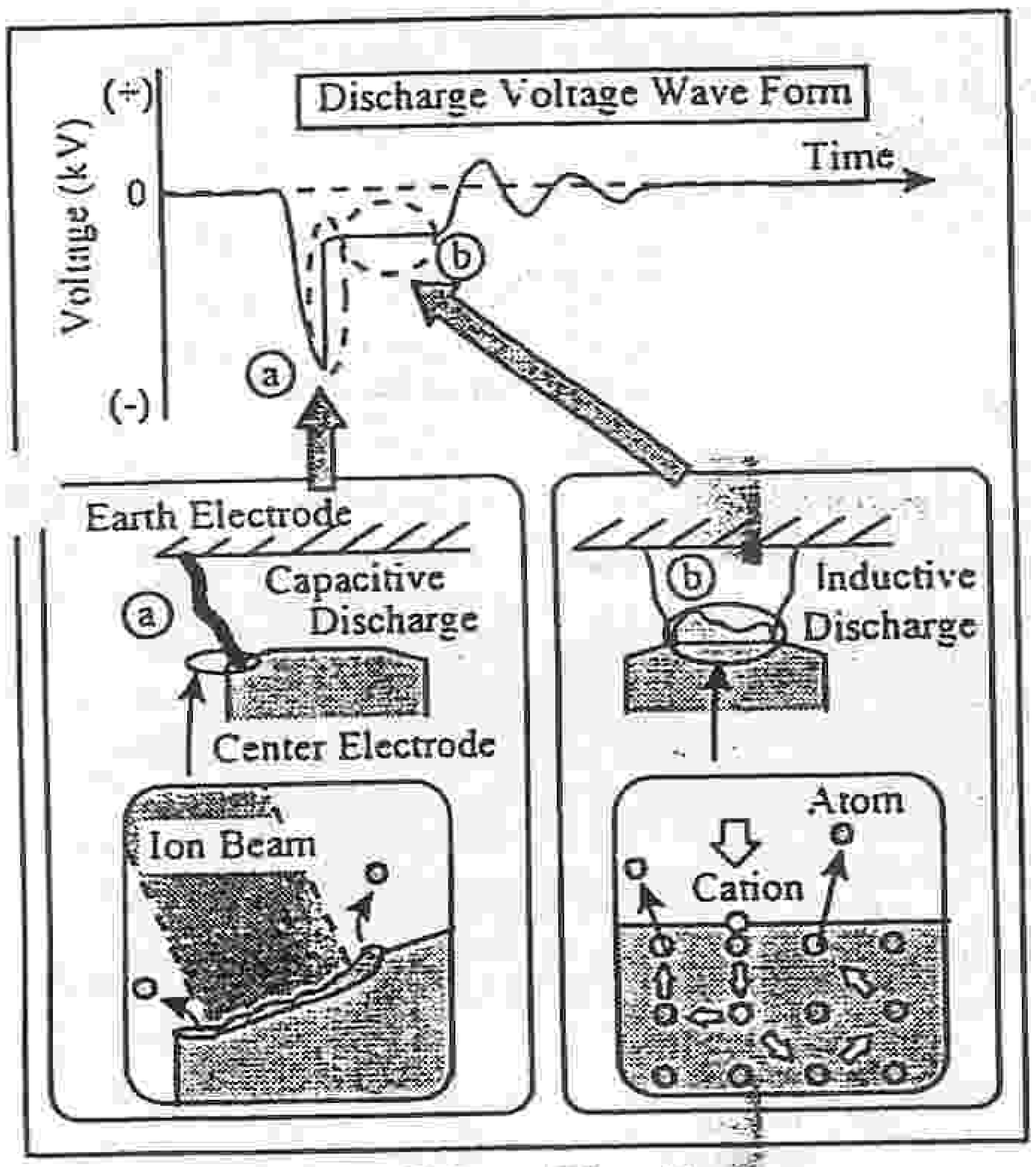


Fig.5 Discharge Voltage Wave Form and Electrode Wear Mechanism (REF.5)

(2) OXIDATION WEAR

The process of electrode wear also proceeds due to oxidation and repeated damage to the oxidized layers. That is, oxidation proceeds from the surface of a healthy electrode and weakened oxidized scales peel away from the electrode surface causing wear.

As shown in Figure 6, spark plugs are exposed to an environment of high temperatures and oxidation. Therefore, it is important that the material from which spark plug electrodes are made be highly resistant to oxidation. The forming oxidation coating must be stable. In other words, low oxidated substance vapor pressure, and less diffusion to the interior are the requirements.

We have discussed the mechanism of electrode wear above. As the electrode becomes hotter, the speed of both sparking wear and oxidation wear accelerates. Then, it is necessary to improve sparking wear resistance and oxidation wear resistance at the same time.

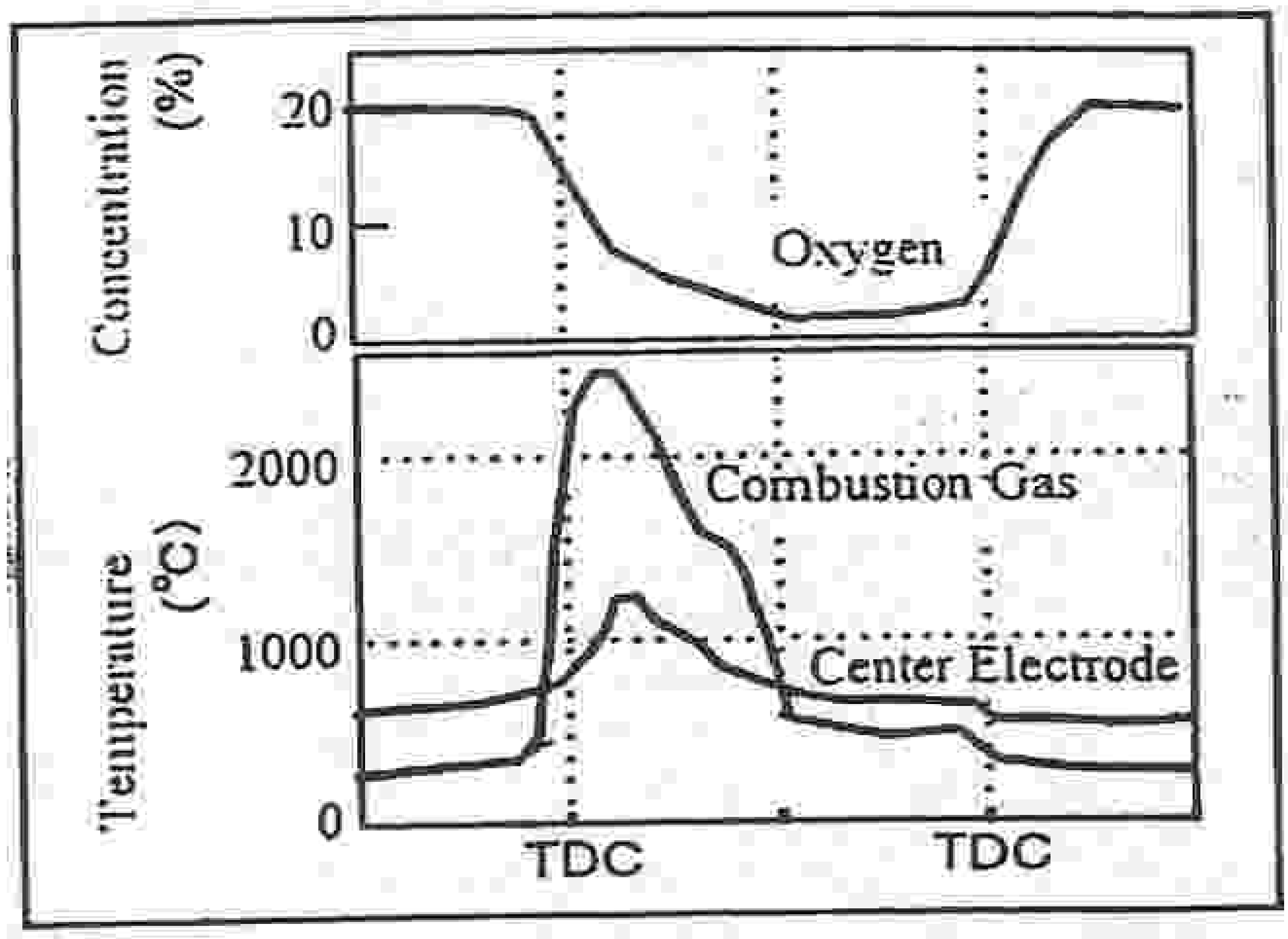


Fig.6 Plug Environment in Engine Combustion Chamber

As explained , reducing the size of the electrode diameter tends to dramatically worsen wear resistance. Therefore, the usefulness of current platinum spark plug technology in engines of the future is limited.
Therefore, We embarked on the development of a new electrode material.

CHAPTER 2

DEVELOPMENT OF ELECTRODE MATERIALS

As explained above, the material for use in a spark plug must be both resistant to sparking wear and resistant to oxidation wear.

Firstly we classified and tested materials for sparking wear and oxidation wear.

We will first discuss the results obtained in our study of sparking wear.

First, we fixed a typical high-melting-point-material to the top of the inconel-made center electrode. Then, we tested for which type of electrode materials may be effective in reducing sparking wear.

To eliminate the effects of oxidation on the spark plug, the test was performed in a 0.5 MPa nitrogen chamber, a 50 mJ ignition coil with a sparking rate of 60 Hz.

Figure 7 shows the volume wear ratios for platinum and shows how the order of wear was determined by the melting point of the electrode material. Note however, that at approximately 2,000°C, there is a change in the trends.

hat is. up to 2,000°C. the higher the melting point the greater he wear resistance. However. when 2,000°C was exceeded. his influence of the melting point was harder to detect. he reason is that this event is related to temperature rise of the lectrode sparking portion, and during the discharge, the lectrode sparking portion momentarily rises up to 2,000°C.

