



US 20170271686A1

(19) **United States**

(12) **Patent Application Publication**  
**OGO**

(10) **Pub. No.: US 2017/0271686 A1**

(43) **Pub. Date: Sep. 21, 2017**

(54) **ELECTRIC POWER GENERATION METHOD  
USING ELECTRODE CATALYST FOR FUEL  
CELL**

(30) **Foreign Application Priority Data**

Oct. 6, 2009 (JP) ..... 2009-139401

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**Publication Classification**

(51) **Int. Cl.**  
**H01M 4/90** (2006.01)

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(52) **U.S. Cl.**  
CPC ..... **H01M 4/9008** (2013.01)

(21) Appl. No.: **15/612,992**

(57) **ABSTRACT**

(22) Filed: **Jun. 2, 2017**

To provide an economical fuel cell electrode catalyst which can be used in place of platinum as a simple substance or a platinum alloy and has easy-to-control catalytic power, a molecular metal complex is used as a fuel cell electrode catalyst which molecular metal complex is a mononuclear or multinuclear coordination compound that has a particular structure, that is not a polymer compound, and that does not have a layered structure.

**Related U.S. Application Data**

(62) Division of application No. 13/377,327, filed on Dec. 9, 2011, now abandoned, filed as application No. PCT/JP2010/059773 on Jun. 9, 2010.

**ELECTRIC POWER GENERATION METHOD  
USING ELECTRODE CATALYST FOR FUEL  
CELL**

TECHNICAL FIELD

**[0001]** The present invention relates to an electrode catalyst for a fuel cell (fuel cell electrode catalyst) and use thereof. Particularly, the present invention relates to (i) an economical fuel cell electrode catalyst which can be used in place of platinum as a simple substance or a platinum alloy and has easy-to-control catalytic power, and (ii) use thereof.

BACKGROUND ART

**[0002]** Conventionally, a typical fuel cell electrode catalyst has been a platinum catalyst. However, the platinum catalyst is expensive and an exhaustible resource. Therefore, a lot of research has been done to develop an economical fuel cell electrode catalyst which can be used in place of the platinum catalyst, and various electrode catalysts therefor have been reported so far.

**[0003]** As such the electrode catalysts, a heat-treated metal complex, a layered metal complex, a polymer metal complex, etc. have been reported.

**[0004]** Examples of the heat-treated metal complex are as follows. A heat-treated iron complex including, as a ligand, 2,4,6-tris(2-pyridyl)-1,3,5-triazine has been reported to exhibit oxygen reduction ability (see Non-Patent Literature 1). Further, a heat-treated cobalt complex including a porphyrin derivative as a ligand has been disclosed as the electrode catalyst (see Patent Literature 1). Furthermore, heat-treated mononuclear and dinuclear complexes each having a phenolate skeleton have been disclosed as the electrode catalyst (see Non-Patent Literature 2). In cases of each of these heat-treated metal complexes, at the point of synthesis of a catalyst, a metal complex is burned at a high temperature. Consequently, the metal complex is thermally decomposed, so that the heat-treated metal complex no longer maintains its complex structure. Namely, each of the above heat-treated metal complexes is not a complex but a metal catalyst.

**[0005]** Examples of the layered metal complex are as follows. A layered metal complex including a dithiooxamide derivative as a ligand has been reported as the electrode catalyst (see Patent Literature 3). Further, an interlayer metal complex including a cobalt complex which includes a dithiooxamide derivative as a ligand and into which platinum is inserted has been reported as the electrode catalyst (see Patent Literature 4).

**[0006]** Examples of the polymer metal complex are as follows. A polymer metal complex including pyrrole which is polymerized with hydrogen peroxide and coordinates to cobalt has been reported as the electrode catalyst (see Non-Patent Literature 2). Further, a polymer metal complex of cobalt including a polymerized ligand has been reported to function as the electrode catalyst (see Patent Literature 5).

**[0007]** Additionally, it has been reported that, in a solid polymer fuel cell which uses a carbon monoxide directly as a fuel, a rhodium complex including a porphyrin derivative as a ligand is used as an anode catalyst (see Non-Patent Literature 3).

**[0008]** Furthermore, it has been reported that a ruthenium complex and an osmium complex are used as a part of a biotechnological fuel cell and work for electron transfer,

although the ruthenium complex and the osmium complex do not constitute a fuel cell electrode catalyst (See Non-Patent Literatures 4 and 5).

CITATION LIST

Patent Literatures

Patent Literature 1

**[0009]** Japanese Patent Application Publication (Translation of PCT Application), Tokuhyo, No. 2004-532734 A (Publication Date: Oct. 28, 2004)

Patent Literature 2

**[0010]** International Application, Pamphlet of WO No. 2008/111569 (Publication Date: Sep. 18, 2008)

Patent Literature 3

**[0011]** Japanese Patent Application Publication, Tokukai, No. 2004-031174 A (Publication Date: Jan. 29, 2004)

Patent Literature 4

**[0012]** Japanese Patent Application Publication, Tokukai, No. 2008-204894 A (Publication Date: Sep. 4, 2008)

Patent Literature 5

**[0013]** Japanese Patent Application Publication, Tokukai, No. 2008-189837 A (Publication Date: Aug. 21, 2008)

Non-Patent Literatures

Non-Patent Literature 1

**[0014]** Bezerra (C. W. B. Bezerra) and other nine members, *Electrochimica Acta*, Vol. 53, p. 7703, 2008

Non-Patent Literature 2

**[0015]** Bashyam (R. Bashyam) and other one member, *Nature*, Vol. 443, p. 63, 2006

Non-Patent Literature 3

**[0016]** Yamazaki (S. Yamazaki) and other four members, *Angew. Chem. Int. Ed.* 2006, 45, 3120-3122

Non-Patent Literature 4

**[0017]** Jelliss (P. A. Jelliss) and other five members, *Journal of Materials Chemistry*, Vol. 18, p. 2104, 2008

Non-Patent Literature 5

**[0018]** Tam (T. K. Tam) and other five members, *Journal of the American Chemical Society*, Vol. 130, p. 10888, 2008

SUMMARY OF INVENTION

Technical Problem

**[0019]** However, it is impossible to easily control catalytic power of the above conventional fuel cell electrode catalysts.

**[0020]** Specifically, each of the heat-treated metal complexes is merely a metal catalyst. Further, each of the above

layered metal complexes, the polymer metal complexes, etc. has a layered structure or a structure in which a polymer coordinates to a metal atom. Therefore, it is impossible to freely design a ligand of each of these metal complexes. Namely, it is impossible to easily control the catalytic power of the metal complexes.

**[0021]** Further, the metal catalyst disclosed in Non-Patent Literature 3 includes the porphyrin derivative as the ligand. Therefore, it is difficult to make a great modification in the structure of this metal catalyst in order to control its catalytic power.

**[0022]** Note that each of the metal complexes disclosed in Non-Patent Literatures 4 and 5 does not function as the fuel cell electrode catalyst.

**[0023]** The present invention was made in view of the above problems, and an object of the present invention is to provide an economical fuel cell electrode catalyst which can be used in place of platinum as a simple substance or a platinum alloy and has easy-to-control catalytic power.

#### Solution to Problem

**[0024]** The inventors of the present invention made diligent studies in order to attain the above object. As a result, the inventors of the present invention reached the unique finding that use of a molecular metal complex having a certain structure makes it possible to provide an economical fuel cell electrode catalyst which can be used in place of platinum as a simple substance or a platinum alloy and has easy-to-control catalytic power. Consequently, the inventors of the present invention completed the present invention.

**[0025]** A fuel cell electrode catalyst of the present invention includes one or more molecular metal complexes, each of the one or more molecular metal complexes being a metal complex (i) having a molecular weight of 2000 or less, (ii) not having a layered structure, and (iii) including a total of one or more but not more than three metal atoms and/or metal ions to each of which three or more but not more than six ligands coordinate, each of the one or more molecular metal complexes being a metal complex other than a porphyrin derivative, in a case where (i) the each of the one or more molecular metal complexes includes one metal atom or one metal ion and (ii) four ligands coordinate to the one metal atom or the one metal ion.

**[0026]** The molecular metal complex included in the fuel cell electrode catalyst of the present invention is not a polymer compound and does not have a layered structure. Therefore, it is possible to thermodynamically and kinetically control reaction of the molecular metal complex with hydrogen or oxygen. Further, the molecular metal complex is water-soluble and stable in water. Therefore, the molecular metal complex is very effective as an electrode catalyst in a fuel cell which uses (i) hydrogen including saturated steam and (ii) oxygen. Furthermore, the molecular metal complex has high flexibility in designing of the structure of the ligand. Therefore, it is possible to easily control the catalytic power by changing the ligand. Namely, with the molecular metal complex, it is possible to easily control electronic effects, and also to reveal a mechanism of electrode reaction.

#### Advantageous Effects of Invention

**[0027]** As described above, a fuel cell electrode catalyst of the present invention includes one or more molecular metal

complexes, each of the one or more molecular metal complexes being a metal complex (i) having a molecular weight of 2000 or less, (ii) not having a layered structure, and (iii) including a total of one or more but not more than three metal atoms and/or metal ions to each of which three or more but not more than six ligands coordinate, each of the one or more molecular metal complexes being a metal complex other than a porphyrin derivative, in a case where (i) the each of the one or more molecular metal complexes includes one metal atom or one metal ion and (ii) four ligands coordinate to the one metal atom or the one metal ion.

**[0028]** According to the above arrangement of the fuel cell electrode catalyst of the present invention, it is possible to provide an economical fuel cell electrode catalyst which can be used in place of platinum as a simple substance or a platinum alloy and has easy-to-control catalytic power. Namely, the use of the above molecular metal complex as the fuel cell electrode catalyst makes it possible to freely and precisely design the ligand, thereby enabling to freely control the nature of the electrode complex catalyst. Furthermore, the above molecular metal complex has such a structure that it would not be burned at a high temperature. Therefore, it is possible to provide a fuel cell electrode catalyst maintaining a chemical structure of a metal complex.

#### DESCRIPTION OF EMBODIMENTS

**[0029]** (I) Fuel Cell Electrode Catalyst of the Present Invention

**[0030]** In order to provide a fuel cell electrode catalyst having easy-to-control catalytic power, it is considered to be necessary to use a chemical species whose chemical structure can be freely designed so that reaction of the chemical species with hydrogen or oxygen can be controlled thermodynamically and kinetically.

**[0031]** Conventionally, a lot of attempts have been made to use an organic metal complex as the fuel cell electrode catalyst. However, the organic metal complex has been considered not to function as the catalyst. Therefore, it has almost never reported that a molecular metal complex can be used as the fuel cell electrode catalyst. Only such the report has been made in Non-Patent Literature 3, which describes that the rhodium complex including the porphyrin derivative as the ligand has a catalytic property only in the hydrogen electrode.

**[0032]** However, as described above, this rhodium complex includes, as the ligand, the porphyrin derivative having a porphyrin structure. Therefore, even by modifying the structure of the ligand, it is impossible to significantly change the complex structure. Namely, this rhodium complex is not the one having easy-to-control catalytic power. Meanwhile, the inventors of the present invention used, as the fuel cell electrode catalyst, molecular metal complexes that the inventors of the present invention had developed so far. As a result, the inventors of the present invention found for the first time that a molecular metal complex can function as the fuel cell electrode catalyst.

**[0033]** (I-1) Molecular Metal Complex

**[0034]** A fuel cell electrode catalyst of the present invention is a fuel cell electrode catalyst including one or more molecular metal complexes, each of the one or more molecular metal complexes being a metal complex (i) including a total of one or more but not more than three

metal atoms and/or metal ions to each of which three or more but not more than six ligands coordinate, (ii) having a molecular weight of 2000 or less, and (iii) not having a layered structure. Each of the one or more molecular metal complexes is a metal complex other than a porphyrin derivative, in a case where (i) said each of the one or more molecular metal complexes includes one metal atom or one metal ion and (ii) four ligands coordinate to the one metal atom or the one metal ion. This electrode catalyst may be either a solid or a solution.

**[0035]** In the present invention, the molecular metal complex refers to a mononuclear or multinuclear coordination compound whose central atom or central ion is a metal atom or a metal ion and which is not a polymer and does not have a layered structure. Note that the expression that “a coordination compound is not a polymer compound” means that the coordination compound is not a polymer complex or a coordination polymer and has a molecular weight of 2000 or less.

**[0036]** Namely, the molecular metal complex is not a polymer complex in which a lateral group of a polymer serves as a ligand so as to form coordinate bond with a metal atom or a metal ion. In other words, the ligand included in the molecular metal complex is a low-molecular-weight molecule or ion, more preferably an unpolymerized molecule or ion. Further, the molecular metal complex is not a polymer which is made of a low-molecular-weight organic polydentate ligand and a metal atom or a metal ion and which is a coordination polymer whose main chain includes repeating units coordinate-bonded to each other. Note that the expression “low-molecular-weight” means a molecular weight of 2000 or less. Note also that the expression “a coordination compound does not have a layered structure” means that the coordination compound is not the above-described layered metal complex (e.g., Patent Literature 3) or the interlayer metal complex (e.g., Patent Literature 4).

**[0037]** The molecular metal complex is a metal complex other than a porphyrin derivative, in a case where (i) the molecular metal complex includes one metal atom or one metal ion and (ii) four ligands coordinate to the one metal atom or the one metal ion. The “porphyrin derivative” herein is used synonymously with a “porphyrin complex”. Examples of the porphyrin derivative include ( $\alpha,\beta,\gamma,\delta$ -tetraphenylporphyrine)iron(II), (1,2,3,4,5,6,7,8-octaethylporphyrine)iron(II), and the like. Herein, the molecular metal complex including (i) one metal atom or one metal ion and (ii) four ligands coordinating to the one metal atom or the one metal ion is not a porphyrin derivative.

**[0038]** The molecular metal complex includes, in its molecule, a total of one or more but not more than three metal atoms and/or metal ions to each of which three or more but not more than six ligands coordinate. For example, a molecular metal complex expressed by the later-described General Formula (9) includes, in its molecule,  $M^{13}$  and  $M^{14}$ , i.e., a total of (i) two metal atoms, (ii) two metal ions, or (iii) one metal atom and one metal ion. Further,  $L^{41}$  through  $L^{44}$ , i.e., four ligands coordinate to  $M^{13}$ , whereas  $L^{43}$  through  $L^{46}$ , i.e., four ligands coordinate to  $M^{14}$ .