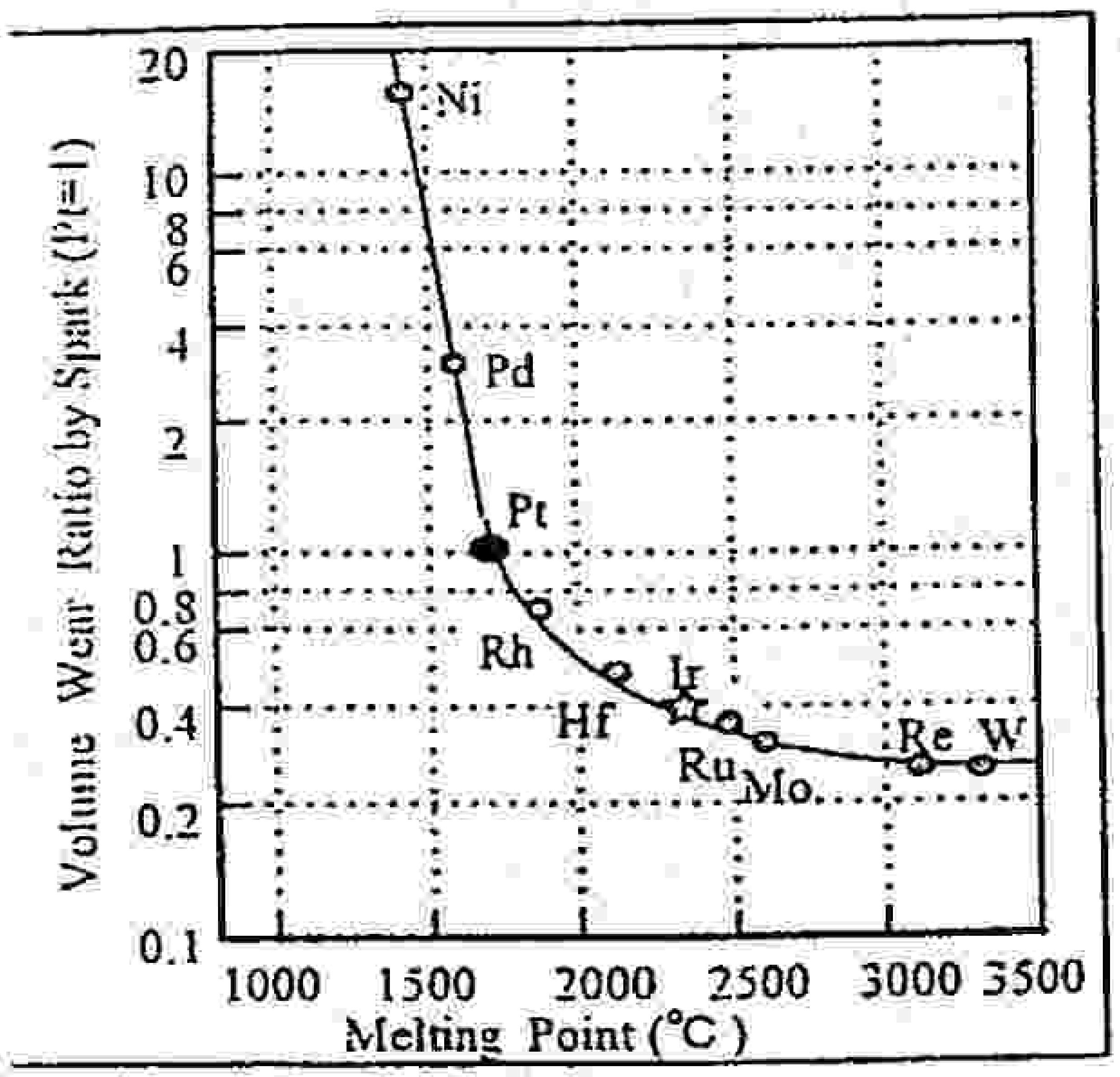


Fig.7 Each Metal's Wear Ratio by Spark Compared to Platinum

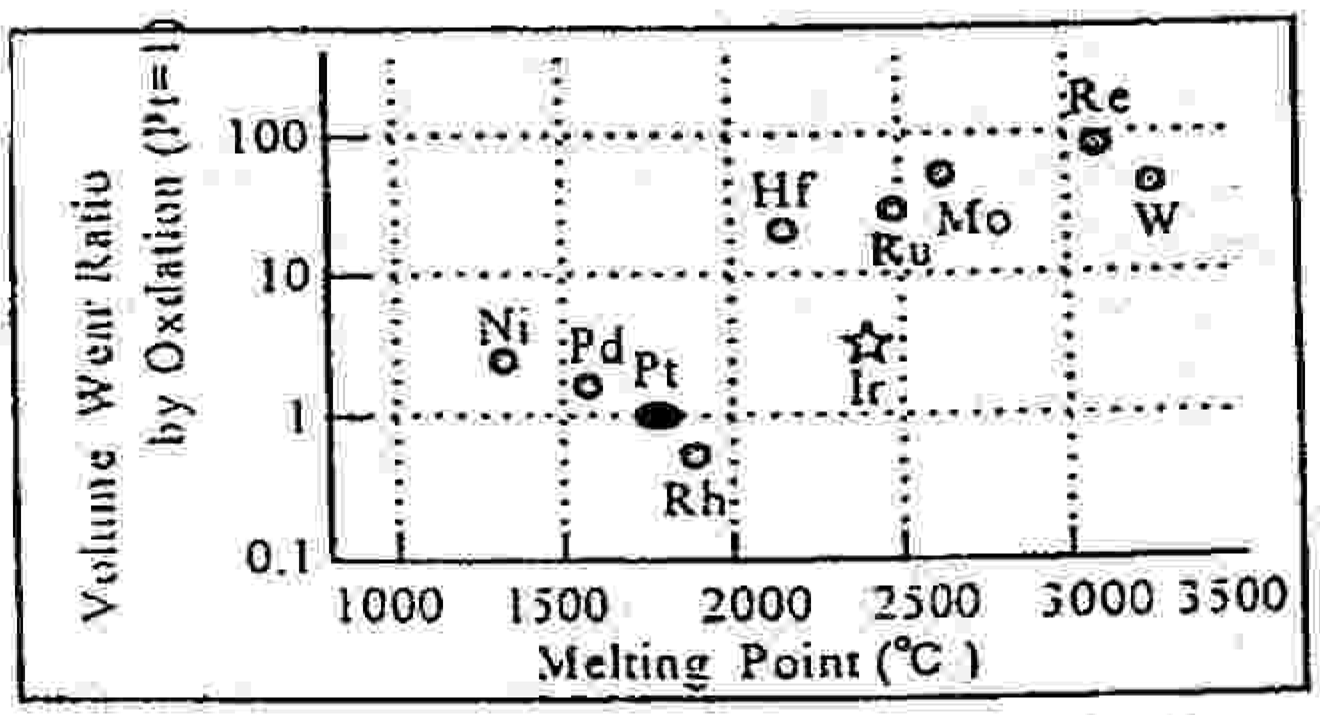


Fig.8 Each Metal's Wear Ratio by Oxidation Compared to Platinum

Next we will discuss the results of our tests relating to oxidation wear.

In our evaluation of oxidation resistance we processed some materials with high melting point into a cylinder 2.0 mm long and 1.0 mm in diameter. This was left for 100 hours in an electric furnace with air at 1,000°C. We studied any weight loss. The results are shown in Figure 8.

There was no correlation between oxidation resistance and melting point. Rather, oxidation resistance was affected by the high temperature characteristic of the material, that is, its vapor pressure in oxygen, and by the coefficient of ion diffusion to interior. We found that materials desirable for their superior resistance to sparking wear, such as tungsten, rhenium and molybdenum, have deteriorated with inferior oxidation.

The combined results of sparking wear and oxidation wear are shown in Figure 9.

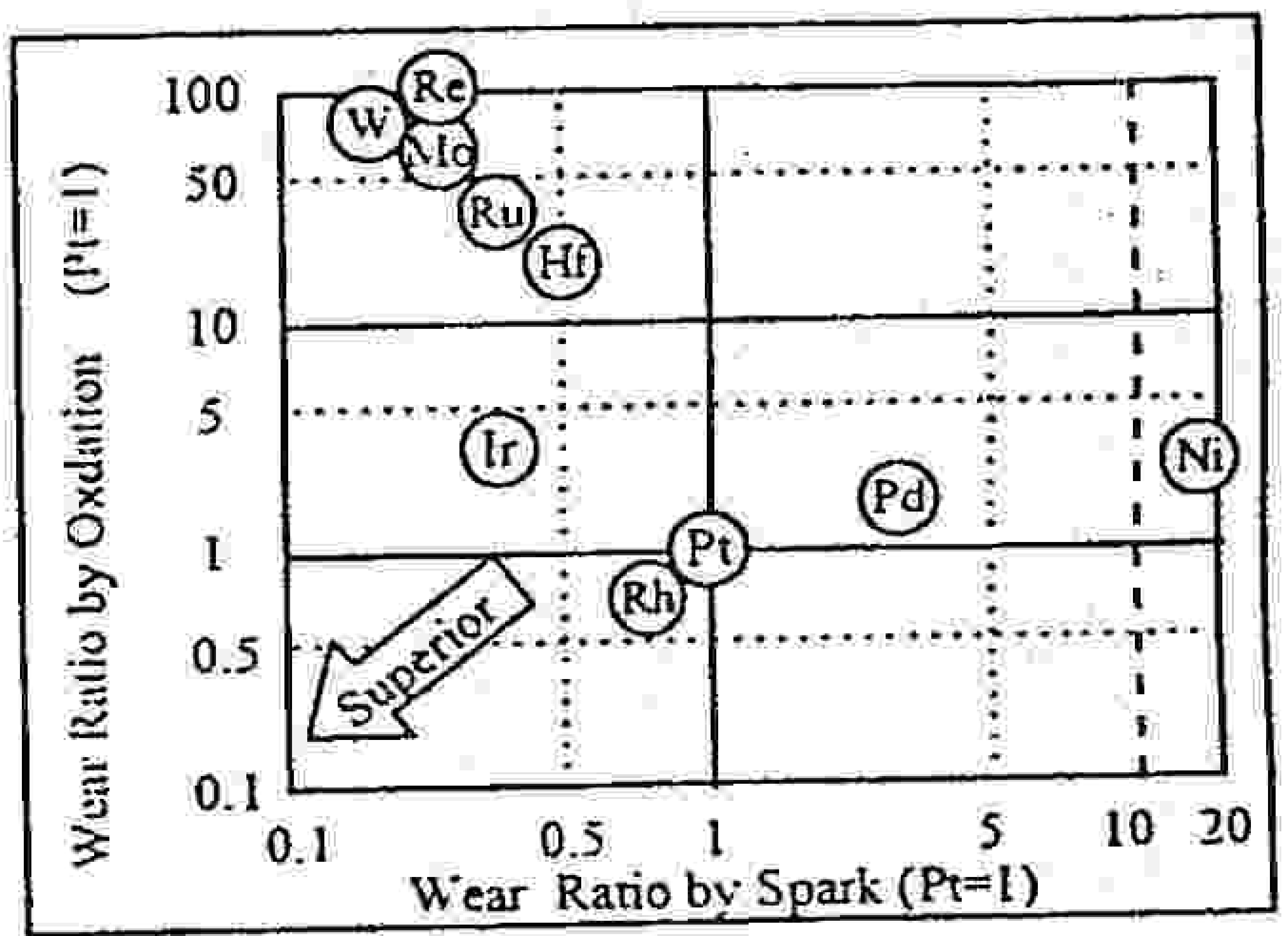


Fig.9 Combined Effect (by Spark & Oxidation) on Wear of Each Metal Compared to Platinum

Platinum, a material previously used for long life spark plug electrodes was resistant to both sparking and oxidation wear. However, we found that iridium, with a melting point almost 700°C higher than Platinum, had the greatest potential for resistance against wear. Because while it was not as resistant against oxidation as pure metals, it was far superior in terms of sparking wear resistance.

We therefore turned our eyes to this iridium and looked at ways of improving its resistance to oxidation.

First we investigated the oxidation characteristic of pure iridium.

As before, we made a cylinder 2.0 mm long and 1.0 mm in diameter made of a iridium solution. This was left for 100

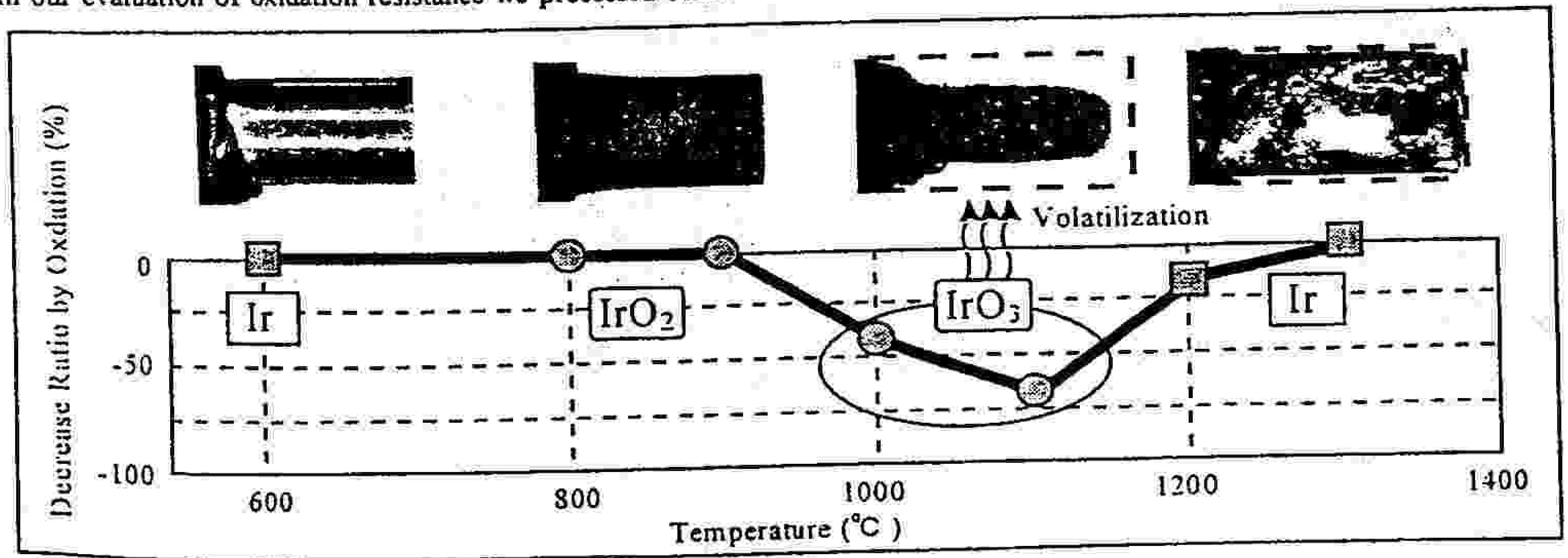


Fig.10 Oxidation Characteristic of Pure Iridium

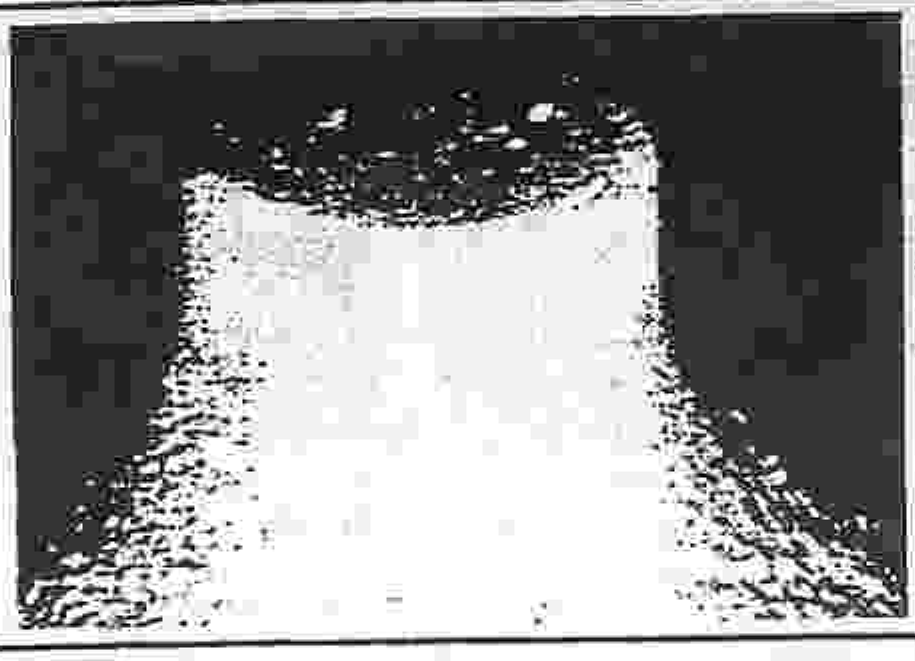
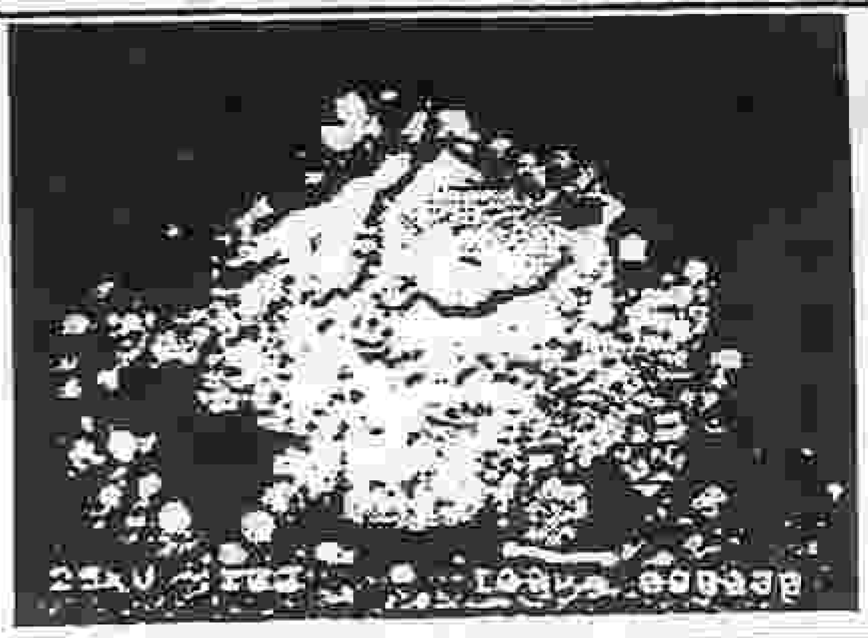
Low Load Test	High Load Test
Field Test Driving Distance : 60,000 miles	WOT Continuous Test 5600r/min . 100h
	

Fig.11 Appearance of Pure Ir Tip after Endurance Test

hours in an electric furnace in which the temperature of the air was changed. And we looked at its resistance to oxidation. The results are shown in Figure 10.