**[0039]** The metal atom or the metal ion is not limited to any specific kind. Examples of the metal atom or the metal ion encompass metal atoms or metal ions of 3A group elements (Sc, Y), 4A group elements (Ti, Zr, Hf, Rf), 5A group elements (V, Nb, Ta, Db), 6A group elements (Cr, Mo, W, Sg), 7A group elements (Mn, Tc, Re, Bh), 8 group

elements (Fe, Ru, Os, Hs, Co, Rh, Ir, Mt, Ni, Pd, Pt, Uun), 1B group elements (Cu, Ag, Au, Uuu), 3B group elements (Al, Ga, In, Tl), and 6B group elements (Se, Te, Po) in a periodic table. Note that the periodic table herein refers to the periodic table defined in page 1079, Table 1 of “*Tokyo Kagaku Doujin, Kagaku Daijiten*, First Edition” Ed. Michinori Ohki et al., published on Oct. 20, 1989, Tokyo Kagaku Doujin.

**[0040]** Among these, the metal atom or the metal ion is more preferably one or more kinds selected from the metal atoms or the metal ions of the 6A group elements, the 7A group elements, and the 8 group elements, specifically, atoms or ions of Cr, Mn, Fe, Co, Ni, Mo, Tc, Ru, Rh, Pd, Ag, W, Re, Os, Ir, and the like. Alternatively, the metal atom or the metal ion may be selected from the metal atoms or the metal ions of the 8 group elements.

**[0041]** The metal ion may have any valence, as long as the valence is possible for the metal.

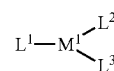
**[0042]** The “ligand” herein refers to a molecule or an ion that is coordinate-bonded to a certain atom, as described in page 1751 of “*Tokyo Kagaku Doujin, Kagaku Daijiten*, First Edition” Ed. Michinori Ohki et al., published on Oct. 20, 1989, Tokyo Kagaku Doujin.

**[0043]** The ligand is not limited to any specific kind, as long as it is a low-molecular-weight molecule or ion. Preferably, each of ligand atoms of the ligands included in the molecule is independently a hydrogen atom, a carbon atom, a nitrogen atom, an oxygen atom, a phosphorus atom, a sulfur atom, or a halogen atom. Examples of the halogen atom encompass a fluorine atom, a chlorine atom, a bromine atom, and an iodine atom. Note that the “ligand atom” herein refers to an atom which is included in the ligand and directly involves coordinate bond with the metal atom or the metal ion.

**[0044]** The molecular metal complex of the present invention has a low molecular weight, and has a relatively simple structure as compared with complexes having layered structures such as the layered metal complex and the interlayer metal complex. Therefore, the molecular metal complex of the present invention has high flexibility in designing of the ligand. Accordingly, it is easy to control the catalytic power of the molecular metal complex of the present invention. Furthermore, the molecular metal complex of the present invention would not be burned even at a high temperature. Therefore, even at a high temperature, the molecular metal complex of the present invention would not be changed into a mere metal catalyst, and accordingly can maintain a structure of a metal complex. The inventors of the present invention designed various complexes as the above molecular metal complex, and found that each of these complexes functions as the fuel cell electrode catalyst.

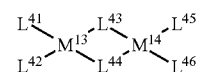
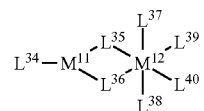
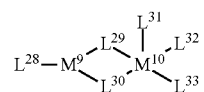
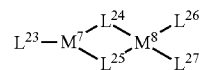
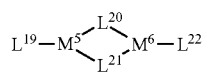
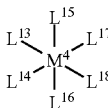
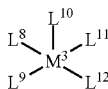
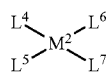
**[0045]** Preferably, the one or more molecular metal complexes include one or more molecular metal complexes selected from molecular metal complexes expressed by the following General Formulae (1) through (73):

Chem. 1

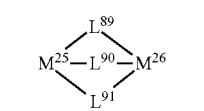
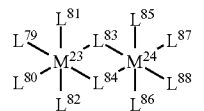
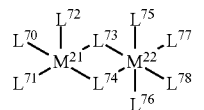
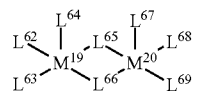
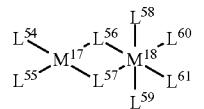
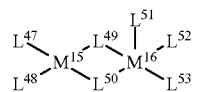


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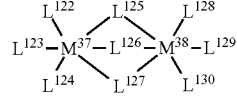
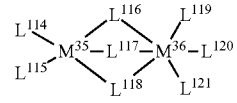
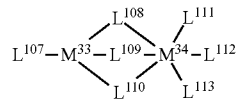
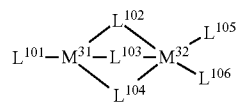
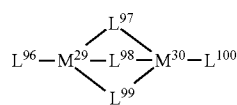
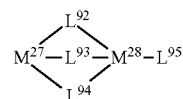
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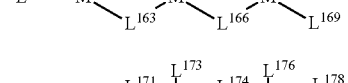
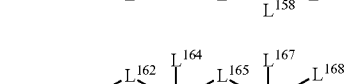
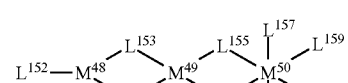
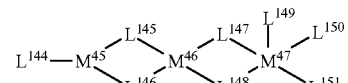
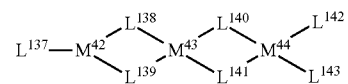
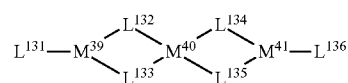
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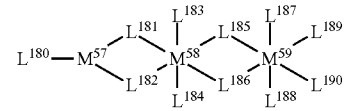
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Chem. 3



Chem. 4



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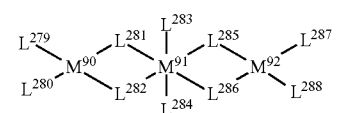
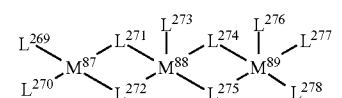
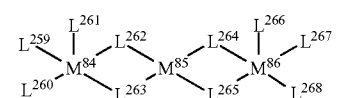
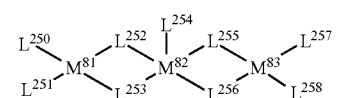
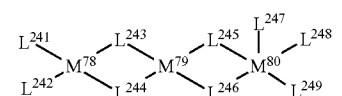
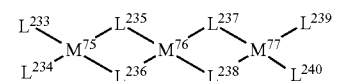
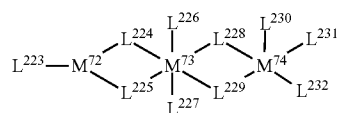
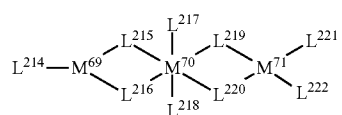
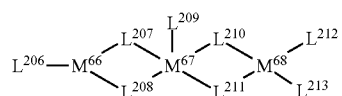
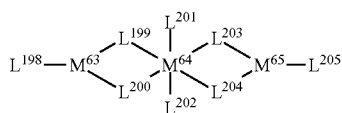
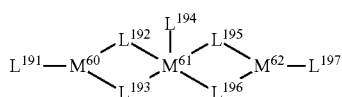
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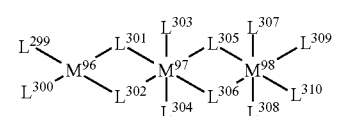
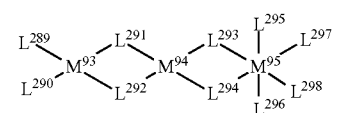
(27)

(28)

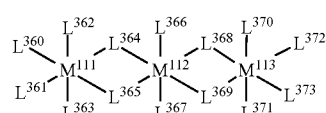
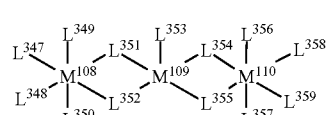
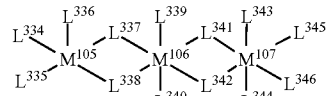
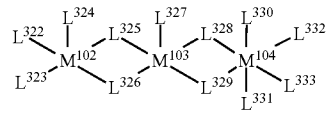
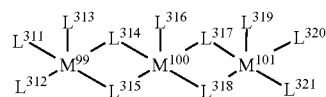
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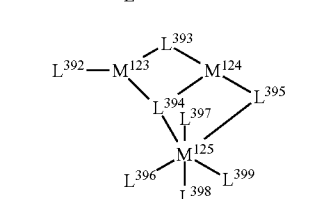
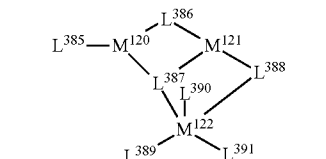
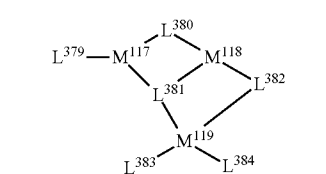
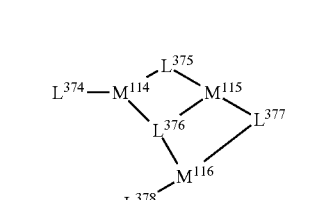
Chem. 5



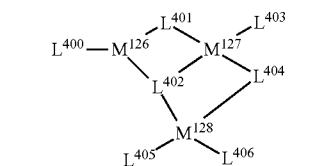
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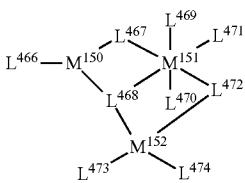
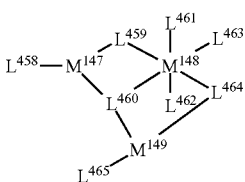
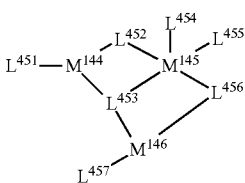
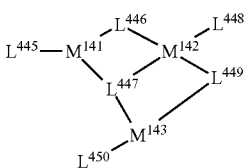
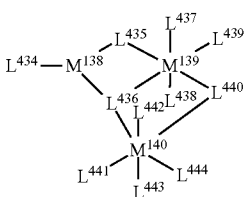
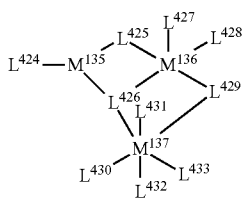
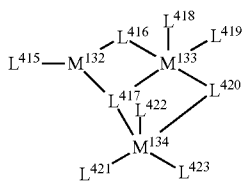
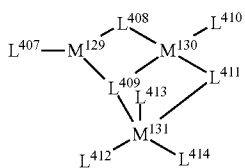
Chem. 6



Chem. 7

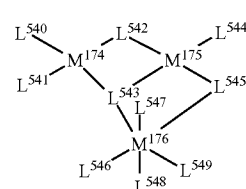
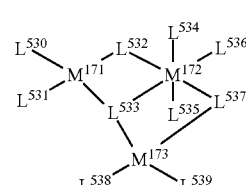
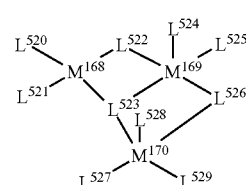
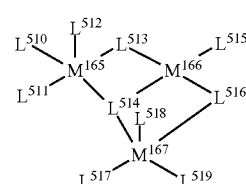
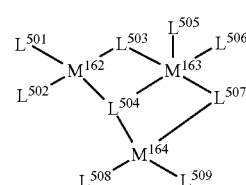
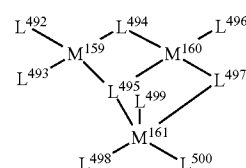
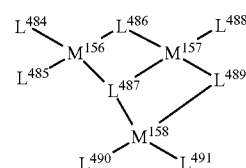
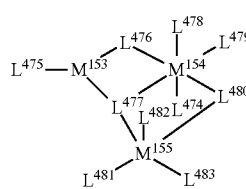


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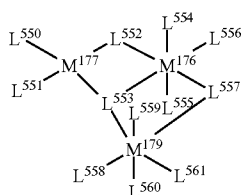
Chem. 8

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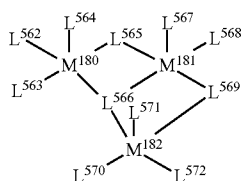
Chem. 9

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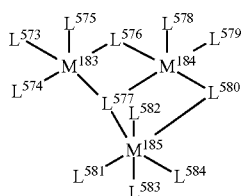


(68)

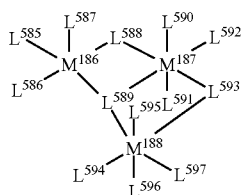
Chem. 10



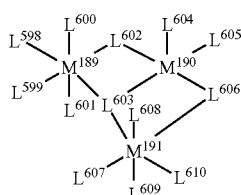
(69)



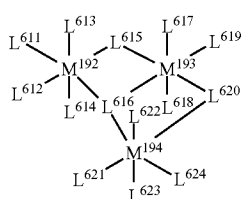
(70)



(71)



(72)



(73)

[0046] where each of  $L^1$  through  $L^{624}$  independently indicates a ligand, each of  $M^1$  through  $M^{194}$  independently indicates a metal atom or a metal ion, and the molecular metal complex expressed by the General Formula (2) is a metal complex other than a porphyrin derivative.

[0047] Further preferably, the one or more molecular metal complexes selected from the molecular metal complexes expressed by the General Formulae (1) through (73) include one or more molecular metal complexes selected from the molecular metal complexes expressed by the General Formulae (5) through (21). The later-described Examples indicate that the dinuclear molecular metal com-

plexes expressed by the General Formulae (5) through (21) include molecular metal complexes exhibiting high electro-motive forces.

[0048] As  $M^1$  through  $M^{194}$ , the above-described metal atoms or metal ions can be used. Each of  $L^1$  through  $L^{624}$  independently indicates a ligand. As described above, the ligand is not limited to any particular kind, as long as it is a low-molecular-weight molecular or ion. Preferably, each of ligand atoms of  $L^1$  through  $L^{624}$  is independently a hydrogen atom, a carbon atom, a nitrogen atom, an oxygen atom, a phosphor atom, a sulfur atom, or a halogen atom.