When the iridium reached temperatures of over 600°C it generated an IrO_2 oxide. This oxide was stable and oxidation reduction was not observed. However, at temperatures of over 900°C, an IrO_3 oxide was generated. This oxide has a sublimation (volatility) characteristic and resulted in substantial oxidation reduction. Note however, that while this characteristic was prevalent up to 1,200°C, at higher temperatures the oxygen and the pure metal dissociated and further oxidation reduction was not seen.

If an actual engine was operated under high load, the temperature where the discharge occurs on the center electrode rises above 900°C and so the iridium would be placed in an atmosphere of sublimation.

Figure 11. Shows the results of evaluating pure iridium. In ordinary driving around the city and suburbs the temperature remains low and so no abnormal wear was seen . And we found very little electrode wear. However, when we implemented a durability test under continuous high load on the engine bench, we found abnormal wear caused by oxidation volatility.

Next, we examined the suppression of oxidation volatility.

Broadly speaking, there are two ways in which this can be done. The first involves using insulation made from a highly oxidation resistant metal. The second involves creating an alloy. The insulating method involves surface processing, that is , plating or cladding the surface with an insulating thin plate. In either case of insulating method (plating and cladding), practical application is difficult when cost and mass production are taken into consideration.

Therefore, we investigated whether or not it was possible to inhibit the iridium oxidation volatility by creating an alloy from iridium and an additive metal.

We focused on three groups when selecting the metal to be added and then evaluated oxidation wear. The three groups are explained below.

Group One consists of base metals such as Al, Si, and Cr. When these oxidize they generate passive coatings of Al_2O_3, SiO_2, and Cr_2O_3 respectively and so we expected that they would be able to provide stable surface coating.

Group Two consists of metals such as Rh, Pt, and Pd. They are precious metals like iridium in the same family as platinum. The amount lost through volatility at high atmospheric temperatures is less than iridium and so they are materials that can inhibit volatility.

Group Three consists of easily-oxidated metals such as W and Mo. These elements capture oxygen ions more easily than iridium and so could be expected to suppress iridium oxidation. We used the same test method as when we tested the pure iridium. The test materials consisted of alloys created with pure iridium and 10% by weight proportions of the added metal.

The results are shown in Figure 12. The Group Two metals, that is the platinum family of metals, were most effective in improving the oxidation resistance of iridium. Of these, the greatest improvement was made by adding rhodium. Addition of the metals in Groups One and Three resulted in no substantial change. We assume this is because of the difficulty of obtaining an even solution mix of these metals with iridium, and the oxidation coating formation and oxidation capturing not achieved as expected.

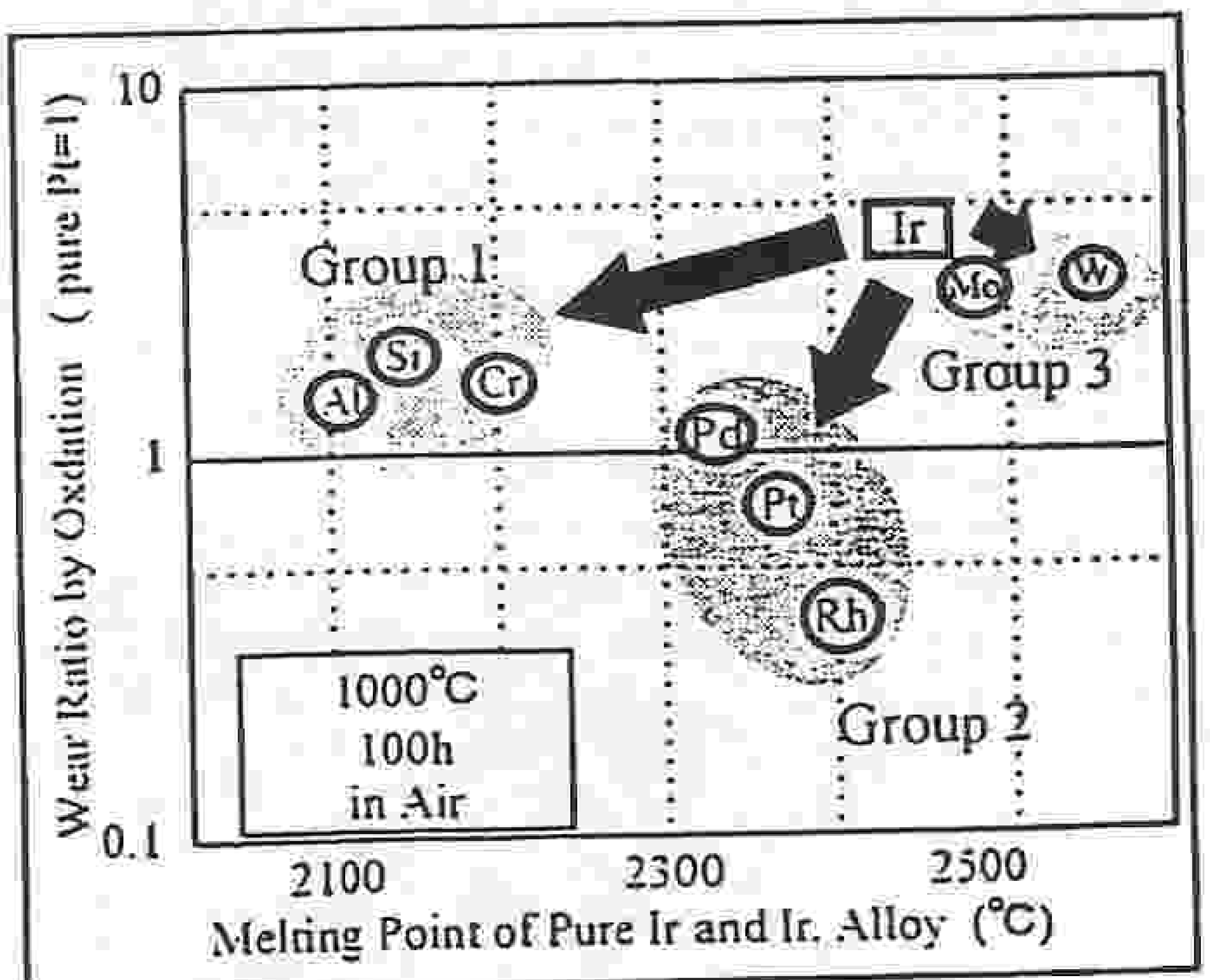


Fig.12 Additive Metals' Effect to Oxidation Resistance

We can assume that the fact that the improvement was reatest with the addition of rhodium in Group Two. is because odium has the most stable oxidation resistance at high mperatures of rhodium, platinum, and palladium. urthermore, rhodium has the highest melting point, at 1,966°C f these metals and we can therefore also assume that it also as a good resistance to sparking wear.

Next we determined the optimum amount of rhodium to add o the iridium.
Ve tested additions of 0, 1, 3, 5, 10, 20, and 40% weight by olume additions of rhodium. The results are shown in Figure 3. Although the oxidation resistance increased as the amount f rhodium increased, there was little difference to be seen hen the rhodium exceeded 10%.

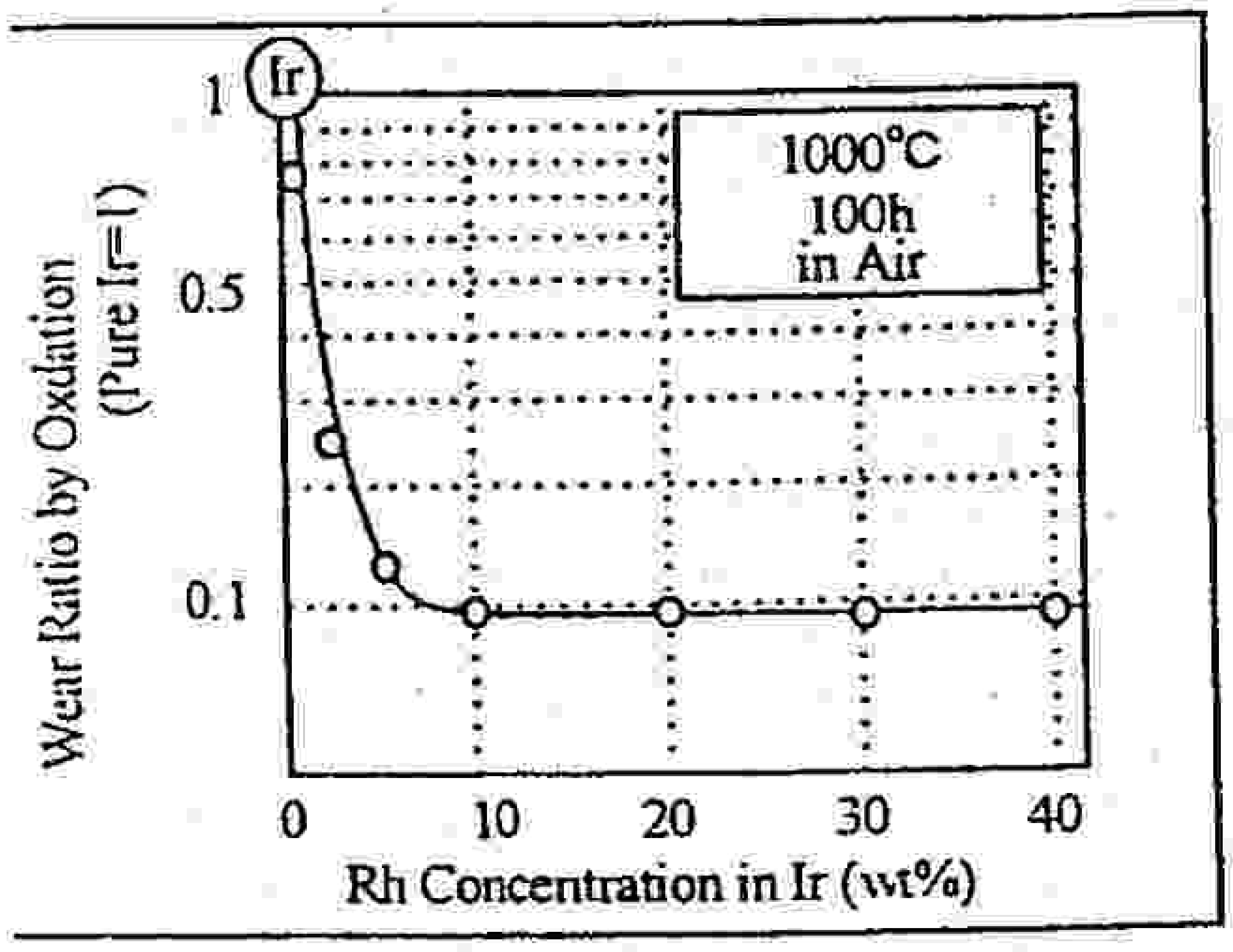


Fig.13 Oxidation Wear Resistance Improvement by Adding Rhodium to Iridium

We then took the following two points into consideration in determining the optimum amount of rhodium to be added.
Firstly, the more added, the lower the melting point of the iridium-rhodium alloy. This was not good in terms of sparking wear resistance. Next, rhodium ore is more expensive than iridium ore and so the more added, the greater the cost.
We therefore decided upon a 10% weight by volume addition as the optimum minimum amount.

The results of a durability test under continuous high load of this Ir-10Rh material are shown in Figure 14.
Whereas abnormal wear had occurred because of oxidation volatility in the pure iridium, no abnormal wear was seen in the new material developed. Its sparking wear resistance was also superior.

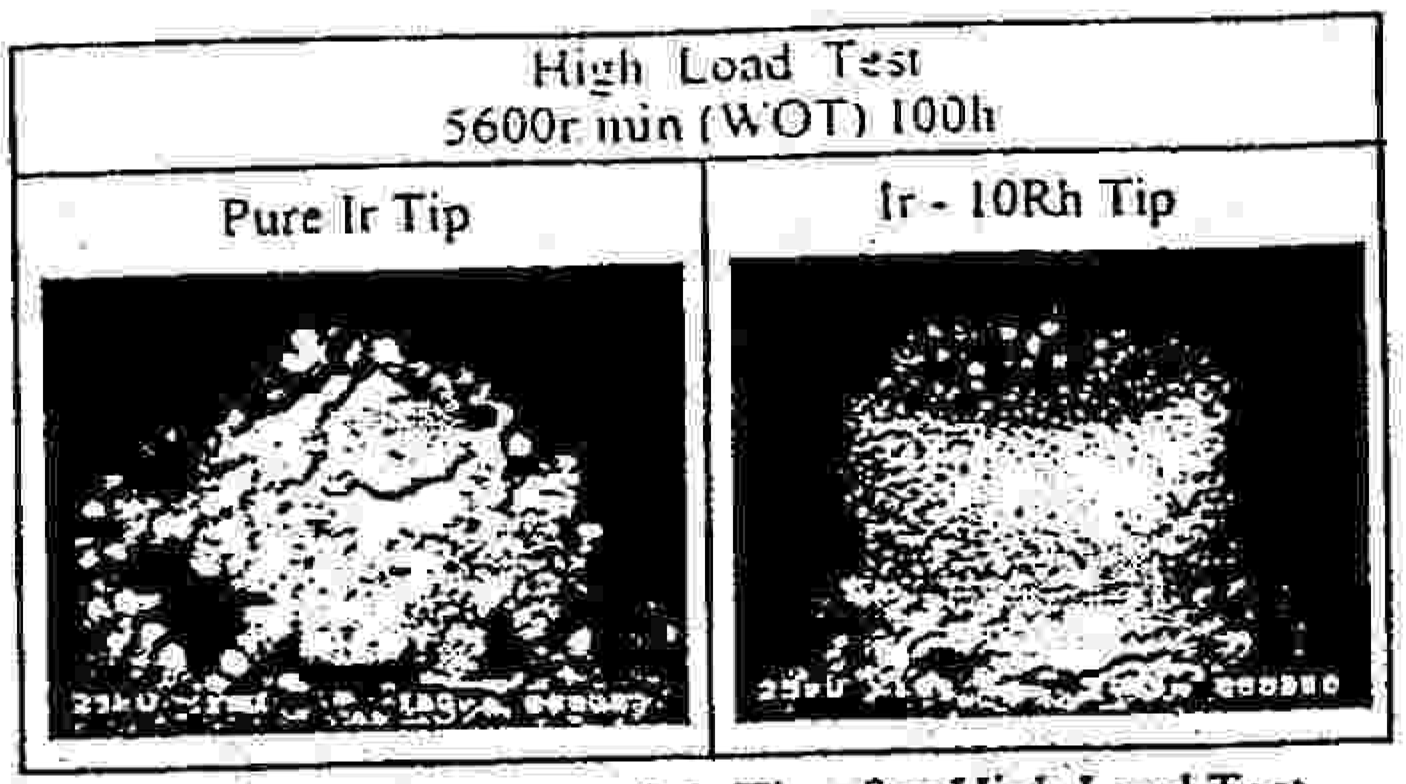


Fig.14 Appearance of Ir Tip after High Load Test

We then analyzed the improvement in wear resistance in detail. Figure 15. shows the results of a cross-sectional chip component analysis implemented after the end of the durability test.
The SEM (Scanning Electron Microscope) image is shown at the top of the figure. The bottom pictures show the cross section analysis by EDS (Energy Dispersive Spectrometer) of Rh, O, and Ir concentration. The EDS analysis shows that the Rh and O concentration at the chip surface is higher than that of the interior. On the other hand, the Ir concentration is low at the surface. This means that while Ir surface is partially volatilizing, the rhodium oxide (Rh_2O_3) is still remaining on the chip surface. We believe that this oxide mantle prevents further oxidation volatility.

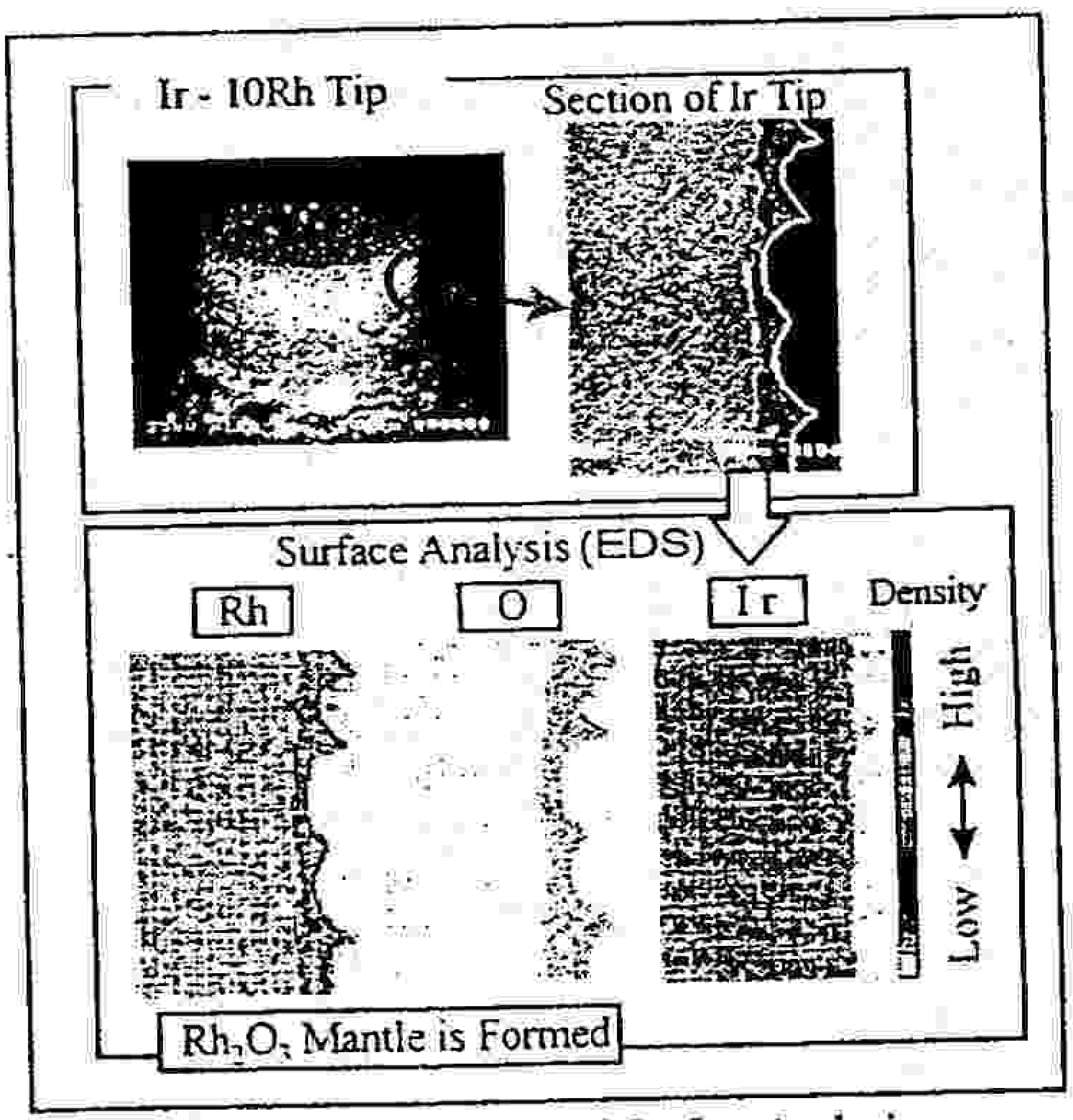


Fig.15 SEM Image and Surface Analysis

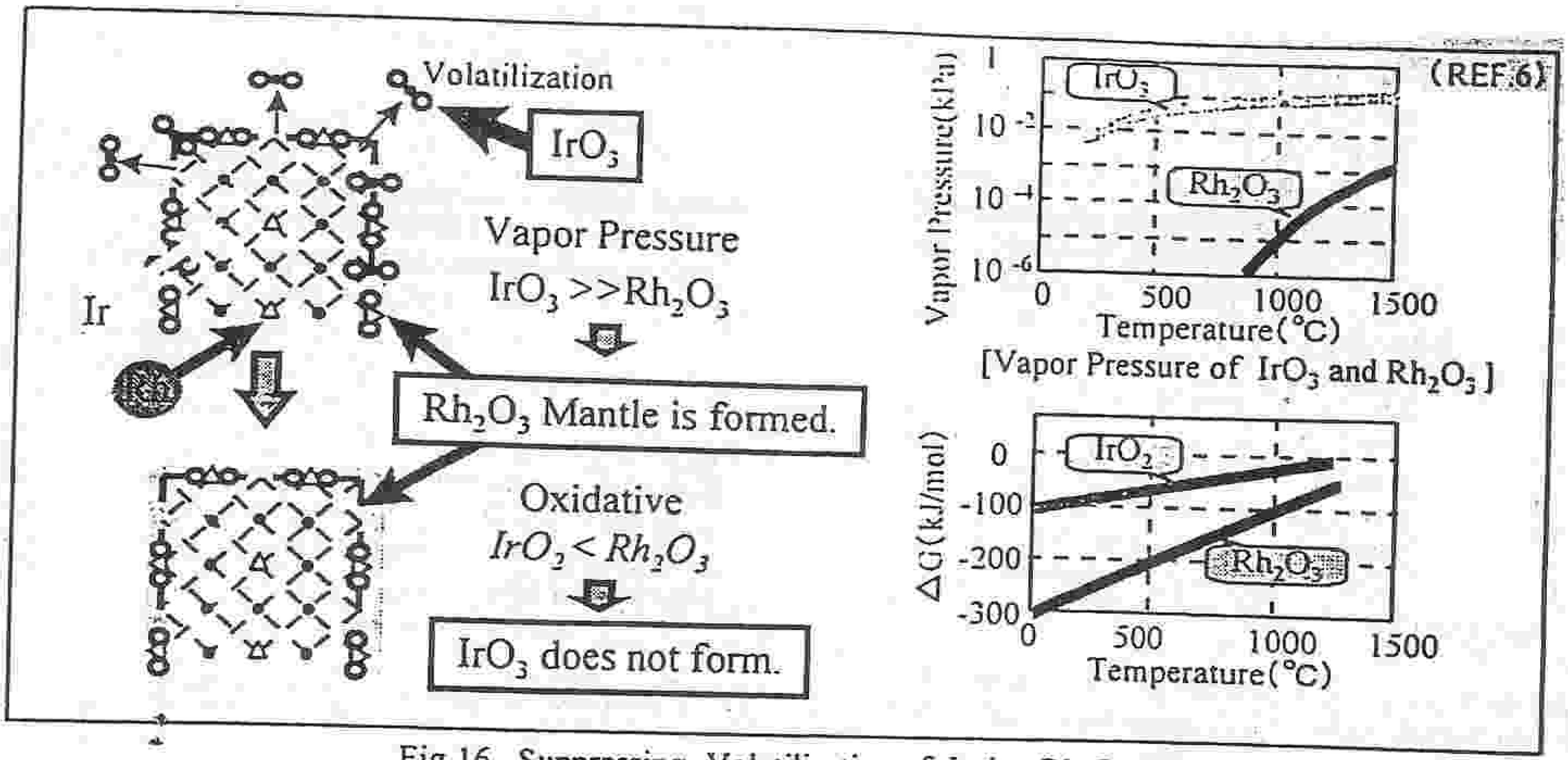


Fig.16 Suppressing Volatilization of Ir by Rh_2O_3 Mantle

We will now explain the mechanism by which volatility is inhibited using Figure 16. In an atmosphere of high temperatures and oxidation, Ir becomes the IrO_3 oxide and flies off the surface layer. Rh also creates the Rh_2O_3 oxide but the vapor pressure of this is much less than that of IrO_3 and so it ıains on the surface as an oxide. When we look at the free rgy generated by the Ir and Rh oxides, we see that the Rh_2O_3 is a more stable oxide than the IrO_2. This makes it difficult for the internal Ir to react with the oxygen in the Rh_2O_3 in the surface layer and generate IrO_2. In other words, we found that oxidation does not proceed inwards.

We believe that this mechanism enabled us to obtain the excellent oxidation resistance results in the engine bench tests.

Next we will discuss the manufacture of this iridium-rhodium alloy chip. Iridium is a material that is difficult to use in manufacturing because of its high melting point and hardness. Ordinarily it is sintered. However, sintering is not good in mass production and is therefore not appropriate for mass produced goods such as spark plugs.

We therefore trialed a solution method to manufacture chips. Iridium and rhodium are both totally soluble metals. That is, they are able to dissolve evenly across an entire solution thus preventing the effective rhodium proportion from becoming too high. Also, because rhodium is not as hard as iridium and more malleable, it has the advantage of being able to improve the ability with which iridium can be rolled and drawn.

Figure 17 is a flow chart of a simple manufacturing method.

A melted alloy ingot is formed into a rough rectangular parallelopiped, and is hot forged, to make chips with small cross-sectional areas. This hot forging destroys the coarse ıcture of blow holes in the ingot, and enables a fine, fibrous ıructure to be obtained. This also prevents cracking of the ngot surface when the ingot is stretched.

After hot forging, hot rolling is repeated using a grooved roll to create chips with a small cross-sectional area. Then, a cylindrical die is used for repeated hot drawing to obtain the prescribed round cross-section. Lastly, hundreds of these thin wires are held together to be cut at once.

This enables the manufacture of precious metal chips for cheap, mass-produced spark plugs. Figure 18 shows the appearance of the precious metal chip and a photograph of its cross-sectional structure.