[0049] Concrete examples of a more preferable ligand encompass ligands expressed by the following Chemical Formulae (74) through (116):

Chem. 11

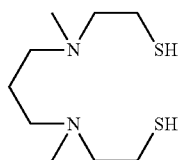
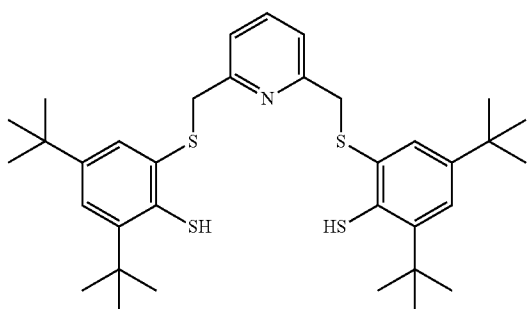
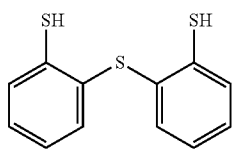
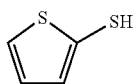
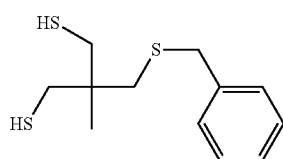
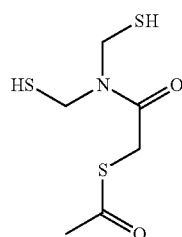
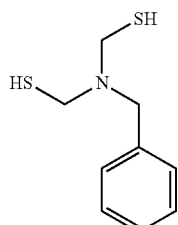
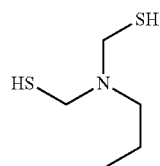


Chem. 12.

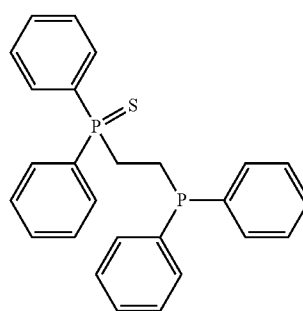
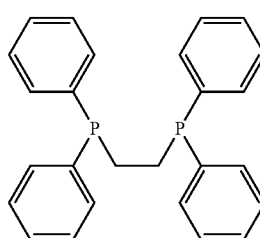
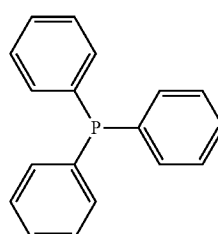
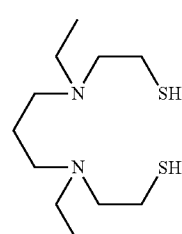




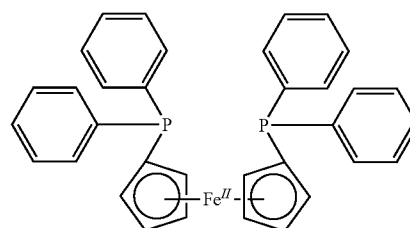
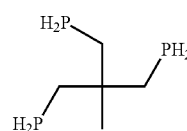
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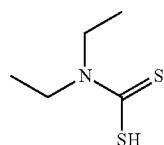
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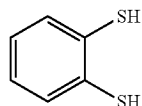
Chem. 13



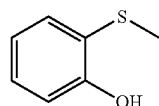
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(107)



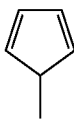
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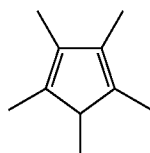
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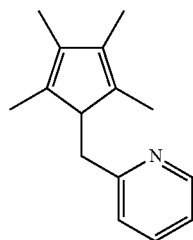
(110)



(111)



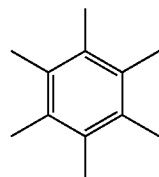
(112)



(113)

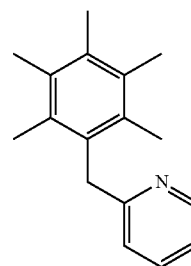


(114)



(115)

-continued



(116)

**[0050]** Note that each of the above ligands can coordinate to a metal through deprotonation.

**[0051]** In the molecular metal complexes expressed by the General Formulae (1) through (73), as  $L^1$  through  $L^{624}$  and  $M^1$  through  $M^{194}$ , any combination of the above ligands and the above metal atoms or metal ions can be selected. Similarly, in the molecular metal complexes expressed by the General Formulae (5) through (21), as  $L^{19}$  through  $L^{150}$  and  $M^5$  through  $M^{38}$ , any combination of the above ligands and the above metal atoms or metal ions can be selected.

**[0052]** The molecular metal complexes whose structures are made of such combinations would not be burned at a high temperature. With this, it is possible to prepare a fuel cell electrode catalyst maintaining a chemical structure of a metal complex.

**[0053]** Further, with the various combinations described above, it is possible to freely design a ligand in a complex so as to easily control the catalytic power of the complex. Furthermore, use of the above molecular metal complex makes it possible to freely design a ligand in a complex so as to reveal a mechanism of electrode reaction. This can provide a new method and technique for research and development of catalysts. Moreover, in a case where the above molecular metal complex includes an organic metal group, it is possible to easily control electronic effects by changing a substituent.

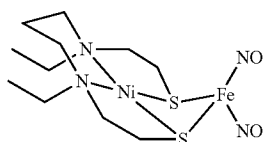
**[0054]** In addition, the above molecular metal complex is water-soluble and stable in water. Therefore, the above molecular metal complex is very effective in a fuel cell which uses (i) hydrogen including saturated steam, etc. and (ii) oxygen.

**[0055]** For the above molecular metal complex, any combination of (i) the above ligands and (ii) the above metal atoms or metal ions can be selected. For example, the above molecular metal complex can be a dinuclear metal complex in which two metal atoms or two metal ions are crosslinked by a sulfur atom. This dinuclear metal complex is, for example, a dinuclear metal complex including a sulfur atom as at least one of  $L^{20}$  and  $L^{21}$  in the General Formula (5), at least one of  $L^{24}$  and  $L^{25}$  in the General Formula (6), at least one of  $L^{29}$  and  $L^{30}$  in the General Formula (7), at least one of  $L^{35}$  and  $L^{36}$  in the General Formula (8), at least one of  $L^{43}$  and  $L^{44}$  in the General Formula (9), at least one of  $L^{49}$  and  $L^{50}$  in the General Formula (10), at least one of  $L^{56}$  and  $L^{57}$  in the General Formula (11), at least one of  $L^{65}$  and  $L^{66}$  in the General Formula (12), at least one of  $L^{73}$  and  $L^{74}$  in the General Formula (13), at least one of  $L^{83}$  and  $L^{84}$  in the General Formula (14), at least one of  $L^{89}$ ,  $L^{90}$ , and  $L^{91}$  in the General Formula (15), at least one of  $L^{92}$ ,  $L^{93}$ , and  $L^{94}$  in the General Formula (16), at least one of  $L^{97}$ ,  $L^{98}$ , and  $L^{99}$  in the General Formula (17), at least one of  $L^{102}$ ,  $L^{103}$ , and  $L^{104}$  in

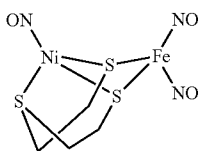
the General Formula (18), at least one of  $L^{108}$ ,  $L^{109}$ , and  $L^{110}$  in the General Formula (19), at least one of  $L^{116}$ ,  $L^{117}$ , and  $L^{118}$  in the General Formula (20), or at least one of  $L^{125}$ ,  $L^{126}$ , and  $L^{127}$  in the General Formula (21).

**[0056]** More concrete examples of the one or more molecular metal complexes selected from the molecular metal complexes expressed by the General Formulae (1) through (73) encompass molecular metal complexes expressed by the following Chemical Formulae (117) through (151):

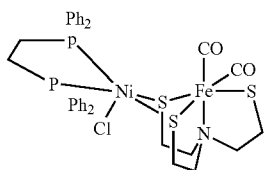
Chem. 14



(117)

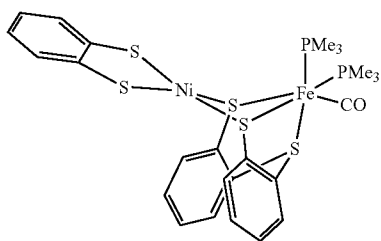


(118)

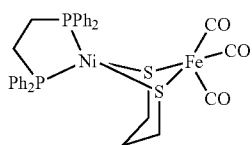


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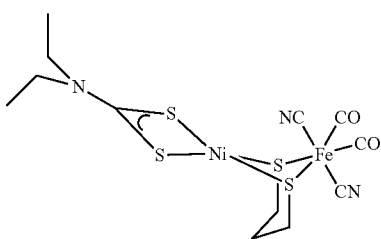
Chem. 15



(120)

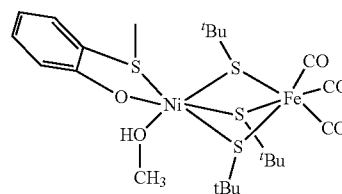


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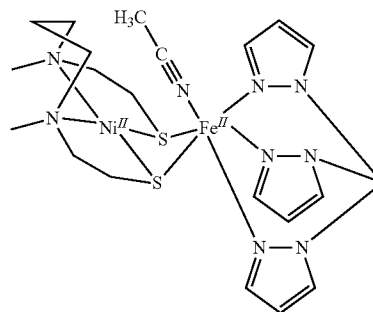


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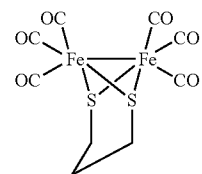
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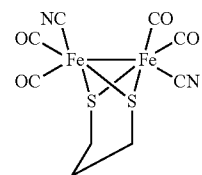
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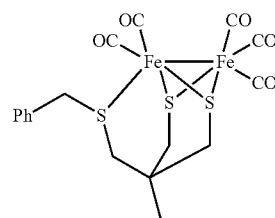
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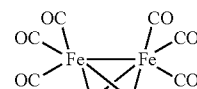
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(126)

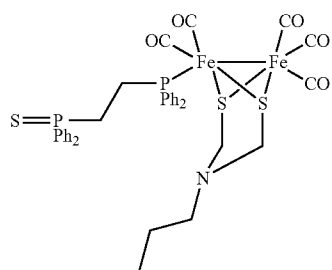


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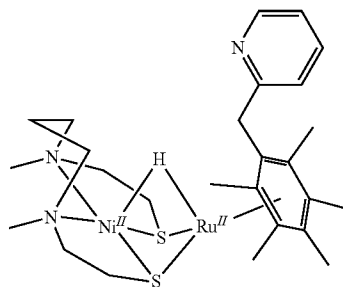
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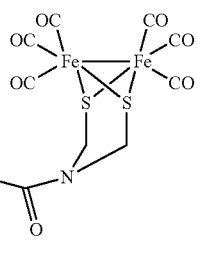


(129)

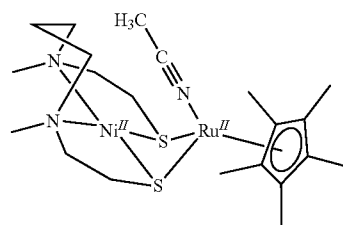
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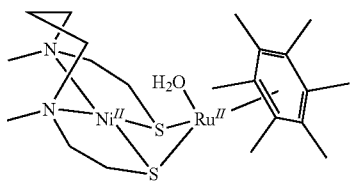
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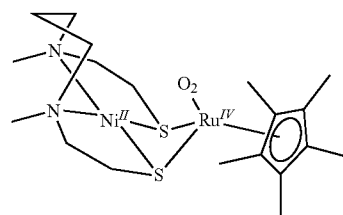
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(136)

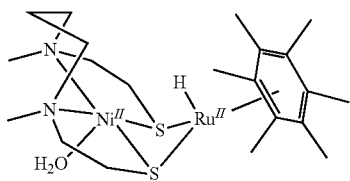


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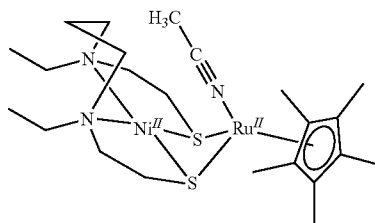


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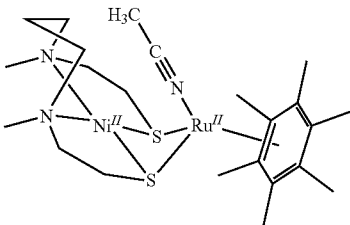
Chem. 16



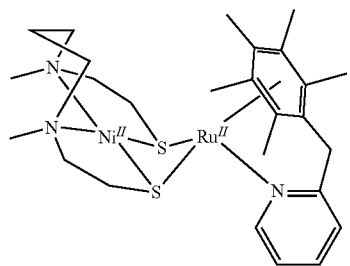
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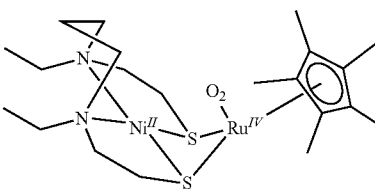
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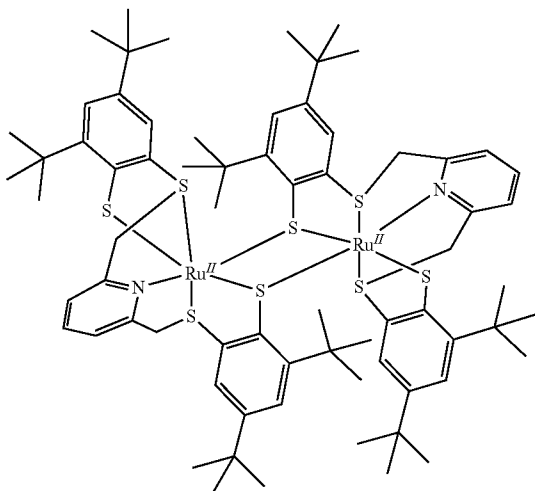
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(139)

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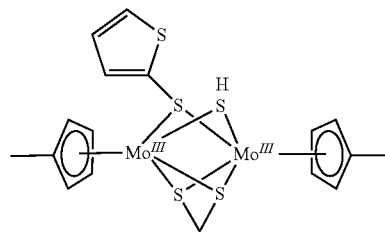
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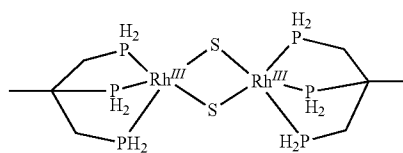
Chem. 17