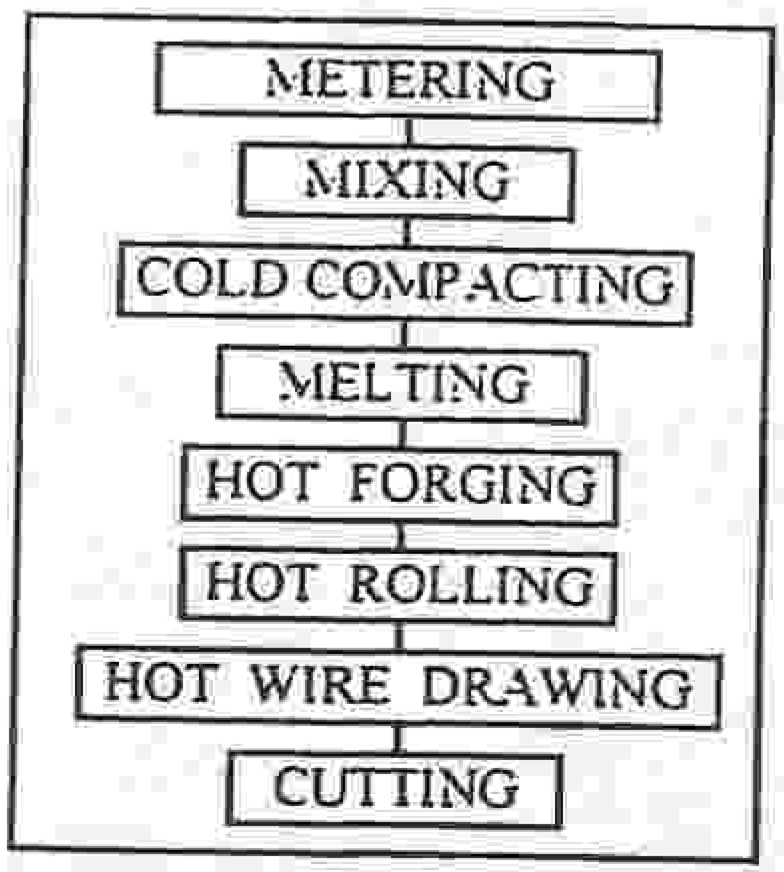


Fig.17 Flowchart of Ir Alloy Tip

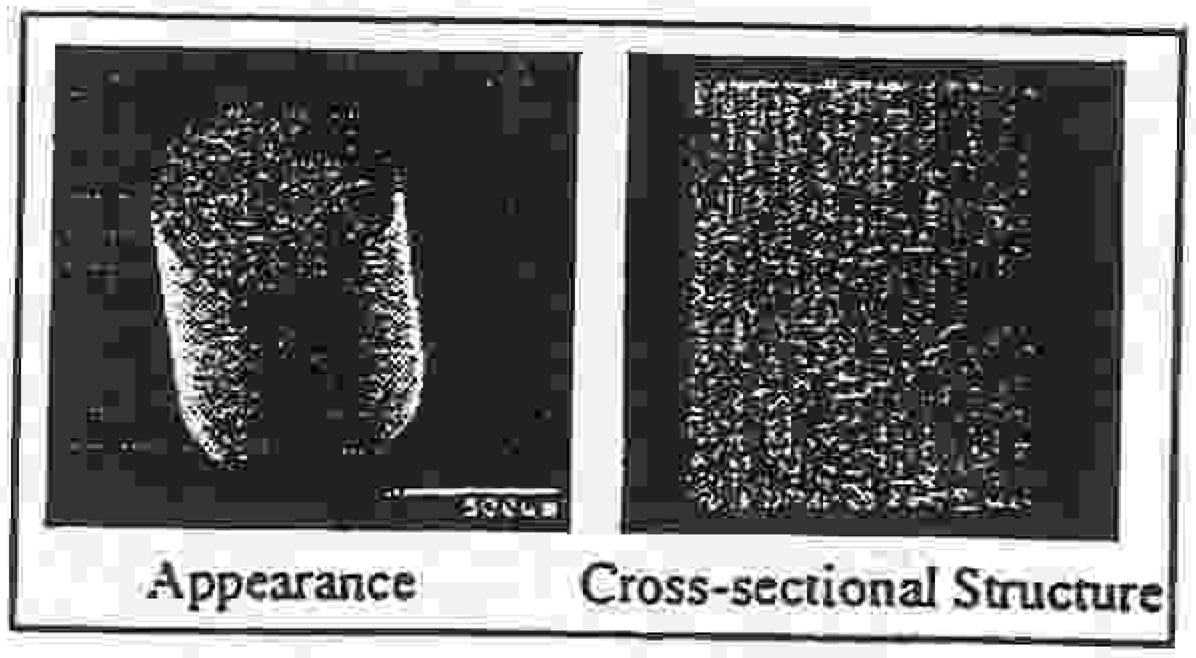

Appearance Cross-sectional Structure

Fig.18 SEM Image of Ir Alloy Tip

APPLICATION IN SPARK PLUGS

Through our study of materials, we have been able to develop an iridium alloy that is both resistant to sparking wear and to oxidation wear. We applied this in a spark plug electrode to realize an ultimate performance which was unable to achieve with the conventional platinum technology.

Our aim in development was to assure a smaller electrode as well as achieving a wear resistance that is equal to the life of an ordinary passenger vehicle, or to make a maintenance free spark plug. Another aim was to exhibit the highest performance possible with achievement of an ultimately small electrode while assuring a life as long as the platinum.

We set the following two types of spark plug that could be mass produced.

1) High-performance and maintenance free spark plugs
(with a wear resistance of 200,000 miles)
2) Super high-performance spark plugs
(with a wear resistance of 100,000 miles)

1. HIGH- PERFORMANCE AND MAINTENANCE FREE SPARK PLUGS

To achieve the engine trends of higher performance, low fuel consumption, and less environmental pollution, the spark plugs are demanded to have lower required voltage and higher ignitability. Also, to reduce the maintenance costs for the users, a spark plug with life as long as the automobile itself is demanded.

The following specific development targets were then established to meet these needs.

- Wear resistance: 200,000 miles
  (twice that of platinum spark plugs)
- Required voltage: Reduction of 5kV or more
  (smaller ignition coil in size)
- Ignitability performance: Improvement of 1.0 or more in critical lean air-to-fuel ratio
  (less NOx in exhaust gas)

We will now explain how we selected the optimum electrode size to achieve these targets.

Figure 19. shows the results of wear resistance after changes in the size of electrodes in both platinum and iridium spark plugs. In our evaluation of wear resistance, we implemented durability pattern test in an engine bench, and investigated how much the gap had enlarged after 100,000 miles.

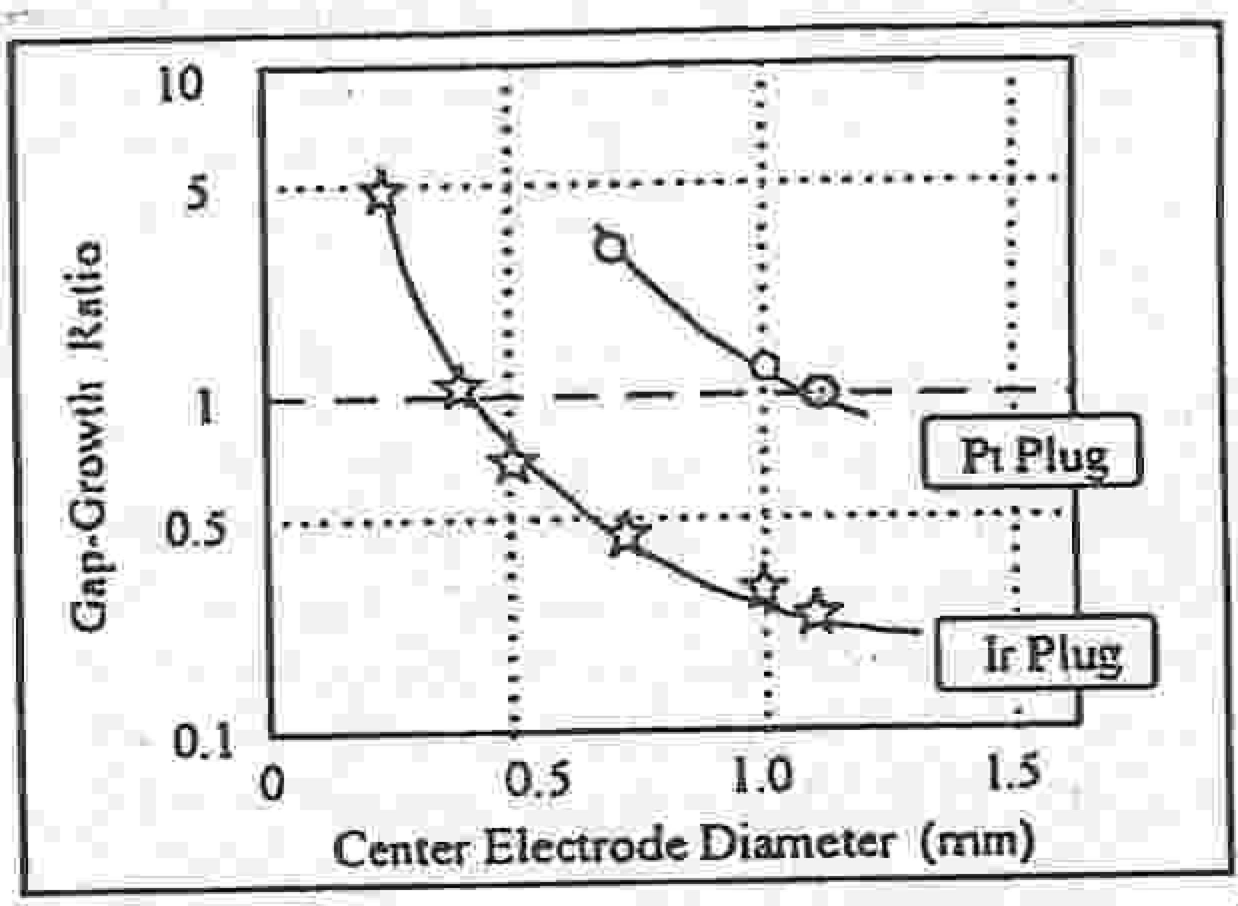
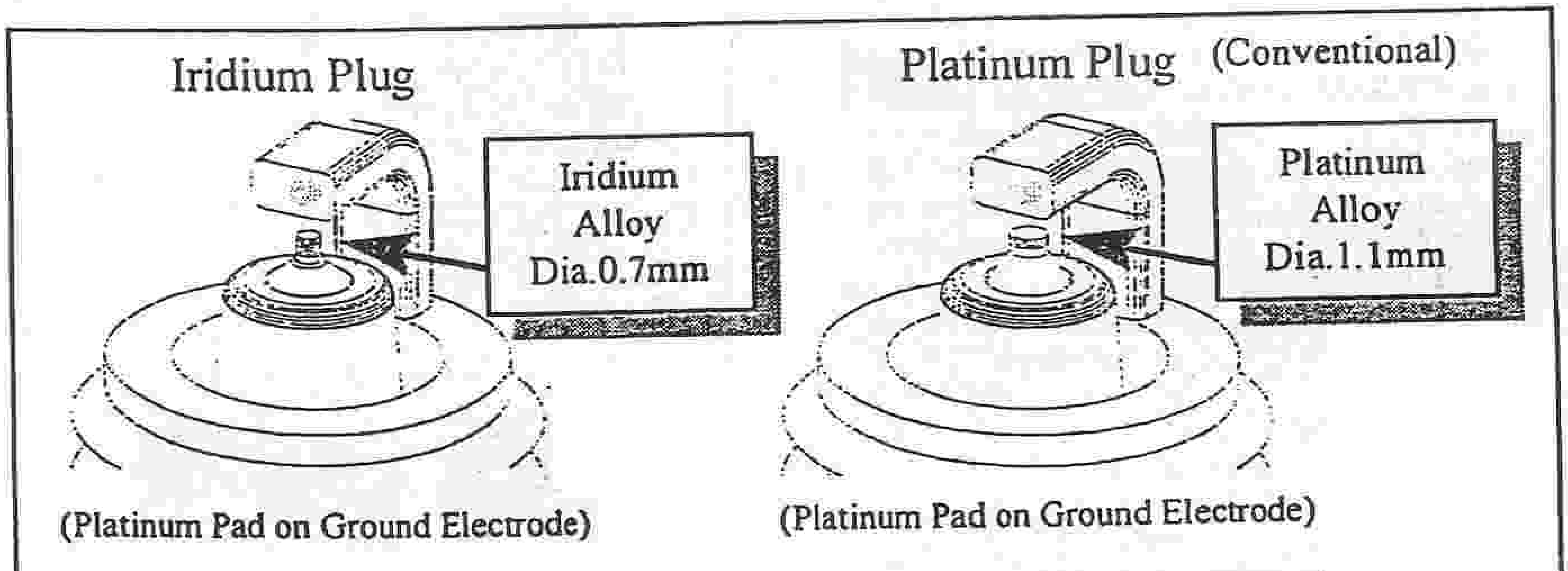


Fig.19 Wear Resistance of Platinum and Iridium Electrode Compared to 1.1mm dia. Platinum Electrode



	Iridium Plug	Platinum Plug
Center material	Ir-10Rh Alloy	Pt-20Ir Alloy
Center diameter	0.7mm	1.1mm
Welding method	Laser Welding	Resistance Welding

Fig.20 Outline of Iridium Plug

Comparison of the same electrode sizes in platinum and iridium spark plugs revealed that the iridium spark plugs were four to five times as resistant to wear as the platinum spark plugs.

The reduction in the voltage required and the improvement ignitability performance resulting from the reduction in electrode size are clear from Figures 2. and 3. These figures show the results using an ordinary nickel spark plug but it is common knowledge that the effects on electrode size are little different for iridium, platinum, or nickel spark plugs.

Now, after taking into consideration the effects of wear resistance, required voltage, and ignitability performance, we selected an iridium electrode diameter of 0.7 mm to satisfy our development targets.

As shown in Figure 19, setting the electrode diameter of an iridium spark plug at 0.7 mm secures a half or less of wear a platinum plug with an electrode diameter of 1.1 mm exhibits.

Figure 20 shows the major features of the iridium spark plug developed here and conventional platinum spark plugs.

Now let us view the results of the evaluation of this iridium spark plug.

Firstly, we will explain the results of the durability tests in field. The results of this test are shown in Figure 21.

In ordinary use, the iridium spark plug showed an increase in gap size of less than half that of a platinum plug. It easily lasted the required distance of 200,000 miles and is, in fact, a maintenance free plug.

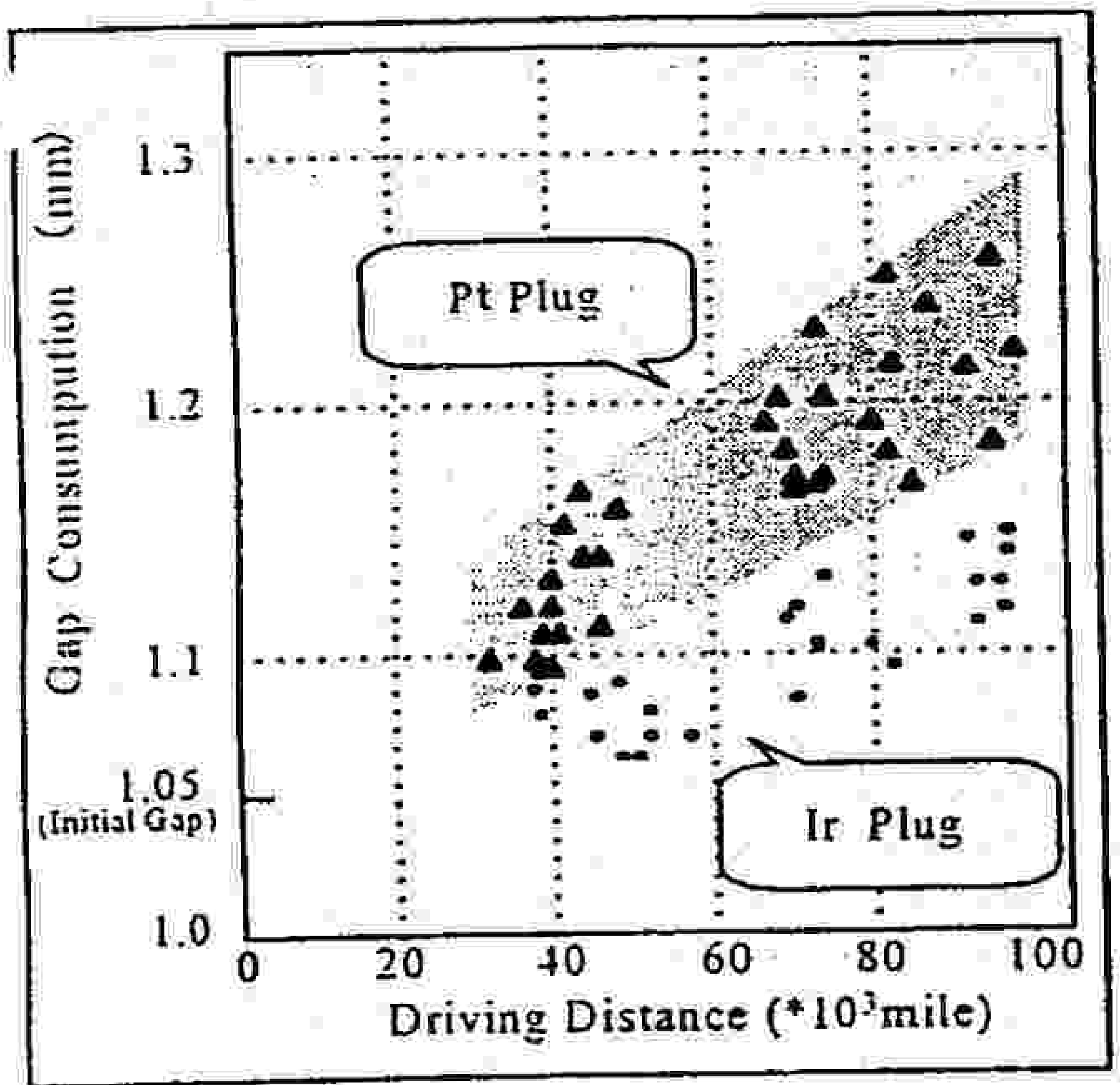


Fig.21 Wear Resistance Test in Field

Next we implemented a "toughness" test to see whether or not one disadvantage of pure iridium, an abnormal wear that occurs in areas of high temperatures and oxidation, would be problematic in the newly developed material.

We selected conditions where high temperatures would be reached and that would be oxygen rich.

In Test One, the engine was driven continuously under full load for 300 hours. In Test Two, over 300 hours the engine was repeatedly left idling for one minute then driven at full load for one minute. In Test Three, a lean combustion engine was used and driven for 500 hours at high speed (60 miles/hour), with a air to fuel ratio sweep of between 14 and 21. In Test Four, the engine was tested by raising the engine revolutions to maximum racing revolutions from idling, cutting off the fuel and allowing only electric discharge 10,000 times.

The results of these four tests are shown in Figure 22.

In all tests, the iridium spark plug shows a gap growth less than that of a platinum spark plug.

We were also able to confirm good resistance to wear under all driving conditions.

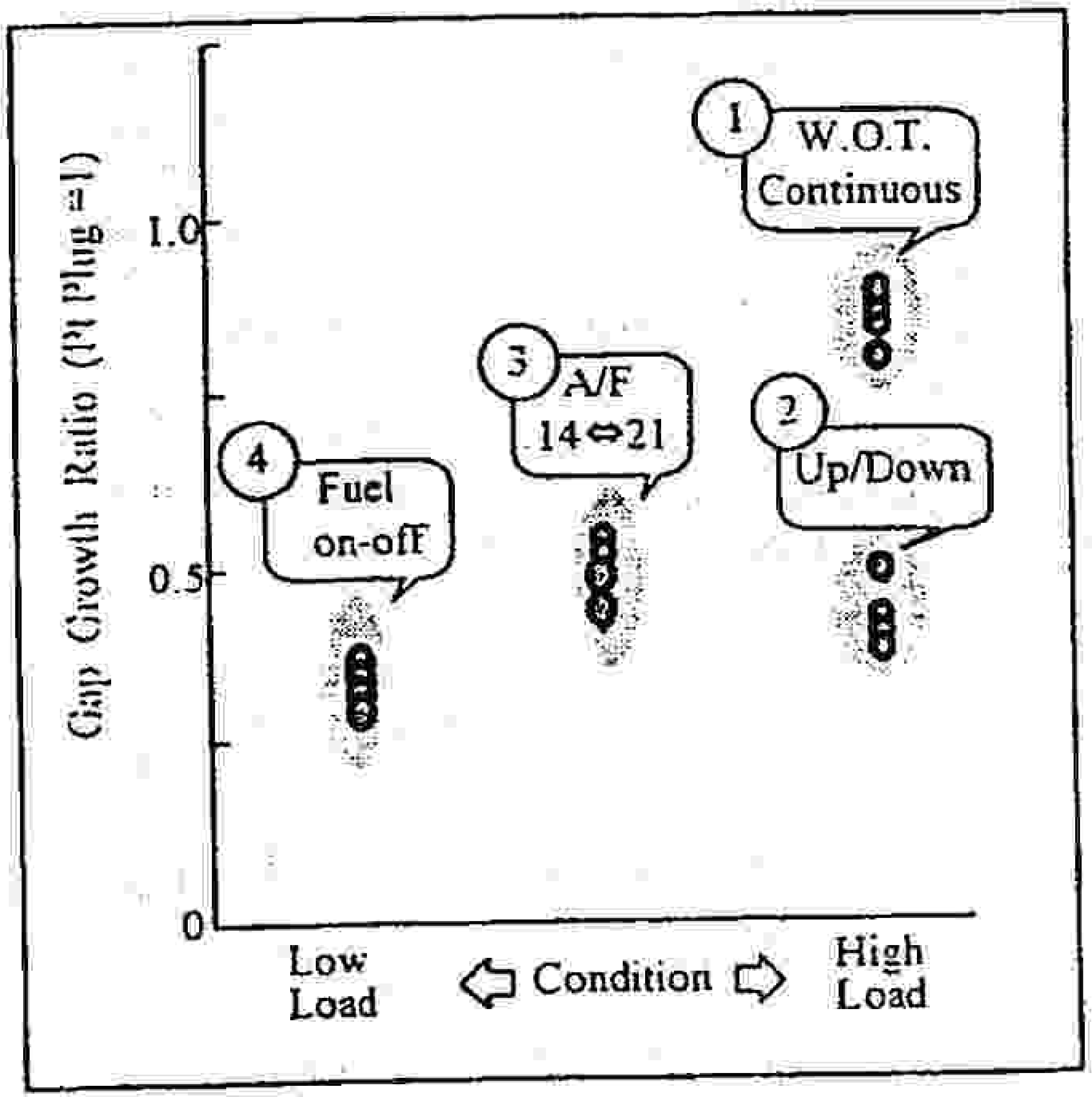


Fig.22 Toughness Test by Engine Bench

Next we will explain the results of our evaluation of required voltage.

With the ignition coil trend of smaller in size under concern, we targeted to lower the voltage by 5 kV. Figure 23 shows the required voltages for different driving conditions. In all cases, the voltage was reduced, especially in condition of highest required voltage, or rapid acceleration, the voltage was reduced by 5 kV.

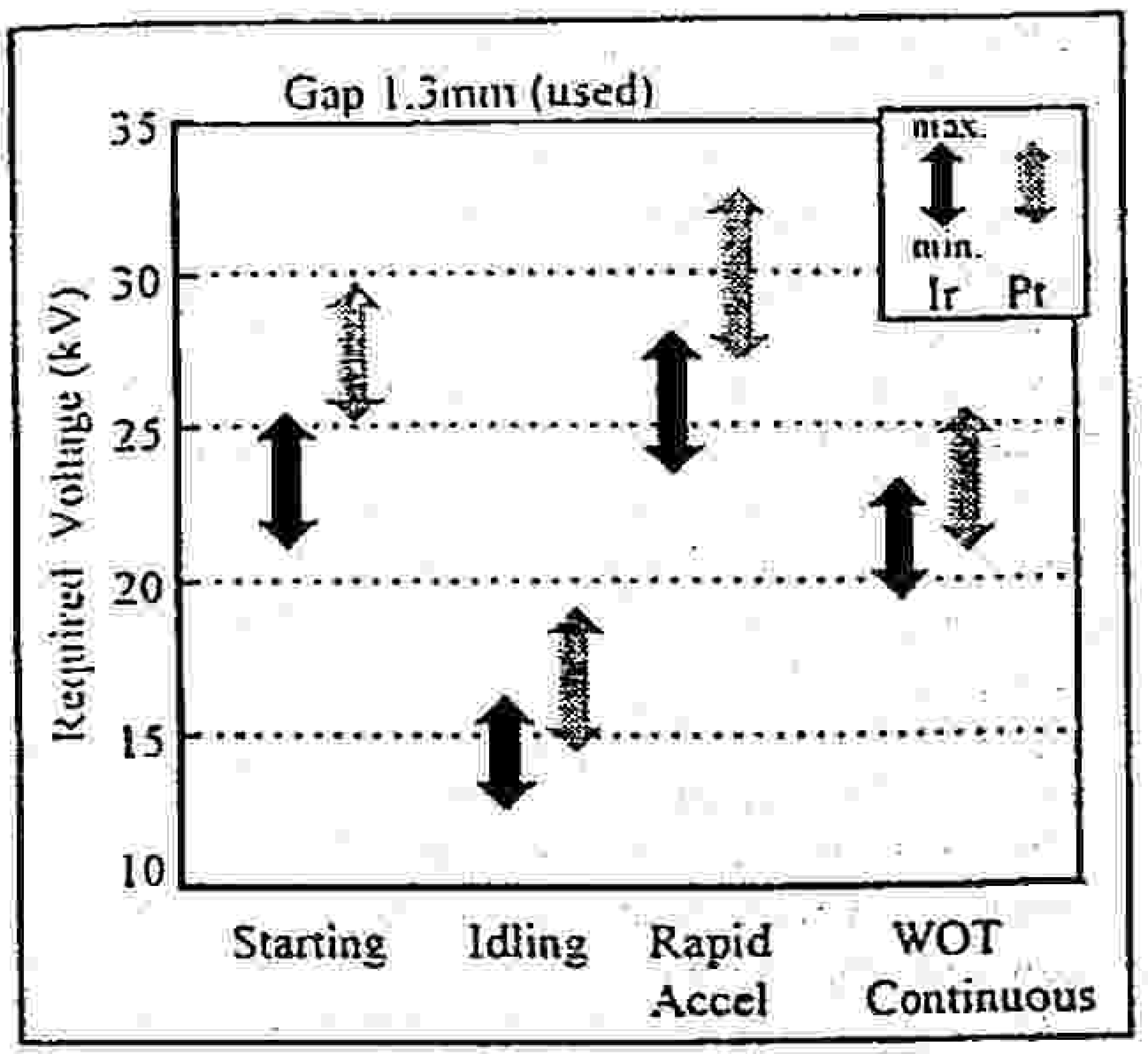


Fig.23 Iridium Plug's Required Voltage Reducing Effect

Lastly, we will discuss the results of ignitability performance tests. Figure 24 shows the air to fuel ratios at the ignitability boundary in a lean combustion engine. The leaner the air to fuel ratio, the more unstable the combustion and the greater the fluctuations in torque. As a test standard we used 0.4 Nm as the value at which the driver and passengers could adequately feel changes in torque within the cabin.

Due to the reduction in electrode size, in iridium spark plug can be used in an air-to-fuel ratio setting of 1.0 more lean than that which a platinum spark plug can be used in.