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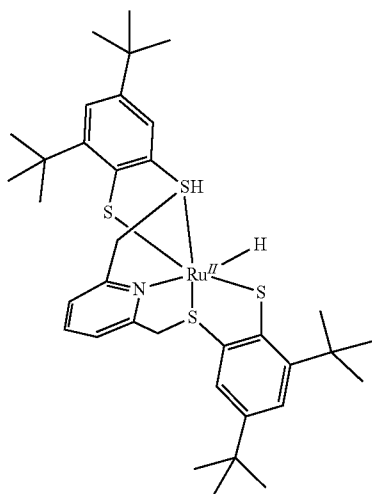
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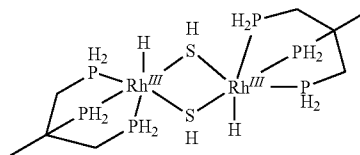
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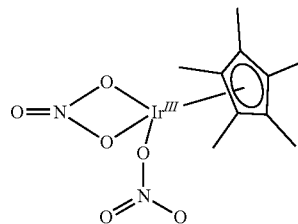
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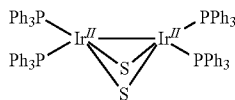


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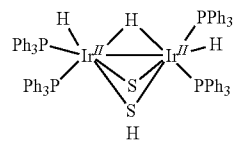


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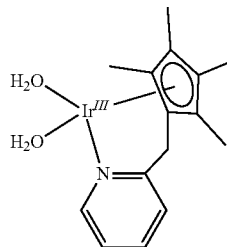
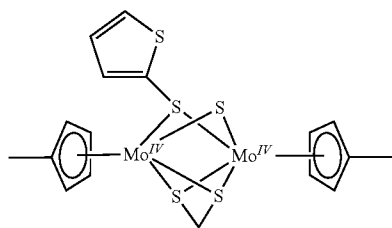
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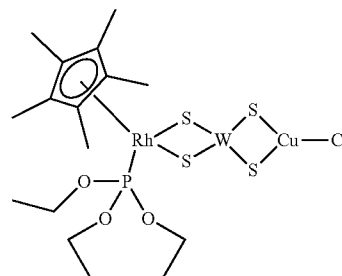
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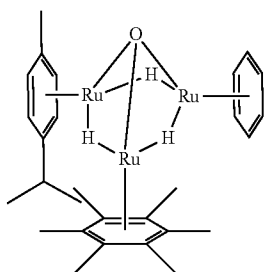


(150)



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(151)



[0057] Among these, the molecular metal complexes expressed by the Chemical Formulae (131) through (138) are more preferable, because each of these molecular metal complexes exhibits high electromotive force, as indicated by the later-described Examples.

[0058] A method for producing the above molecular metal complex is not particularly limited. The method for producing the above molecular metal complex can be suitably selected from conventionally-known methods according to a ligand coordinating to the molecular metal complex, and can be a combination of such the methods. Further, the above molecular metal complex can be a commercially available molecular metal complex.

[0059] (I-2) Fuel Cell Electrode Catalyst

[0060] A fuel cell electrode catalyst of the present invention includes one or more molecular metal complexes selected from the molecular metal complexes indicated above.

[0061] The fuel cell electrode catalyst of the present invention can be suitably used in any fuel cells. In particular, the fuel cell electrode catalyst of the present invention can be more suitably used in a solid polymer fuel cell.

[0062] Typically, the solid polymer fuel cell is configured so as to include an electrolyte membrane sandwiched by an anode and a cathode. Further, electricity and thermal energy are taken from the solid polymer fuel cell through electrochemical reaction of (i) hydrogen, etc. serving as a fuel and (ii) oxygen (or the air) serving as an oxidant. In this process, oxidation reaction of the fuel occurs in the anode (also called a negative electrode or a fuel electrode), whereas reduction of the oxidant occurs in the cathode (also called a positive electrode or an air electrode). Instead of hydrogen, the fuel can be gasoline, methanol, diethyl ether, carbon hydride, or the like, each of which is reformed into hydrogen and supplied to the fuel cell. Further, the fuel cell electrode catalyst of the present invention is applicable also to a direct-type fuel cell to which methanol, diethyl ether, or the like can be directly supplied as a fuel.

[0063] The fuel cell electrode catalyst of the present invention only needs to include one or more molecular metal complexes selected from the molecular metal complexes indicated above. Namely, the fuel cell electrode catalyst of the present invention may include a single kind of molecular metal complex selected from the molecular metal complexes exemplified above. Alternatively, the fuel cell electrode catalyst of the present invention may include two or more kinds of molecular metal complexes selected from the molecular metal complexes indicated above.

[0064] Further, the fuel cell electrode catalyst of the present invention may include only the above molecular metal complex. Alternatively, if necessary, the fuel cell

electrode catalyst of the present invention may include other component(s) in addition to the above molecular metal complex.

[0065] Examples of the "other component(s)" encompass: catalyst supports such as Vulcan (manufactured by Cabot Corporation), carbon black, acetylene black, furnace black, graphite, carbon nanotube, carbon nanofiber, black smoke, carbon fiber, and activated charcoal; and conductive polymers such as polyacetylene, polypyrrole, polythiol, polyimidazole, polypyridine, polyaniline, and polythiophene. In the case where the fuel cell electrode catalyst includes other component(s), a percentage of (i) other component(s) with respect to (ii) the molecular metal complex included in the fuel cell electrode catalyst is not particularly limited. However, a percentage of the catalyst support with respect to the molecular metal complex is 0 wt % or more but not more than 50 wt %, and a percentage of the conductive polymer with respect to the molecular metal complex is 0 wt % or more but not more than 50 wt %.

[0066] Further, if necessary, the fuel cell electrode catalyst of the present invention may contain a proton-conductive polymer electrolyte such as Nafion (Registered Trademark), Flemion (Registered Trademark), or Aciplex (Registered Trademark).

[0067] (I-3) Fuel Cell Electrode Catalyst Usable in Each of Anode and Cathode

[0068] The present invention is based on the following finding that the inventors of the present invention have reached for the first time: A molecular metal complex, which has been conventionally considered not to have ability as the fuel cell electrode catalyst, functions as the fuel cell electrode catalyst.

[0069] Surprisingly, in the present invention, such an unexpected effect has been found that the above molecular metal complex functions as the fuel cell electrode catalyst not only in the anode but also in the cathode.

[0070] Typically, different kinds of catalysts are used for (i) an electrode catalyst for the anode which activates hydrogen molecules and (ii) an electrode catalyst for the cathode which activates oxygen molecules. Also from this, it has not been expected that the above molecular metal complex functions as the fuel cell electrode catalyst not only in the anode but also in the cathode. Further, it has never reported that a molecular metal complex functions as the fuel cell electrode catalyst in the cathode.

[0071] However, the above molecular metal complex exhibits an ability to function as the fuel cell electrode catalyst also in the cathode. Namely, the fuel cell electrode catalyst of the present invention including the above molecular metal complex is a fuel cell electrode catalyst usable in each of the anode and the cathode, which fuel cell electrode catalyst can be used in each of the anode and the cathode of the fuel cell.

[0072] Since the above molecular metal complex can be used not only in the anode but also in the cathode, it is possible to further reduce a use amount of platinum as a simple substance or a platinum alloy and to more easily control the catalytic power.

[0073] (II) Use of Fuel Cell Electrode Catalyst of the Present Invention

[0074] A fuel cell electrode catalyst of the present invention is economical and has easy-to-control catalytic power. Therefore, the fuel cell electrode catalyst of the present invention can be suitably used in a fuel cell electrode, a fuel

cell, and an electric power generation method. Namely, the scope of the present invention encompasses a fuel cell electrode including the fuel cell electrode catalyst, a fuel cell including the fuel cell electrode catalyst, and an electric power generation method using the fuel cell electrode catalyst.

**[0075]** (II-1) Fuel Cell Electrode

**[0076]** A fuel cell electrode of the present invention is not particularly limited, as long as it includes the above fuel cell electrode catalyst. The fuel cell electrode of the present invention can include any of various conventionally-known structures according to a type of a fuel cell.

**[0077]** Taking the solid polymer fuel cell as an example, the fuel cell electrode of the present invention can be applied to a catalyst layer-attached gas diffusion layer electrode for the cathode and/or the anode. In the catalyst layer-attached gas diffusion layer electrode, a catalyst layer containing the above fuel cell electrode catalyst is laminated on a gas diffusion layer. The gas diffusion layer is made of porous carbon or the like such as carbon cloth or carbon paper, and is configured to diffuse a fuel or oxygen (the air) supplied via a gas flow path so that the fuel or oxygen (the air) is efficiently supplied to the catalyst.

**[0078]** The catalyst layer provided on the gas diffusion layer is produced, e.g., in such a manner that the above fuel cell electrode catalyst is applied onto the gas diffusion layer in the form of a solution, a suspension, slurry, paste, or the like and is then dried. There is no particular limitation on a medium for making the above fuel cell electrode catalyst into the form of the solution, suspension, slurry, paste, or the like. Such the medium may be suitably selected from conventionally-known media.

**[0079]** Note that, if necessary, the catalyst layer may contain the above catalyst support, conductive polymer, ionomer, and/or the like, in addition to the above fuel cell electrode catalyst. The catalyst support, conductive polymer, ionomer, and/or the like may be added to the solution, suspension, slurry, paste, or the like of the above fuel cell electrode catalyst. Alternatively, the catalyst support, conductive polymer, ionomer, and/or the like may be applied in the form of a solution, a suspension, slurry, paste, or the like before/after or at the same time with the application of the catalyst layer, independently of the solution, suspension, slurry, paste, or the like of the above fuel cell electrode catalyst.

**[0080]** (II-2) Fuel Cell

**[0081]** A configuration of a fuel cell of the present invention is not particularly limited, as long as it is employed in a generally-used fuel cell. For example, the fuel cell of the present invention is configured to include at least an electrolyte membrane, an anode, and a cathode, the electrolyte membrane being sandwiched by the anode and the cathode.

**[0082]** Such the fuel cell can be produced, for example, as follows. In the above-described manner, (i) a catalyst layer-attached gas diffusion layer electrode for the cathode and (ii) a catalyst layer-attached gas diffusion layer electrode for the anode are produced. Between the catalyst layer-attached gas diffusion layer electrodes thus produced, an electrolyte membrane is provided so that catalyst layers of the respective catalyst layer-attached gas diffusion layer electrodes face each other via the electrolyte membrane. Consequently, a membrane electrode assembly (MEA) is obtained. The membrane electrode assembly thus obtained can be incorporated into a fuel cell for use.

**[0083]** The fuel cell of the present invention only needs to include the above fuel cell electrode catalyst(s) independently for the anode and/or the cathode. Namely, the fuel cell electrodes of the present invention may be used in both of the anode and the cathode. Alternatively, the fuel cell electrode of the present invention may be used in either one of the anode and the cathode. In the case where the fuel cell electrode of the present invention is used in either one of the anode and the cathode, an opposing electrode catalyst may be any of conventionally-known catalysts, for example, a catalyst containing platinum as a simple substance, a platinum alloy, or the like.

**[0084]** The electrolyte membrane is not particularly limited, as long as it is a polymer membrane having high hydrogen ion conductivity. The electrolyte membrane can be any of generally-used electrolyte membranes such as perfluorosulfonic acid proton exchanging membranes, examples of which encompass Nafion (Registered Trademark), Flemion (Registered Trademark), and Aciplex (Registered Trademark).

**[0085]** (II-3) Electric Power Generation Method

**[0086]** An electric power generation method of the present invention only needs to include the step(s) of: oxidizing a fuel through use of the above fuel cell electrode catalyst; and/or reducing an oxidant through use of the above fuel cell electrode catalyst. Namely, the electric power generation method of the present invention may include both of or either one of the steps of: oxidizing a fuel through use of the above fuel cell electrode catalyst; and reducing an oxidant through use of the above fuel cell electrode catalyst.

**[0087]** To be more specific, for example, the electric power generation method of the present invention includes the step(s) of: causing, through use of the above fuel cell electrode catalyst, a hydrogen molecule to release an electron so that the hydrogen molecule is turned into a hydrogen ion; and/or causing, through use of the above fuel cell electrode catalyst, the hydrogen ion, the electron, and an oxygen molecule to react each other so that water is generated.

**[0088]** The electric power generation method of the present invention is not particularly limited, and may be carried out by any of generally-known processes. For example, hydrogen gas is supplied to the anode of the fuel cell, whereas oxygen is supplied to the cathode of the fuel cell. In this process, the hydrogen gas and oxygen may be moistured through a bubbler.

**[0089]** When the hydrogen gas is supplied to the anode, hydrogen molecules in the hydrogen gas release electrons in response to an effect of the above fuel cell electrode catalyst, so that the hydrogen molecules are turned into hydrogen ions. The hydrogen ions pass through an electrolyte membrane so as to move to the cathode, which faces the anode. In the cathode, (i) the hydrogen ions thus moved to and (ii) oxygen molecules supplied to the cathode react with each other in response to an effect of the above fuel cell electrode catalyst, so that water is generated. In this process, a flow of the electrons in an electric cable is taken as direct-current electricity.

**[0090]** The present invention can be expressed also as follows:

**[0091]** The fuel cell electrode catalyst of the present invention may preferably be arranged such that the one or more molecular metal complexes include, as the above molecular metal complex, one or more molecular metal

complexes selected from molecular metal complexes expressed by General Formulae (1) through (73) above, where each of  $L^1$  through  $L^{624}$  independently indicates a ligand, each of  $M^1$  through  $M^{194}$  independently indicates a metal atom or a metal ion, and the molecular metal complex expressed by the General Formula (2) is a metal complex other than a porphyrin derivative.

**[0092]** The fuel cell electrode catalyst of the present invention may preferably be arranged such that the one or more molecular metal complexes selected from the molecular metal complexes expressed by the General Formulae (1) through (73) include one or more molecular metal complexes selected from the molecular metal complexes expressed by the General Formulae (5) through (21).

**[0093]** The fuel cell electrode catalyst of the present invention may preferably be arranged such that the fuel cell electrode catalyst is usable in each of an anode and a cathode.

**[0094]** The fuel cell electrode catalyst of the present invention may preferably be arranged such that the one metal atom or one metal ion is a metal atom or a metal ion thereof, the metal atom being selected from the group consisting of metal atoms and metal ions of 3A group elements, 4A group elements, 5A group elements, 6A group elements, 7A group elements, 8 group elements, 1B group elements, 3B group elements, and 6B group elements in a periodic table.