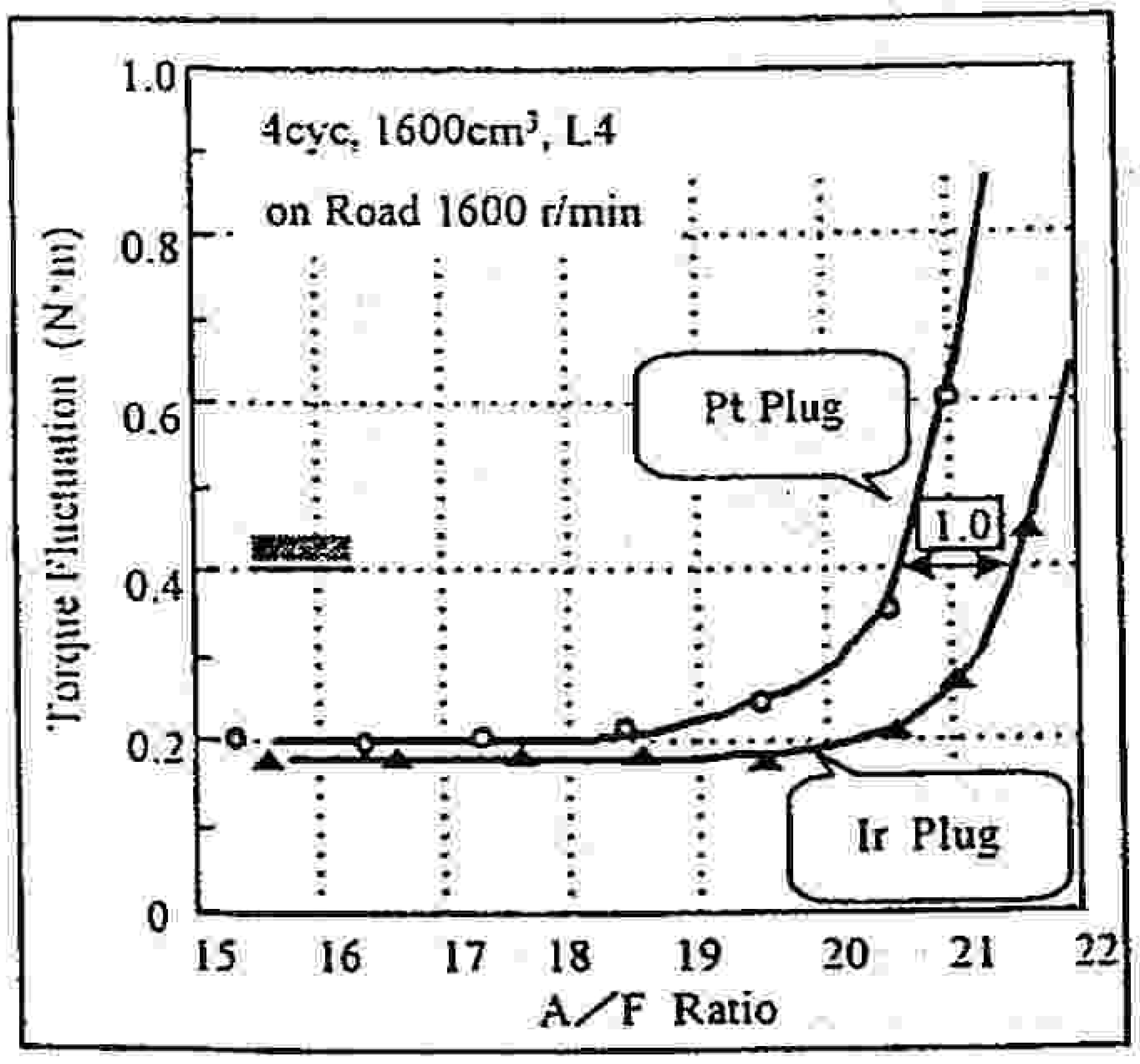


Fig.24 Iridium Plug's Ignitability Improvement Effect

Figure 25 shows the collated results of the evaluations of the newly developed iridium spark plugs and widely used platinum spark plugs.

This iridium spark plug is the first in the world to be used in mass produced vehicles. (7) We expect that it will be used more frequently given the trends in engine development.

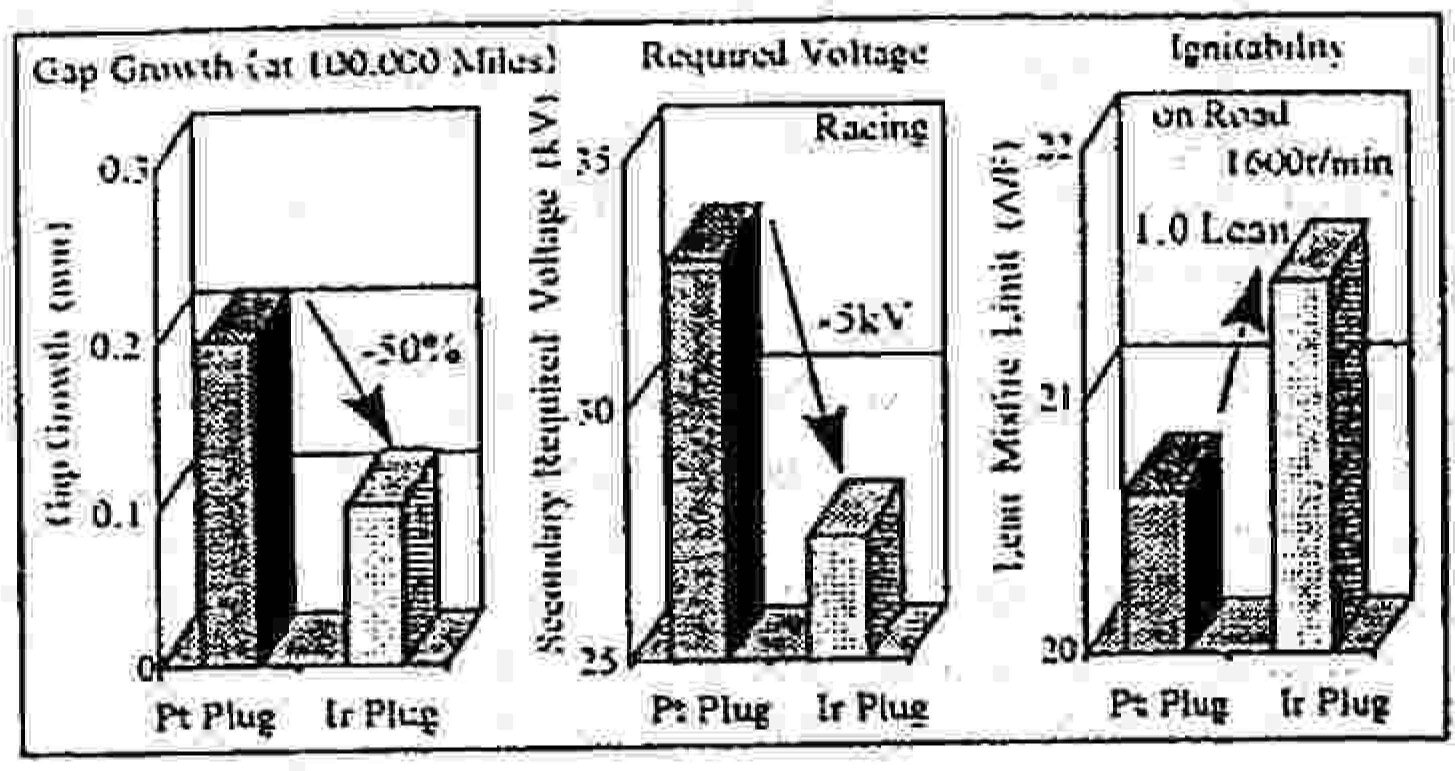


Fig.25 Features

2. SUPER HIGH-PERFORMANCE PLUGS

We aimed to even more effectively utilize our newly developed iridium alloy to produce a super high performance spark plug ,with an even smaller electrode and with the same life expectancy as a the commonly used platinum spark plug.

As we have explained previously, a reduction in electrode diameter can be expected to reduce voltage and improve ignitability performance. And, shown in Figure 19 above, wear resistance of about the same level as that found in platinum plugs (diameter of 1.1 mm) could be achieved using the new iridium alloy with an electrode diameter of 0.4 mm.

Then, taking wear resistance and material strength into consideration, we decided to mass produce long life spark plugs with the world's smallest electrode diameter of 0.4 mm.

The major issue involved here was the manufacture of the chips. As explained previously, iridium is very hard and therefore very difficult to roll or draw.

Even to produce a wire 0.7 mm in diameter required much repetition of processing as shown in Figure 17.

To further reduce the diameter to 0.4 mm in diameter, we need to optimize forging conditions, hot processing temperatures, and cross-sectional reduction rates in hot drawing. To do so, we eliminated surface and internal cracks and created a finer crystalline structure.

In drawing process, the work hardened wire material is repeatedly heat treated at temperature below the recrystallization point (about 1000 ℃) to remove the strain.

In other words, a crack-less most possibly thin wire material was created without overly raising the work hardening rate and repeatedly reducing the cross-sectional area.

Improvements in engine performance resulting from the adoption of a 0.4 mm diameter electrode are shown below.

(1) Idling stability

Figure 26 shows the idling stability test results by a 4-cycle.) cm^3 . 4 cylinder engine.

In the test, the idle speed control (ISC) was disconnected. After warming the engine, the fluctuations in engine revolutions were measured.

Firstly a platinum spark plug was installed and the average revolutions set at 650r/min. Fluctuations were observed during a 40 second interval. Next, an iridium spark plug was installed and the engine checked again.

Merely be replacing the spark plug we were able to achieve an increase in average revolutions of 20r/min. The range of fluctuations decreased from approximately 25r/min to 10r/min. This is a result of the improved sparking performance and combustion efficiency caused by the smaller electrode.

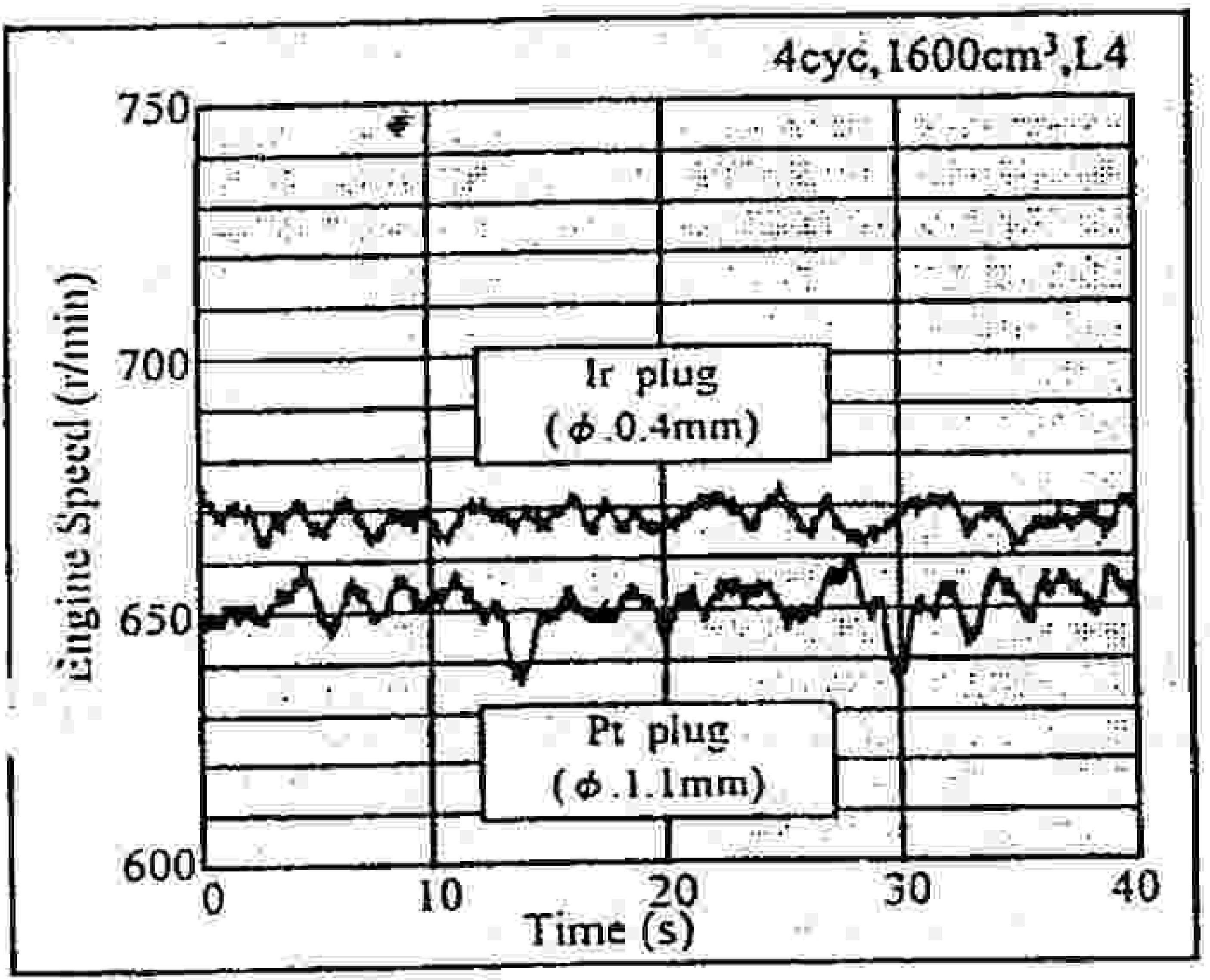


Fig.26 Idling Stability

(2) Improved fuel efficiency

In the above idling test, an increase in the number of revolutions was seen when the iridium spark plug was used. Therefore, we tested the fuel consumption for the same number of revolutions.

Figure 27 shows the differences in the fuel consumption for idling and city driving in which platinum and iridium spark plugs were used.

The iridium spark plug showed an approximately 3.0% improvement in fuel consumption during idling, and an approximately 1.3% improvement during city driving, versus the platinum spark plug.