**[0095]** The fuel cell electrode catalyst of the present invention may preferably be arranged such that the one metal atom or one metal ion is a metal atom or a metal ion thereof, the metal atom being selected from the group consisting of the metal atoms and the metal ions of the 8 group elements.

**[0096]** The fuel cell electrode catalyst of the present invention may preferably be arranged such that each of ligand atoms of the ligands indicated by  $L^1$  through  $L^{624}$  is independently a hydrogen atom, a carbon atom, a nitrogen atom, an oxygen atom, a phosphorus atom, a sulfur atom, or a halogen atom.

**[0097]** The fuel cell electrode catalyst of the present invention may preferably be arranged such that each of the ligands indicated by  $L^1$  through  $L^{624}$  is independently selected from ligands expressed by the above Chemical Formulae (74) through (11.6).

**[0098]** The fuel cell electrode catalyst of the present invention may preferably be arranged such that the one or more molecular metal complexes selected from the molecular metal complexes expressed by the General Formulae (1) through (73) are selected from molecular metal complexes expressed by the above Chemical Formulae (117) through (151).

**[0099]** The fuel cell electrode catalyst of the present invention may preferably be arranged such that the one or more molecular metal complexes selected from the molecular metal complexes expressed by the Chemical Formulae (117) through (151) are selected from the molecular metal complexes expressed by the Chemical Formulae (131) through (138).

**[0100]** A fuel cell electrode of the present invention includes a fuel cell electrode catalyst of the present invention.

**[0101]** A fuel cell of the present invention includes a fuel cell electrode catalyst of the present invention independently for each of an anode and/or a cathode.

**[0102]** An electric power generation method of the present invention includes the steps of: oxidizing a fuel through use of a fuel cell electrode catalyst of the present invention; and/or reducing an oxidant through use of a fuel cell electrode catalyst of the present invention.

## EXAMPLES

### Example 1

**[0103]** <Production of Carbon Cloth to which Fuel Cell Electrode Catalyst of the Present Invention is Applied>

**[0104]** 10 mg of the molecular metal complex expressed by the Chemical Formula (117) was evenly applied onto a carbon cloth (manufactured by E-TEK) of 5 cm<sup>2</sup>. Specifically, the molecular metal complex was dispersed in 100 mg of a Nafion (Registered Trademark) solution, and a dispersion solution thus obtained was applied to the carbon cloth. Then, the resultant was dried at 25° C. under reduced pressure.

**[0105]** Note that the molecular metal complex expressed by the Chemical Formula (117) was synthesized with reference to F. Osterloh, W. Saak, D. Haase and S. Pohl, Chem. Commun., 1997, 979-980.

#### Example 1-1: Production of Fuel Cell Including, in Anode, Fuel Cell Electrode Catalyst of the Present Invention

**[0106]** A membrane electrode assembly (MEA) was produced by (i) providing, on the hydrogen electrode (anode) side, a carbon cloth to which the molecular metal complex was applied and (ii) providing, on the oxygen electrode (cathode) side, a carbon cloth to which platinum carbon TEC10V50E (manufactured by Takana Kikinzo Kogyo K.K.) was applied so that a polymer membrane (Nafion (Registered Trademark) NRE212, manufactured by DuPont) was sandwiched by these carbon cloths. The membrane electrode assembly thus obtained was incorporated into a fuel cell (manufactured by Toyo Corporation). In this manner, a fuel cell was produced. In the above process, the polymer membrane was sandwiched by the carbon cloths so that (i) a side of one of the carbon cloths to which side the molecular metal complex was applied and (ii) a side of the other of the carbon cloths to which side platinum was applied face each other via the polymer membrane. Hydrogen and oxygen were supplied to the fuel cell thus produced, and an electromotive force of the fuel cell was measured. The result of the measurement is shown in Table 1.

**[0107]** Note that the fuel cell thus produced was configured such that each of the hydrogen electrode (anode) and the oxygen electrode (cathode) contains Vulcan (manufactured by Cabot Corporation) and Nafion (Registered Trademark) functioning as an ionomer. Specifically, 10 mg of the molecular metal complex and 60 mg of Vulcan were added to 100 mg of a Nafion (Registered Trademark) solution (Nafion perfluorinated ion-exchange resin, 5 wt % soln in lower aliphatic alcohols/H<sub>2</sub>O mix (product name), manufactured by Aldrich), and the mixture was dispersed by an ultrasonic vibration machine. Then, the resultant solution was applied to a carbon cloth. In a similar way, platinum carbon was applied to a carbon cloth.



Example 1-2: Production of Fuel Cell Including, in Cathode, Fuel Cell Electrode Catalyst of the Present Invention

[0108] A membrane electrode assembly (MEA) was produced by (i) providing, on the hydrogen electrode side, a carbon cloth to which platinum carbon TEC10V50E (manufactured by Takana Kikinzoku Kogyo K.K.) was applied and (ii) providing, on the oxygen electrode side, a carbon cloth to which the molecular metal complex was applied so that a polymer membrane (Nafion (Registered Trademark) NRE212, manufactured by DuPont) was sandwiched by these carbon cloths. The membrane electrode assembly thus obtained was incorporated into a fuel cell (manufactured by Toyo Corporation). In this manner, a fuel cell was produced. In the above process, the polymer membrane was sandwiched by the carbon cloths so that (i) a side of one of the carbon cloths to which side the molecular metal complex was applied and (ii) a side of the other of the carbon cloths to which side platinum was applied face each other via the polymer membrane. Hydrogen and oxygen were supplied to the fuel cell thus produced, and an electromotive force of the fuel cell was measured. The result of the measurement is shown in Table 1.

[0109] Note that the fuel cell thus produced was configured such that each of the hydrogen electrode (anode) and the oxygen electrode (cathode) contains Vulcan (manufactured by Cabot Corporation) and Nafion (Registered Trademark) functioning as an ionomer. Specifically, 10 mg of the molecular metal complex and 60 mg of Vulcan were added to 100 mg of a Nafion (Registered Trademark) solution (Nafion perfluorinated ion-exchange resin, 5 wt % soln in lower aliphatic alcohols/H<sub>2</sub>O mix (product name), manufactured by Aldrich), and the mixture was dispersed by the ultrasonic vibration machine. Then, the resultant solution was applied to a carbon cloth. In a similar way, platinum carbon was applied to a carbon cloth. Further, the hydrogen electrode includes, as a conductive polymer, polypyrrole which was caused to be supported by Vulcan with reference to Non-Patent Literature 2.

Example 1-3: Production of Fuel Cell Including, in Anode and Cathode, Fuel Cell Electrode Catalysts of the Present Invention

[0110] A membrane electrode assembly (MEA) was produced by providing, on both of the hydrogen electrode side and the oxygen electrode side, carbon cloths to each of which the molecular metal complex was applied so that a polymer membrane (Nafion (Registered Trademark) NRE212, manufactured by DuPont) was sandwiched by these carbon cloths. The membrane electrode assembly thus obtained was incorporated into a fuel cell (manufactured by Toyo Corporation). In this manner, a fuel cell was produced. In the above process, the polymer membrane was sandwiched by the carbon cloths so that sides of the respective carbon cloths to each of which sides the molecular metal complex was applied face each other via the polymer membrane. Hydrogen and oxygen were supplied to the fuel

cell thus produced, and an electromotive force of the fuel cell was measured. The result of the measurement is shown in Table 1.

[0111] Note that the fuel cell thus produced was configured such that each of the hydrogen electrode (anode) and the oxygen electrode (cathode) contains Vulcan (manufactured by Cabot Corporation) and Nafion (Registered Trademark) functioning as an ionomer. Specifically, 10 mg of the molecular metal complex and 60 mg of Vulcan were added to 100 mg of a Nafion (Registered Trademark) solution (Nafion perfluorinated ion-exchange resin, 5 wt % soln in lower aliphatic alcohols/H<sub>2</sub>O mix (product name), manufactured by Aldrich), and the mixture was dispersed by the ultrasonic vibration machine. Then, the resultant solution was applied to a carbon cloth. Note that the hydrogen electrode includes, as a conductive polymer, polypyrrole which was caused to be supported by Vulcan with reference to Non-Patent Literature 2.

Example 2

[0112] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (118) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 2-4) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 2-5) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 2-6) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 1.

[0113] Note that the molecular metal complex expressed by the Chemical Formula (118) was synthesized with reference to W.-F. Liaw, C.-Y. Chiang, G.-H. Lee, S.-M. Peng, C.-H. Lai and M. Y. Darensbourg, *Inorg. Chem.*, 2000, 39, 480-484.

Example 3

[0114] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (119) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 3-7) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 3-8) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 3-9) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 1.

[0115] Note that the molecular metal complex expressed by the Chemical Formula (119) was synthesized with reference to S. C. Davies, D. J. Evans, D. L. Hughes, S. Longhurst and J. R. Sanders, *Chem. Commun.*, 1999, 1935-1936.

## Example 4

[0116] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (120) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 4-10) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 4-11) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 4-12) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 1.

[0117] Note that the molecular metal complex expressed by the Chemical Formula (120) was synthesized with reference to D. Sellmann, F. Geipel, F. Lauderbach and F. W. Heinemann, *Angew. Chem., Int. Ed.*, 2002, 41, 632-634.

the present invention, and a fuel cell (Example 5-15) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 2.

[0119] Note that the molecular metal complex expressed by the Chemical Formula (121) was synthesized with reference to W. Zhu, A. C. Marr, Q. Wang, F. Neese, D. J. E. Spencer, A. J. Blake, P. A. Cooke, C. Wilson and M. Schroder, *Proc. Natl. Acad. Sci. U.S.A.*, 2005, 102, 18280-18285.

## Example 6

[0120] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (122) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Ex-

TABLE 1

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/ A cm <sup>-2</sup>
1-1	Yes	Yes	No	Chemical Formula (117)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001
1-2	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (117)	No	Yes	Yes	0.35	0.001
1-3	Yes	Yes	Yes	Chemical Formula (117)	Nafion	Nafion NRE212	Nafion	Chemical Formula (117)	No	Yes	Yes	0.1	0.001
2-4	Yes	Yes	No	Chemical Formula (118)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.4	0.001
2-5	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (118)	No	Yes	Yes	0.4	0.001
2-6	Yes	Yes	Yes	Chemical Formula (118)	Nafion	Nafion NRE212	Nafion	Chemical Formula (118)	No	Yes	Yes	0.15	0.001
3-7	Yes	Yes	No	Chemical Formula (119)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001
3-8	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (119)	No	Yes	Yes	0.3	0.001
3-9	Yes	Yes	Yes	Chemical Formula (119)	Nafion	Nafion NRE212	Nafion	Chemical Formula (119)	No	Yes	Yes	0.2	0.001
4-10	Yes	Yes	No	Chemical Formula (120)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.2	0.001
4-11	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (120)	No	Yes	Yes	0.1	0.001
4-12	Yes	Yes	Yes	Chemical Formula (120)	Nafion	Nafion NRE212	Nafion	Chemical Formula (120)	No	Yes	Yes	0.05	0.001

## Example 5

[0118] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (121) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 5-13) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 5-14) including, in the cathode, the fuel cell electrode catalyst of

ample 6-16) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 6-17) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 6-18) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 2.

[0121] Note that the molecular metal complex expressed by the Chemical Formula (122) was synthesized with reference to Z. Li, Y. Ohki and K. Tatsuni, J. Am. Chem. Soc., 2005, 127, 8950-8951.

#### Example 7

[0122] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (123) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 7-19) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 1-20) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 1-21) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 2.

[0123] Note that the molecular metal complex expressed by the Chemical Formula (123) was synthesized with ref-

erence to Y. Ohki, K. Yasumura, K. Kuge, S. Tanino, M. Ando, Z. Li and K. Tatsuni, Proc. Natl. Acad. Sci. U.S.A, 2008, 105, 7652-7657.

#### Example 8

[0124] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (124) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 8-22) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 8-23) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 8-24) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 2.

[0125] Note that the molecular metal complex expressed by the Chemical Formula (124) was synthesized with reference to K. Ichikawa, T. Matsumoto and S. Ogo, Dalton Trans., 2009, 4304-4309.

TABLE 2

	Carbon cloth	Vulcan	Con- ductive polymer	Hydrogen electrode	Ionomer	Polymer mem- brane	Ionomer	Oxygen electrode	Con- ductive polymer	Vulcan	Carbon cloth	Electro- motive force/V	Maximum current/ A cm <sup>-2</sup>
5-13	Yes	Yes	No	Chemical Formula (121)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.35	0.001
5-14	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (121)	No	Yes	Yes	0.3	0.001
5-15	Yes	Yes	Yes	Chemical Formula (121)	Nafion	Nafion NRE212	Nafion	Chemical Formula (121)	No	Yes	Yes	0.15	0.001
6-16	Yes	Yes	No	Chemical Formula (122)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001
6-17	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (122)	No	Yes	Yes	0.3	0.001
6-18	Yes	Yes	Yes	Chemical Formula (121)	Nafion	Nafion NRE212	Nafion	Chemical Formula (122)	No	Yes	Yes	0.1	0.001
7-19	Yes	Yes	No	Chemical Formula (123)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.4	0.001
7-20	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (123)	No	Yes	Yes	0.35	0.001
7-21	Yes	Yes	Yes	Chemical Formula (123)	Nafion	Nafion NRE212	Nafion	Chemical Formula (123)	No	Yes	Yes	0.25	0.001
8-22	Yes	Yes	No	Chemical Formula (124)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.2	0.001
8-23	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (124)	No	Yes	Yes	0.33	0.001
8-24	Yes	Yes	Yes	Chemical Formula (124)	Nafion	Nafion NRE212	Nafion	Chemical Formula (124)	No	Yes	Yes	0.12	0.001

## Example 9

[0126] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (125) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 9-25) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 9-26) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 9-27) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 3.

[0127] Note that the molecular metal complex expressed by the Chemical Formula (125) was synthesized with reference to E. J. Lyon, I. P. Georgakaki, J. H. Reibenspies and M. Y. Darensbourg, *Angew. Chem., Int. Ed.*, 1999, 38, 3178-3180.

## Example 10

[0128] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (126) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 10-28) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 10-29) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 10-30) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 3.

[0129] Note that the molecular metal complex expressed by the Chemical Formula (126) was synthesized with reference to M. Schmidt, S. M. Contakes and T. B. Rauchfuss, *J. Am. Chem. Soc.*, 1999, 121, 9736-9737.

## Example 11

[0130] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (127) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 11-31) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 11-32) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 11-33) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 3.

[0131] Note that the molecular metal complex expressed by the Chemical Formula (127) was synthesized with reference to M. Razavet, S. C. Davies, D. L. Hughes and C. J. Pickett, *Chem. Commun.*, 2001, 847-848.

## Example 12

[0132] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (128) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 12-34) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 12-35) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 12-36) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 3.

[0133] Note that the molecular metal complex expressed by the Chemical Formula (128) was synthesized with reference to S. Ott, M. Kritikos, B. Akermark, L. Sun and R. Lomoth, *Angew. Chem., Int. Ed.*, 2004, 43, 1006-1009.

TABLE 3

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/A cm <sup>-2</sup>
9-25	Yes	Yes	No	Chemical Formula (125)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.36	0.001
9-26	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (125)	No	Yes	Yes	0.25	0.001
9-27	Yes	Yes	Yes	Chemical Formula (125)	Nafion	Nafion NRE212	Nafion	Chemical Formula (125)	No	Yes	Yes	0.17	0.001
10-28	Yes	Yes	No	Chemical Formula (126)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.37	0.001
10-29	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (126)	No	Yes	Yes	0.37	0.001
10-30	Yes	Yes	Yes	Chemical Formula (126)	Nafion	Nafion NRE212	Nafion	Chemical Formula (126)	No	Yes	Yes	0.21	0.001

TABLE 3-continued

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/A cm <sup>-2</sup>
11 - 31	Yes	Yes	No	Chemical Formula (127)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.35	0.001
11 - 32	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (127)	No	Yes	Yes	0.21	0.001
11 - 33	Yes	Yes	Yes	Chemical Formula (127)	Nafion	Nafion NRE212	Nafion	Chemical Formula (127)	No	Yes	Yes	0.1	0.001
12 - 34	Yes	Yes	No	Chemical Formula (128)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.33	0.001
12 - 35	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (128)	No	Yes	Yes	0.35	0.001
12 - 36	Yes	Yes	Yes	Chemical Formula (128)	Nafion	Nafion NRE212	Nafion	Chemical Formula (128)	No	Yes	Yes	0.16	0.001

## Example 13

[0134] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (129) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 13-37) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 13-38) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 13-39) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 4.

[0135] Note that the molecular metal complex expressed by the Chemical Formula (129) was synthesized with reference to W. Gao, J. Ekstrm, J. Liu, C. Chen, L. Eriksson, L. Weng, B. Akermarck and L. Sun, *Inorg. Chem.*, 2007, 46, 1981-1991.

## Example 14

[0136] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (130) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 14-40) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 14-41) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 14-42) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 4.

[0137] Note that the molecular metal complex expressed by the Chemical Formula (130) was synthesized with reference to L.-C. Song, L.-X. Wang, B.-S. Yin, Y.-L. Li, X.-G. Zhang, Y.-W. Zhang, X. Luo and Q.-M. Hu, *Eur. J. Inorg. Chem.*, 2008, 291-297.

## Example 15

[0138] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (131) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 15-43) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 15-44) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 15-45) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 4.

[0139] Note that the molecular metal complex expressed by the Chemical Formula (131) was synthesized with reference to S. Ogo, R. Kabe, K. Uehara, B. Kure, T. Nishimura, S. C. Menon, R. Harada, S. Fukuzumi, Y. Higuchi, T. Ohhara, T. Tamada and R. Kuroki, *Science*, 2007, 316, 585-587.

## Example 16

[0140] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (132) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 16-46) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 16-47) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 16-48) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 4.

[0141] Note that the molecular metal complex expressed by the Chemical Formula (132) was synthesized with reference to S. Ogo, R. Kabe, K. Uehara, B. Kure, T. Nishimura, S. C. Menon, R. Harada, S. Fukuzumi, Y. Higuchi, T. Ohhara, T. Tamada and R. Kuroki, *Science*, 2007, 316, 585-587.

TABLE 4

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/ A cm <sup>-2</sup>
13 - 37	Yes	Yes	No	Chemical Formula (129)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.23	0.001
13 - 38	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (129)	No	Yes	Yes	0.25	0.001
13 - 39	Yes	Yes	Yes	Chemical Formula (129)	Nafion	Nafion NRE212	Nafion	Chemical Formula (129)	No	Yes	Yes	0.12	0.001
14 - 40	Yes	Yes	No	Chemical Formula (130)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.35	0.001
14 - 41	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (130)	No	Yes	Yes	0.35	0.001
14 - 42	Yes	Yes	Yes	Chemical Formula (130)	Nafion	Nafion NRE212	Nafion	Chemical Formula (130)	No	Yes	Yes	0.1	0.001
15 - 43	Yes	Yes	No	Chemical Formula (131)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.29	0.001
15 - 44	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (131)	No	Yes	Yes	0.36	0.001
15 - 45	Yes	Yes	Yes	Chemical Formula (131)	Nafion	Nafion NRE212	Nafion	Chemical Formula (131)	No	Yes	Yes	0.13	0.001
16 - 46	Yes	Yes	No	Chemical Formula (132)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.75	0.0019
16 - 47	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (132)	No	Yes	Yes	0.6	0.001
16 - 48	Yes	Yes	Yes	Chemical Formula (132)	Nafion	Nafion NRE212	Nafion	Chemical Formula (132)	No	Yes	Yes	0.4	0.001

## Example 17

[0142] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (133) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 17-49) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 17-50) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 17-51) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 5.

[0143] Note that the molecular metal complex expressed by the Chemical Formula (133) was synthesized with reference to K. Ichikawa, T. Matsumoto and S. Ogo, Dalton Trans., 2009, 4304-4309.

## Example 18

[0144] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (134) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 18-52) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 18-53) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 18-54)

including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 5.

[0145] Note that the molecular metal complex expressed by the Chemical Formula (134) was synthesized with reference to (a) S. Ogo, N. Makihara, Y. Kaneko and Y. Watanabe, Organometallics, 2001, 20, 4903-4910; (b) S. Ogo, R. Kabe, K. Uehara, B. Kure, T. Nishimura, S. C. Menon, R. Harada, S. Fukuzumi, Y. Higuchi, T. Ohhara, T. Tamada and R. Kuroki, Science, 2007, 316, 585-587.

## Example 19

[0146] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (135) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 19-55) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 19-56) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 19-57) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 5.

[0147] Note that the molecular metal complex expressed by the Chemical Formula (135) was synthesized by using sodium borohydride instead of hydrogen, with reference to

S. Ogo, R. Kabe, K. Uchara, B. Kure, T. Nishimura, S. C. Menon, R. Harada, S. Fukuzumi, Y. Higuchi, T. Ohhara, T. Tamada and R. Kuroki, *Science*, 2007, 316, 585-587.

#### Example 20

**[0148]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (136) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 20-58) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 20-59) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 20-60) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 5.

**[0149]** Note that the molecular metal complex expressed by the Chemical Formula (136) was synthesized with reference to M. A. Reynolds, T. B. Rauchfuss and S. R. Wilson, *Organometallics*, 2003, 22, 1619-1625.

catalyst of the present invention, a fuel cell (Example 21-62) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 21-63) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 6.

**[0151]** Note that the molecular metal complex expressed by the Chemical Formula (137) was synthesized with reference to M. A. Reynolds, T. B. Rauchfuss and S. R. Wilson, *Organometallics*, 2003, 22, 1619-1625.

#### Example 22

**[0152]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (138) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 22-64) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 22-65) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 22-66)

TABLE 5

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/ A cm <sup>-2</sup>
17 - 49	Yes	Yes	No	Chemical Formula (133)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.34	0.001
17 - 50	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (133)	No	Yes	Yes	0.4	0.001
17 - 51	Yes	Yes	Yes	Chemical Formula (133)	Nafion	Nafion NRE212	Nafion	Chemical Formula (133)	No	Yes	Yes	0.2	0.001
18 - 52	Yes	Yes	No	Chemical Formula (134)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.31	0.001
18 - 53	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (134)	No	Yes	Yes	0.35	0.001
18 - 54	Yes	Yes	Yes	Chemical Formula (134)	Nafion	Nafion NRE212	Nafion	Chemical Formula (134)	No	Yes	Yes	0.15	0.001
19 - 55	Yes	Yes	No	Chemical Formula (135)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.37	0.001
19 - 56	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (135)	No	Yes	Yes	0.23	0.001
19 - 57	Yes	Yes	Yes	Chemical Formula (135)	Nafion	Nafion NRE212	Nafion	Chemical Formula (135)	No	Yes	Yes	0.12	0.001
20 - 58	Yes	Yes	No	Chemical Formula (136)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.25	0.001
20 - 59	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (136)	No	Yes	Yes	0.35	0.001
20 - 60	Yes	Yes	Yes	Chemical Formula (136)	Nafion	Nafion NRE212	Nafion	Chemical Formula (136)	No	Yes	Yes	0.15	0.001

#### Example 21

**[0150]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (137) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 21-61) including, in the anode, the fuel cell electrode

including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 6.

**[0153]** Note that the molecular metal complex expressed by the Chemical Formula (138) was synthesized with ref-

erence to M. A. Reynolds, T. B. Rauchfuss and S. R. Wilson, *Organometallics*, 2003, 22, 1619-1625.

#### Example 23

**[0154]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (139) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 23-67) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 23-68) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 23-69)

ample 24-70) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 24-71) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 24-72) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 6.

**[0157]** Note that the molecular metal complex expressed by the Chemical Formula (140) was synthesized with reference to D. Sellmann, R. Prakash, F. W. Heinemann, M. Moll and M. Klimowicz, *Angew. Chem., Int. Ed.*, 2004, 43, 1877-1880.

TABLE 6

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/ A cm <sup>-2</sup>
21 - 61	Yes	Yes	No	Chemical Formula (137)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.27	0.001
21 - 62	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (137)	No	Yes	Yes	0.35	0.001
21 - 63	Yes	Yes	Yes	Chemical Formula (137)	Nafion	Nafion NRE212	Nafion	Chemical Formula (137)	No	Yes	Yes	0.12	0.001
22 - 64	Yes	Yes	No	Chemical Formula (138)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.33	0.001
22 - 65	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (138)	No	Yes	Yes	0.34	0.001
22 - 66	Yes	Yes	Yes	Chemical Formula (138)	Nafion	Nafion NRE212	Nafion	Chemical Formula (138)	No	Yes	Yes	0.17	0.001
23 - 67	Yes	Yes	No	Chemical Formula (139)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.36	0.001
23 - 68	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (139)	No	Yes	Yes	0.35	0.001
23 - 69	Yes	Yes	Yes	Chemical Formula (139)	Nafion	Nafion NRE212	Nafion	Chemical Formula (139)	No	Yes	Yes	0.12	0.001
24 - 70	Yes	Yes	No	Chemical Formula (140)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.32	0.001
24 - 71	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (140)	No	Yes	Yes	0.3	0.001
24 - 72	Yes	Yes	Yes	Chemical Formula (140)	Nafion	Nafion NRE212	Nafion	Chemical Formula (140)	No	Yes	Yes	0.1	0.001

including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 6.

**[0155]** Note that the molecular metal complex expressed by the Chemical Formula (139) was synthesized with reference to M. A. Reynolds, T. B. Rauchfuss and S. R. Wilson, *Organometallics*, 2003, 22, 1619-1625.

#### Example 24

**[0156]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (140) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Ex-

#### Example 25

**[0158]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (141) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 25-73) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 25-74) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 25-75) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 7.

**[0159]** Note that the molecular metal complex expressed by the Chemical Formula (141) was synthesized with ref-



erence to D. Sellmann, R. Prakash, F. W. Heinemann, M. Moll and M. Klimowicz, *Angew. Chem., Int. Ed.*, 2004, 43, 1877-1880.

#### Example 26

**[0160]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (142) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 26-76) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 26-77) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 26-78) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 7.

**[0161]** Note that the molecular metal complex expressed by the Chemical Formula (142) was synthesized with reference to R. C. Linck, R. J. Pafford and T. B. Rauchfuss, *J. Am. Chem. Soc.*, 2001, 123, 8856-8857.

#### Example 27

**[0162]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (143) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 27-79) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 27-80)

including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 27-81) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 7.

**[0163]** Note that the molecular metal complex expressed by the Chemical Formula (143) was synthesized with reference to R. C. Linck, R. J. Pafford and T. B. Rauchfuss, *J. Am. Chem. Soc.*, 2001, 123, 8856-8857.

#### Example 28

**[0164]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (144) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 28-82) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 28-83) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 28-84) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 7.

**[0165]** Note that the molecular metal complex expressed by the Chemical Formula (144) was synthesized with reference to L. L. Lopez, P. Bernatis, J. Birnbaum, R. C. Haltiwanger and M. R. DuBois, *Organometallics*, 1992, 11, 2424-2435.

TABLE 7

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/ A cm <sup>-2</sup>
25 - 73	Yes	Yes	No	Chemical Formula (141)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001
25 - 74	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (141)	No	Yes	Yes	0.35	0.001
25 - 75	Yes	Yes	Yes	Chemical Formula (141)	Nafion	Nafion NRE212	Nafion	Chemical Formula (141)	No	Yes	Yes	0.12	0.001
26 - 76	Yes	Yes	No	Chemical Formula (142)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.31	0.001
26 - 77	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (142)	No	Yes	Yes	0.31	0.001
26 - 78	Yes	Yes	Yes	Chemical Formula (142)	Nafion	Nafion NRE212	Nafion	Chemical Formula (142)	No	Yes	Yes	0.2	0.001
27 - 79	Yes	Yes	No	Chemical Formula (143)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.2	0.001
27 - 80	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (143)	No	Yes	Yes	0.1	0.001
27 - 81	Yes	Yes	Yes	Chemical Formula (143)	Nafion	Nafion NRE212	Nafion	Chemical Formula (143)	No	Yes	Yes	0.05	0.001
28 - 82	Yes	Yes	No	Chemical Formula (144)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001
28 - 83	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (144)	No	Yes	Yes	0.2	0.001
28 - 84	Yes	Yes	Yes	Chemical Formula (144)	Nafion	Nafion NRE212	Nafion	Chemical Formula (144)	No	Yes	Yes	0.1	0.001

## Example 29

[0166] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (145) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 29-85) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 29-86) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 29-87) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 8.