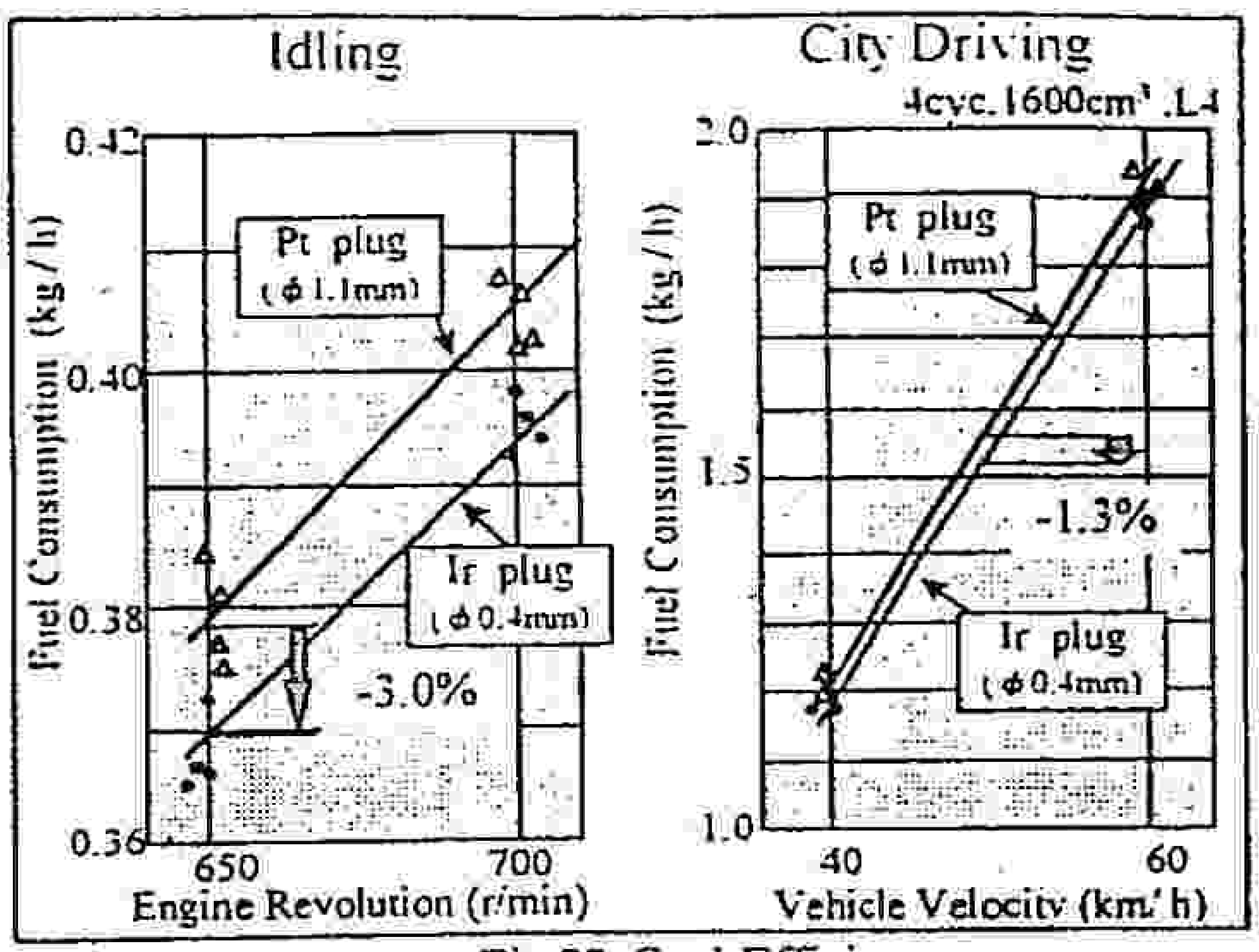


Fig.27 Fuel Efficiency

(3) Acceleration

We tested the distance covered by a 4-cycle 250cm^3 motorcycle under full acceleration after 30 seconds and the time taken to reach 100 km/h under full acceleration.

The smaller the electrode the better the sparking, with less hesitation. This meant improvement in smooth revolution. As shown in Figure 28, this meant an increase in speed over a short time and an increase in the distance covered.

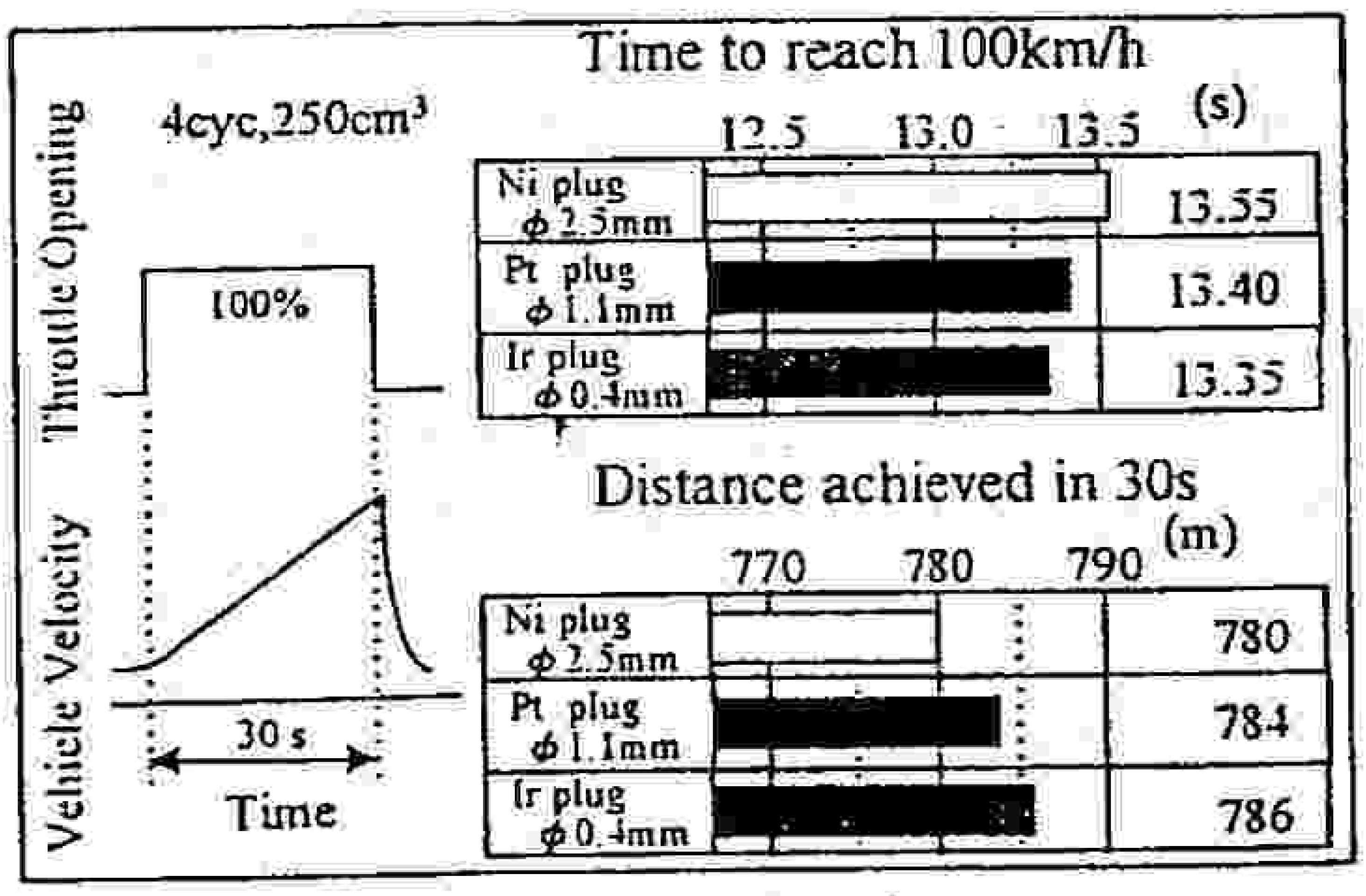


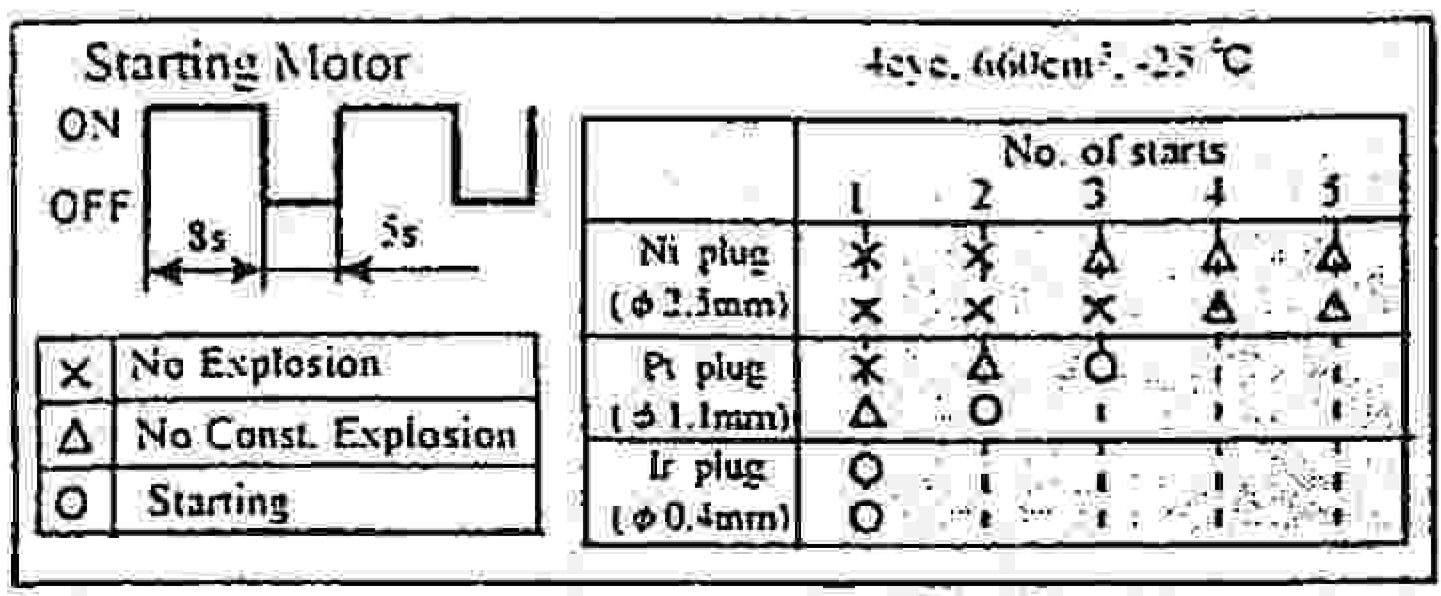
Fig.28 Acceleration

(4) Starting in cold temperatures

Figure 29 shows the results of a test at the cold temperature of -25°C by a 4-cycle 660cm^3 3cylinder engine.

In the test, the starter was switched on and off and the number of times this was done until the engine started was counted.

As opposed to the engine in which the platinum spark plug was used, which took three cycles to start up, the engine in which the 0.4 mm iridium spark plug was used started immediately with only one try. Thus we found that the small electrode diameter was effective even under cold start-up conditions.



×	No Explosion
△	No Const. Explosion
○	Starting

	No. of starts				
	1	2	3	4	5
Ni plug (φ2.5mm)	×	×	△	△	△
	×	×	×	△	△
Pt plug (φ1.1mm)	×	△	○		
	△	○			
Ir plug (φ0.4mm)	○				
	○				

Fig.29 Cold Starting

We have discussed the results of a number of engine performance tests and have been able to confirm the merits in terms of engine performance of a smaller electrode diameter. Thus, we have succeeded in developing the ultimate small diameter spark plug that has a life as long as that of currently used platinum spark plugs and that is better in terms of performance, ease of manufacturing, and handling.

CONCLUSION

To dramatically improve spark plug wear resistance we researched electrode materials that had both high melting point and high resistance to oxidation. The results we obtained were:

1. The melting point of iridium is 700°C higher than that of platinum giving iridium excellent sparking wear resistance. However, under high speed driving, oxidation volatility is great and abnormal wear tends to occur making iridium difficult to apply.
2. To inhibit this oxidation wear at high temperatures, we developed an alloy containing a rhodium additive. The melting point of rhodium is lower than that of iridium but it has excellent resistance to wear at high temperatures. By adding 10% by weight per volume, we can dramatically improve the resistance to high temperatures and oxidation.
3. The mechanism whereby the iridium-rhodium alloy has strong resistance to high temperatures and oxidation is caused because in the high speed driving range in which iridium oxidizes and becomes volatile, the stable rhodium oxide remains on the surface layer of the chip and inhibits the iridium oxidation and volatility.
4. To enable practical use of the iridium chip we studied new methods for drawing the material and established a low cost manufacturing technique that can be used in mass production.

We have succeeded in using this new alloy in a spark plug for the first time in the world and have been able to mass produce spark plugs with higher performance and longer life than any other existing spark plugs.

The following figure contains photographs of the discharge part of an ordinary spark plug, a platinum spark plug, and the two types of iridium spark plugs developed here.

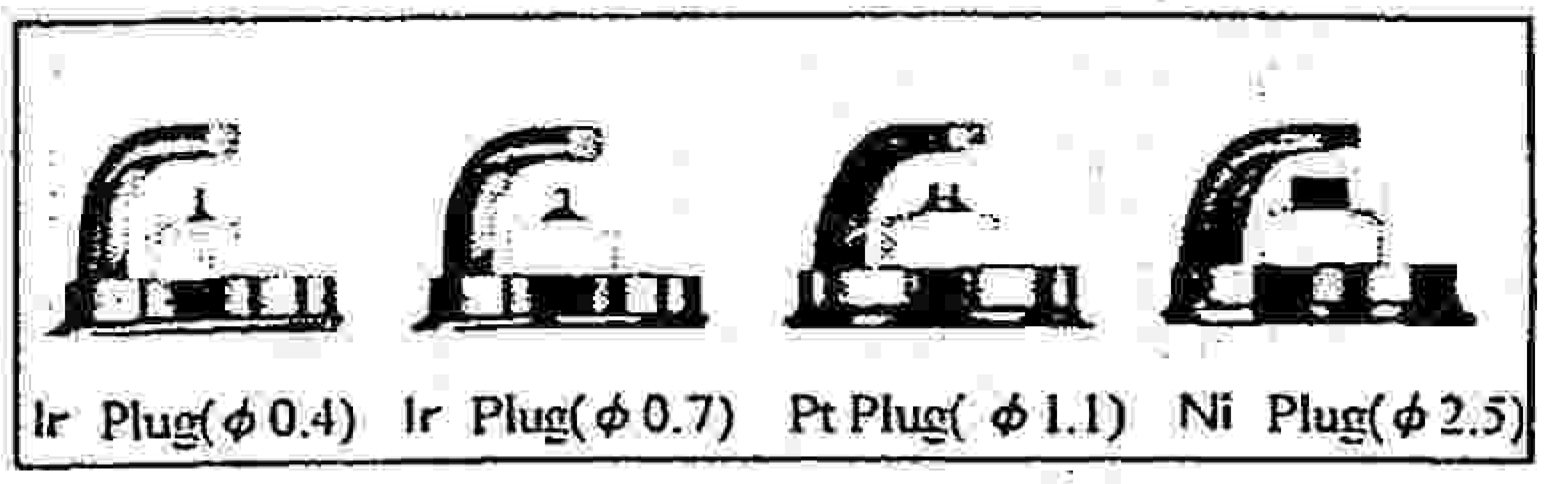


Fig.30 Outline of Spark Plugs

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