[0167] Note that the molecular metal complex expressed by the Chemical Formula (145) was synthesized with reference to L. L. Lopez, P. Bernatis, J. Birnbaum, R. C. Haltiwanger and M. R. DuBois, *Organometallics*, 1992, 11, 2424-2435.

## Example 30

[0168] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (146) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 30-88) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 30-89) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 30-90) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 8.

[0169] Note that the molecular metal complex expressed by the Chemical Formula (146) was synthesized with reference to (a) C. Bianchini, C. Mealli, A. Meli and M. Sabat, *Inorg. Chem.*, 1986, 25, 4617-4618; (b) A. Ienco, M. J. Calhorda, J. Reinhold, F. Reineri, C. Bianchini, M. Peruzzini, F. Vizza and C. Mealli, *J. Am. Chem. Soc.*, 2004, 126, 11954-11965.

## Example 31

[0170] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (147) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 31-91) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 31-92) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 31-93) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 8.

[0171] Note that the molecular metal complex expressed by the Chemical Formula (147) was synthesized with reference to (a) C. Bianchini, C. Mealli, A. Meli and M. Sabat, *Inorg. Chem.*, 1986, 25, 4617-4618; (b) A. Ienco, M. J. Calhorda, J. Reinhold, F. Reineri, C. Bianchini, M. Peruzzini, F. Vizza and C. Mealli, *J. Am. Chem. Soc.*, 2004, 126, 11954-11965.

## Example 32

[0172] In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (148) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 32-94) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 32-95) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 32-96) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 8.

[0173] Note that the molecular metal complex expressed by the Chemical Formula (148) was synthesized with reference to S. Ogo, H. Nakai and Y. Watanabe, *J. Am. Chem. Soc.*, 2002, 124, 597-601.

TABLE 8

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/A cm <sup>-2</sup>
29 - 85	Yes	Yes	No	Chemical Formula (145)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.35	0.001
29 - 86	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (145)	No	Yes	Yes	0.35	0.001
29 - 87	Yes	Yes	Yes	Chemical Formula (145)	Nafion	Nafion NRE212	Nafion	Chemical Formula (145)	No	Yes	Yes	0.2	0.001
30 - 88	Yes	Yes	No	Chemical Formula (146)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.34	0.001
30 - 89	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (146)	No	Yes	Yes	0.31	0.001
30 - 90	Yes	Yes	Yes	Chemical Formula (146)	Nafion	Nafion NRE212	Nafion	Chemical Formula (146)	No	Yes	Yes	0.15	0.001
31 - 91	Yes	Yes	No	Chemical Formula (147)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.38	0.001

TABLE 8-continued

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/ A cm <sup>-2</sup>
31 - 92	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (147)	No	Yes	Yes	0.28	0.001
31 - 93	Yes	Yes	Yes	Chemical Formula (147)	Nafion	Nafion NRE212	Nafion	Chemical Formula (147)	No	Yes	Yes	0.15	0.001
32 - 94	Yes	Yes	No	Chemical Formula (148)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.31	0.001
32 - 95	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (148)	No	Yes	Yes	0.33	0.001
32 - 96	Yes	Yes	Yes	Chemical Formula (148)	Nafion	Nafion NRE212	Nafion	Chemical Formula (148)	No	Yes	Yes	0.12	0.001

## Example 33

**[0174]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (149) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 33-97) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 33-98) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 33-99) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 9.

**[0175]** Note that the molecular metal complex expressed by the Chemical Formula (149) was synthesized with reference to S. Ogo, H. Nakai and Y. Watanabe, *J. Am. Chem. Soc.*, 2002, 124, 597-601.

## Example 34

**[0176]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (150) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 34-100) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 34-101) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example

34-102) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 9.

**[0177]** Note that the molecular metal complex expressed by the Chemical Formula (150) was synthesized with reference to S. Ogo, T. Suzuki, S. Nomura, K. Asakura and K. Isobe, *J. Cluster Science* 1995, 6, 421-436.

## Example 35

**[0178]** In the same manner as in Example 1 except that the molecular metal complex expressed by the Chemical Formula (151) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 35-103) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 35-104) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 35-105) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 9.

**[0179]** Note that the molecular metal complex expressed by the Chemical Formula (151) was synthesized with reference to L. Vieille-Petit, G. Suss-Fink, B. Therrien, T. R. Ward, H. Stoeckli-Evans, G. Labat, L. Karmazin-Brelot, A. Neels, T. Burgi, R. G. Finke and C. M. Hagen, *Organometallics*, 2005, 24, 6104-6119.

TABLE 9

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/ A cm <sup>-2</sup>
33 - 97	Yes	Yes	No	Chemical Formula (149)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.25	0.001
33 - 98	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (149)	No	Yes	Yes	0.29	0.001
33 - 99	Yes	Yes	Yes	Chemical Formula (149)	Nafion	Nafion NRE212	Nafion	Chemical Formula (149)	No	Yes	Yes	0.11	0.001
34 - 100	Yes	Yes	No	Chemical Formula (150)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001

TABLE 9-continued

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/A cm <sup>-2</sup>
34 - 101	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (150)	No	Yes	Yes	0.3	0.001
34 - 102	Yes	Yes	Yes	Chemical Formula (150)	Nafion	Nafion NRE212	Nafion	Chemical Formula (150)	No	Yes	Yes	0.12	0.001
35 - 103	Yes	Yes	No	Chemical Formula (151)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.31	0.001
35 - 104	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (151)	No	Yes	Yes	0.26	0.001
35 - 105	Yes	Yes	Yes	Chemical Formula (151)	Nafion	Nafion NRE212	Nafion	Chemical Formula (151)	No	Yes	Yes	0.1	0.001

## Example 36

**[0180]** <Production of Carbon Cloth to which Fuel Cell Electrode Catalyst of the Present Invention being in the Form of Solution is Applied>

**[0181]** 10 mg of the molecular metal complex expressed by the Chemical Formula (117) being in the form of a solution was evenly applied onto a carbon cloth (manufactured by E-TEK) of 5 cm<sup>2</sup>. Specifically, the molecular metal complex is dissolved in 100 mg of a Nafion (Registered Trademark) solution, and the resultant solution was applied onto the carbon cloth.

**[0182]** Note that the molecular metal complex expressed by the Chemical Formula (117) was synthesized in the same manner as in Example 1.

Example 36-106: Production of Fuel Cell Including, in Anode, Fuel Cell Electrode Catalyst of the Present Invention

**[0183]** A membrane electrode assembly (MEA) was produced by (i) providing, on the hydrogen electrode (anode) side, a carbon cloth to which the molecular metal complex being in the form of a solution was applied and (ii) providing, on the oxygen electrode (cathode) side, a carbon cloth to which platinum carbon TEC10V50E (manufactured by Takana Kikinzoku Kogyo K.K.) was applied so that a polymer membrane (Nafion (Registered Trademark) NRE212, manufactured by DuPont) was sandwiched by these carbon cloths. The membrane electrode assembly thus obtained was incorporated into a fuel cell (manufactured by Toyo Corporation). In this manner, a fuel cell was produced. In the above process, the polymer membrane was sandwiched by the carbon cloths so that (i) a side of one of the carbon cloths to which side the molecular metal complex being in the form of a solution was applied and (ii) a side of the other of the carbon cloths to which side platinum was applied face each other via the polymer membrane. Hydrogen and oxygen were supplied to the fuel cell thus produced, and an electromotive force of the fuel cell was measured. The result of the measurement is shown in Table 10.

**[0184]** Note that the fuel cell thus produced was configured such that each of the hydrogen electrode (anode) and the oxygen electrode (cathode) contains Vulcan (manufactured by Cabot Corporation) and Nafion (Registered Trademark) functioning as an ionomer. Specifically, 10 mg of the molecular metal complex and 60 mg of Vulcan were added to 100 mg of a Nafion (Registered Trademark) solution (Nafion perfluorinated ion-exchange resin, 5 wt % soln in lower aliphatic alcohols/H<sub>2</sub>O mix [product name], manufactured by Aldrich), and the mixture was dispersed by an ultrasonic vibration machine. Then, the resultant solution was applied to a carbon cloth. In a similar way, platinum carbon was applied to a carbon cloth.

Example 36-107: Production of Fuel Cell Including, in Cathode, Fuel Cell Electrode Catalyst of the Present Invention

**[0185]** A membrane electrode assembly (MEA) was produced by (i) providing, on the hydrogen electrode side, a carbon cloth to which platinum carbon TEC10V50E (manufactured by Takana Kikinzoku Kogyo K.K.) was applied and (ii) providing, on the oxygen electrode side, a carbon cloth to which the molecular metal complex in the form of a solution was applied so that a polymer membrane (Nafion [Registered Trademark] NRE212, manufactured by DuPont) was sandwiched by these carbon cloths. The membrane electrode assembly thus obtained was incorporated into a fuel cell (manufactured by Toyo Corporation). In this manner, a fuel cell was produced. In the above process, the polymer membrane was sandwiched by the carbon cloths so that (i) a side of one of the carbon cloths to which side the molecular metal complex in the form of a solution was applied and (ii) a side of the other of the carbon cloths to which side platinum was applied face each other via the polymer membrane. Hydrogen and oxygen were supplied to the fuel cell thus produced, and an electromotive force of the fuel cell was measured. The result of the measurement is shown in Table 10.

**[0186]** Note that the fuel cell thus produced was configured such that each of the hydrogen electrode (anode) and the oxygen electrode (cathode) contains Vulcan (manufac-

tured by Cabot Corporation) and Nafion (Registered Trademark) functioning as an ionomer. Specifically, 10 mg of the molecular metal complex and 60 mg of Vulcan were added to 100 mg of a Nafion (Registered Trademark) solution (Nafion perfluorinated ion-exchange resin, 5 wt % soln in lower aliphatic alcohols/H<sub>2</sub>O mix [product name], manufactured by Aldrich), and the mixture was dispersed by the ultrasonic vibration machine. Then, the resultant solution was applied to a carbon cloth. In a similar way, platinum carbon was applied to a carbon cloth. Further, the hydrogen electrode includes, as a conductive polymer, polypyrrole which was caused to be supported by Vulcan with reference to Non-Patent Literature 2.

Example 36-108: Production of Fuel Cell Including, in Anode and Cathode, Fuel Cell Electrode Catalysts of the Present Invention

**[0187]** A membrane electrode assembly (MEA) was produced by providing, on both of the hydrogen electrode side and the oxygen electrode side, carbon cloths to each of which the molecular metal complex in the form of a solution was applied so that a polymer membrane (Nafion [Registered Trademark] NRE212, manufactured by DuPont) was sandwiched by these carbon cloths. The membrane electrode assembly thus obtained was incorporated into a fuel cell (manufactured by Toyo Corporation). In this manner, a fuel cell was produced. In the above process, the polymer membrane was sandwiched by the carbon cloths so that sides of the respective carbon cloths to each of which sides the molecular metal complex in the form of a solution was applied face each other via the polymer membrane. Hydrogen and oxygen were supplied to the fuel cell thus produced, and an electromotive force of the fuel cell was measured. The result of the measurement is shown in Table 10.

**[0188]** Note that the fuel cell thus produced was configured such that each of the hydrogen electrode (anode) and the oxygen electrode (cathode) contains Vulcan (manufactured by Cabot Corporation) and Nafion (Registered Trademark) functioning as an ionomer. Specifically, 10 mg of the molecular metal complex and 60 mg of Vulcan were added to 100 mg of a Nafion (Registered Trademark) solution (Nafion perfluorinated ion-exchange resin, 5 wt % soln in lower aliphatic alcohols/H<sub>2</sub>O mix [product name], manufactured by Aldrich), and the mixture was dispersed by the ultrasonic vibration machine. Then, the resultant solution was applied to a carbon cloth. Note that the hydrogen electrode includes, as a conductive polymer, polypyrrole which was caused to be supported by Vulcan with reference to Non-Patent Literature 2.

**[0189]** In Examples 1 to 35, the molecular metal complex was dispersed in a Nafion solution, applied to a carbon cloth, and then dried under reduced pressure to function as an electrode catalyst in the form of a solid. In Examples 36 to 58, on the other hand, the molecular metal complex was applied to a carbon cloth in the form of a solution, and was not dried under reduced pressure. This intended to cause the molecular metal complex to function as an electrode catalyst in the form of a solution, and took into consideration the fact

that the molecular metal complex, once dried into the form of a solid, is not easily dissolved in water again.

Example 37

**[0190]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (118) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 37-109) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 37-110) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 37-111) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 10.

**[0191]** Note that the molecular metal complex expressed by the Chemical Formula (118) was synthesized in the same manner as in Example 2.

Example 38

**[0192]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (119) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 38-112) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 38-113) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 38-114) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 10.

**[0193]** Note that the molecular metal complex expressed by the Chemical Formula (119) was synthesized in the same manner as in Example 3.

Example 39

**[0194]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (120) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 39-115) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 39-116) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 39-117) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 10.

**[0195]** Note that the molecular metal complex expressed by the Chemical Formula (120) was synthesized in the same manner as in Example 4.

TABLE 10

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/ A cm <sup>-2</sup>
36 - 106	Yes	Yes	No	Chemical Formula (117)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.35	0.001
36 - 107	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (117)	No	Yes	Yes	0.35	0.001
36 - 108	Yes	Yes	Yes	Chemical Formula (117)	Nafion	Nafion NRE212	Nafion	Chemical Formula (117)	No	Yes	Yes	0.15	0.001
37 - 109	Yes	Yes	No	Chemical Formula (118)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001
37 - 110	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (118)	No	Yes	Yes	0.3	0.001
37 - 111	Yes	Yes	Yes	Chemical Formula (118)	Nafion	Nafion NRE212	Nafion	Chemical Formula (118)	No	Yes	Yes	0.1	0.001
38 - 112	Yes	Yes	No	Chemical Formula (119)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.25	0.001
38 - 113	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (119)	No	Yes	Yes	0.25	0.001
38 - 114	Yes	Yes	Yes	Chemical Formula (119)	Nafion	Nafion NRE212	Nafion	Chemical Formula (119)	No	Yes	Yes	0.15	0.001
39 - 115	Yes	Yes	No	Chemical Formula (120)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.1	0.001
39 - 116	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (120)	No	Yes	Yes	0.1	0.001
39 - 117	Yes	Yes	Yes	Chemical Formula (120)	Nafion	Nafion NRE212	Nafion	Chemical Formula (120)	No	Yes	Yes	0.05	0.001

#### Example 40

[0196] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (121) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 40-118) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 40-119) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 40-120) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 11.

[0197] Note that the molecular metal complex expressed by the Chemical Formula (121) was synthesized in the same manner as in Example 5.

#### Example 41

[0198] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (122) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 41-121) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 41-122) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell

(Example 41-123) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 11.

[0199] Note that the molecular metal complex expressed by the Chemical Formula (122) was synthesized in the same manner as in Example 6.

#### Example 42

[0200] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (123) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 42-1124) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 43-125) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 42-126) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 11.

[0201] Note that the molecular metal complex expressed by the Chemical Formula (123) was synthesized in the same manner as in Example 7.

## Example 43

**[0202]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (124) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 43-127) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 43-128) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 43-129) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 11.

**[0203]** Note that the molecular metal complex expressed by the Chemical Formula (124) was synthesized in the same manner as in Example 8.

the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 12.

**[0205]** Note that the molecular metal complex expressed by the Chemical Formula (125) was synthesized in the same manner as in Example 9.

## Example 45

**[0206]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (126) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 45-133) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 45-134) including, in the cathode, the fuel cell

TABLE 11

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/A cm <sup>-2</sup>
40 - 118	Yes	Yes	No	Chemical Formula (121)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.30	0.001
40 - 119	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (121)	No	Yes	Yes	0.25	0.001
40 - 120	Yes	Yes	Yes	Chemical Formula (121)	Nafion	Nafion NRE212	Nafion	Chemical Formula (121)	No	Yes	Yes	0.1	0.001
41 - 121	Yes	Yes	No	Chemical Formula (122)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.25	0.001
41 - 122	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (122)	No	Yes	Yes	0.25	0.001
41 - 123	Yes	Yes	Yes	Chemical Formula (122)	Nafion	Nafion NRE212	Nafion	Chemical Formula (122)	No	Yes	Yes	0.15	0.001
42 - 124	Yes	Yes	No	Chemical Formula (123)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.35	0.001
42 - 125	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (123)	No	Yes	Yes	0.3	0.001
42 - 126	Yes	Yes	Yes	Chemical Formula (123)	Nafion	Nafion NRE212	Nafion	Chemical Formula (123)	No	Yes	Yes	0.2	0.001
43 - 127	Yes	Yes	No	Chemical Formula (124)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.23	0.001
43 - 128	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (124)	No	Yes	Yes	0.3	0.001
43 - 129	Yes	Yes	Yes	Chemical Formula (124)	Nafion	Nafion NRE212	Nafion	Chemical Formula (124)	No	Yes	Yes	0.1	0.001

## Example 44

**[0204]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (125) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 44-130) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 44-131) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 44-132) including, in the anode and the cathode,

electrode catalyst of the present invention, and a fuel cell (Example 45-135) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 12.

**[0207]** Note that the molecular metal complex expressed by the Chemical Formula (126) was synthesized in the same manner as in Example 10.

## Example 46

[0208] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (127) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 46-136) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 46-137) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 46-138) including, in the anode and the cathode,

electrode catalyst of the present invention, and a fuel cell (Example 47-141) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 12.

[0211] Note that the molecular metal complex expressed by the Chemical Formula (128) was synthesized in the same manner as in Example 12.

TABLE 12

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/ $A\ cm^{-2}$
44 - 130	Yes	Yes	No	Chemical Formula (125)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001
44 - 131	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (125)	No	Yes	Yes	0.2	0.001
44 - 132	Yes	Yes	Yes	Chemical Formula (125)	Nafion	Nafion NRE212	Nafion	Chemical Formula (125)	No	Yes	Yes	0.1	0.001
45 - 133	Yes	Yes	No	Chemical Formula (126)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.32	0.001
45 - 134	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (126)	No	Yes	Yes	0.3	0.001
45 - 135	Yes	Yes	Yes	Chemical Formula (126)	Nafion	Nafion NRE212	Nafion	Chemical Formula (126)	No	Yes	Yes	0.18	0.001
46 - 136	Yes	Yes	No	Chemical Formula (127)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001
46 - 137	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (127)	No	Yes	Yes	0.2	0.001
46 - 138	Yes	Yes	Yes	Chemical Formula (127)	Nafion	Nafion NRE212	Nafion	Chemical Formula (127)	No	Yes	Yes	0.05	0.001
47 - 139	Yes	Yes	No	Chemical Formula (128)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.2	0.001
47 - 140	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (128)	No	Yes	Yes	0.2	0.001
47 - 141	Yes	Yes	Yes	Chemical Formula (128)	Nafion	Nafion NRE212	Nafion	Chemical Formula (128)	No	Yes	Yes	0.1	0.001

the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 12.

[0209] Note that the molecular metal complex expressed by the Chemical Formula (127) was synthesized in the same manner as in Example 11.

## Example 47

[0210] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (128) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 47-139) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 47-140) including, in the cathode, the fuel cell

## Example 48

[0212] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (129) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 48-142) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 48-143) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 48-144) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 13.

[0213] Note that the molecular metal complex expressed by the Chemical Formula (129) was synthesized in the same manner as in Example 13.



## Example 49

[0214] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (130) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 49-145) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 49-146) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 49-147) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 13.

[0215] Note that the molecular metal complex expressed by the Chemical Formula (130) was synthesized in the same manner as in Example 14.

## Example 50

[0216] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (131) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 50-148) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 50-149) including, in the cathode, the fuel cell

electrode catalyst of the present invention, and a fuel cell (Example 50-150) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 13.

[0217] Note that the molecular metal complex expressed by the Chemical Formula (131) was synthesized in the same manner as in Example 15.

## Example 51

[0218] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (132) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 51-151) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 51-152) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 51-153) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 13.

[0219] Note that the molecular metal complex expressed by the Chemical Formula (132) was synthesized in the same manner as in Example 16.

TABLE 13

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/A cm <sup>-2</sup>
48 - 142	Yes	Yes	No	Chemical Formula (129)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.2	0.001
48 - 143	Yes	Yes	Yes		Nafion	Nafion NRE212	Nafion	Chemical Formula (129)	No	Yes	Yes	0.15	0.001
48 - 144	Yes	Yes	Yes	Chemical Formula (129)	Nafion	Nafion NRE212	Nafion	Chemical Formula (129)	No	Yes	Yes	0.1	0.001
49 - 145	Yes	Yes	No	Chemical Formula (130)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.32	0.001
49 - 146	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (130)	No	Yes	Yes	0.3	0.001
49 - 147	Yes	Yes	Yes	Chemical Formula (130)	Nafion	Nafion NRE212	Nafion	Chemical Formula (130)	No	Yes	Yes	0.1	0.001
50 - 148	Yes	Yes	No	Chemical Formula (131)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.7	0.001
50 - 149	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (131)	No	Yes	Yes	0.7	0.001
50 - 150	Yes	Yes	Yes	Chemical Formula (131)	Nafion	Nafion NRE212	Nafion	Chemical Formula (131)	No	Yes	Yes	0.4	0.001
51 - 151	Yes	Yes	No	Chemical Formula (132)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.7	0.001
51 - 152	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (132)	No	Yes	Yes	0.6	0.001
51 - 153	Yes	Yes	Yes	Chemical Formula (132)	Nafion	Nafion NRE212	Nafion	Chemical Formula (132)	No	Yes	Yes	0.4	0.001

## Example 52

**[0220]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (133) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 52-154) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 52-155) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 52-156) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 14.

**[0221]** Note that the molecular metal complex expressed by the Chemical Formula (133) was synthesized in the same manner as in Example 17.

## Example 53

**[0222]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (134) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 53-157) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 53-158) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 53-159) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 14.

**[0223]** Note that the molecular metal complex expressed by the Chemical Formula (134) was synthesized in the same manner as in Example 18.

## Example 54

**[0224]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (135) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 54-160) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 54-161) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 54-162) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 14.

**[0225]** Note that the molecular metal complex expressed by the Chemical Formula (135) was synthesized in the same manner as in Example 19.

## Example 55

**[0226]** In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (136) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 55-163) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 55-164) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 55-165) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 14.

**[0227]** Note that the molecular metal complex expressed by the Chemical Formula (136) was synthesized in the same manner as in Example 20.

TABLE 14

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/A cm <sup>-2</sup>
52 - 154	Yes	Yes	No	Chemical Formula (133)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.6	0.001
52 - 155	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (133)	No	Yes	Yes	0.6	0.001
52 - 156	Yes	Yes	Yes	Chemical Formula (133)	Nafion	Nafion NRE212	Nafion	Chemical Formula (133)	No	Yes	Yes	0.4	0.001
53 - 157	Yes	Yes	No	Chemical Formula (134)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.6	0.001
53 - 158	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (134)	No	Yes	Yes	0.6	0.001
53 - 159	Yes	Yes	Yes	Chemical Formula (134)	Nafion	Nafion NRE212	Nafion	Chemical Formula (134)	No	Yes	Yes	0.3	0.001
54 - 160	Yes	Yes	No	Chemical Formula (135)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.6	0.001
54 - 161	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (135)	No	Yes	Yes	0.5	0.001
54 - 162	Yes	Yes	Yes	Chemical Formula (135)	Nafion	Nafion NRE212	Nafion	Chemical Formula (135)	No	Yes	Yes	0.4	0.001

TABLE 14-continued

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electromotive force/V	Maximum current/ A cm <sup>-2</sup>
55 - 163	Yes	Yes	No	Chemical Formula (136)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.6	0.001
55 - 164	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (136)	No	Yes	Yes	0.6	0.001
55 - 165	Yes	Yes	Yes	Chemical Formula (136)	Nafion	Nafion NRE212	Nafion	Chemical Formula (136)	No	Yes	Yes	0.3	0.001

## Example 56

[0228] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (137) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 56-166) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 56-167) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 56-168) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 15.

[0229] Note that the molecular metal complex expressed by the Chemical Formula (137) was synthesized in the same manner as in Example 21.

## Example 57

[0230] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (138) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 57-169) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 57-170) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 57-171) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 15.

[0231] Note that the molecular metal complex expressed by the Chemical Formula (138) was synthesized in the same manner as in Example 22.

## Example 58

[0232] In the same manner as in Example 36 except that the molecular metal complex expressed by the Chemical Formula (139) was used instead of the molecular metal complex expressed by the Chemical Formula (117), a fuel cell (Example 58-172) including, in the anode, the fuel cell electrode catalyst of the present invention, a fuel cell (Example 58-173) including, in the cathode, the fuel cell electrode catalyst of the present invention, and a fuel cell (Example 58-174) including, in the anode and the cathode, the fuel cell electrode catalysts of the present invention were

produced. Further, performance of these fuel cells was evaluated. The results of the evaluations are shown in Table 15.

[0233] Note that the molecular metal complex expressed by the Chemical Formula (139) was synthesized in the same manner as in Example 23.

[0234] As shown in Tables 1 to 6 and 10 to 14, the molecular metal complex in the form of a solid in some cases had an electromotive force which was different from that of the molecular metal complex in the form of a solution. In particular, the respective molecular metal complexes expressed by Chemical Formulae (131) and (133) to (138) each had an electromotive force that was significantly larger when the molecular metal complex was in the form of a solution than when it was in the form of a solid. This difference is presumed to stem from a difference in nature between the molecular metal complex in the form of a solid and that in the form of a solution. This presumably explains why some molecular metal complexes expressed a better function in the form of a solid, whereas other molecular metal complexes expressed a better function in the form of a solution.

## Example 59

[0235] At the hydrogen electrode (anode) in the fuel cell, the molecular metal complex expressed by Chemical Formula (131) was observed to undergo an isotope exchange reaction between water and heavy hydrogen. The evaluation of the respective fuel cells of Examples 50-148 and 50-150 involved D<sub>2</sub>O as water to moisture the anode and H<sub>2</sub> as hydrogen gas, and analyzed exhaust gas at the anode by gas chromatography. The evaluation resulted in detection of D<sub>2</sub> gas in an amount that was five times as large as the amount of the molecular metal complex (10 mg) expressed by Chemical Formula (131).

[0236] The evaluation further involved H<sub>2</sub>O as water to moisture the anode and D<sub>2</sub> gas as hydrogen gas, and analyzed exhaust gas at the anode by gas chromatography. The evaluation resulted in detection of H<sub>2</sub> gas in an amount that was five times as large as the amount of the molecular metal complex (10 mg) expressed by Chemical Formula (131). The above gas chromatography analysis was made in reference to B. Kure, T. Matsumoto, K. Ichikawa, S. Fukuzumi, Y. Higuchi, T. Yagi, S. Ogo, Dalton Trans., 2008, 4747-4755.

[0237] During measurements of the above isotope exchange reaction, measurements of electromotive forces were also made. Even in the case where the isotope

exchange reaction occurred, the respective electromotive forces had the same measured values as in Examples 50-148 and 50-150 (Table 13).

#### Example 60

**[0238]** At the hydrogen electrode (anode) in the fuel cell, the molecular metal complex expressed by Chemical Formula (132) was observed to undergo an isotope exchange reaction between water and heavy hydrogen. The evaluation of the respective fuel cells of Examples 51-151 and 51-153 involved D<sub>2</sub>O as water to moisture the anode and H<sub>2</sub> as hydrogen gas, and analyzed exhaust gas at the anode by gas chromatography. The evaluation resulted in detection of D<sub>2</sub> gas in an amount that was five times as large as the amount of the molecular metal complex (10 mg) expressed by Chemical Formula (132).

**[0239]** The evaluation further involved H<sub>2</sub>O as water to moisture the anode and D<sub>2</sub> gas as hydrogen gas, and analyzed exhaust gas at the anode by gas chromatography. The evaluation resulted in detection of H<sub>2</sub> gas in an amount that was five times as large as the amount of the molecular metal complex (10 mg) expressed by Chemical Formula (132). The above gas chromatography analysis was made in reference to B. Kure, T. Matsumoto, K. Ichikawa, S. Fukuzumi, Y. Higuchi, T. Yagi, S. Ogo, Dalton Trans., 2008, 4747-4755.

**[0240]** During measurements of the above isotope exchange reaction, measurements of electromotive forces were also made. Even in the case where the isotope exchange reaction occurred, the respective electromotive forces had the same measured values as in Examples 51-151 and 51-153 (Table 13).

#### Example 61

**[0241]** At the hydrogen electrode (anode) in the fuel cell, the molecular metal complex expressed by Chemical Formula (133) was observed to undergo an isotope exchange reaction between water and heavy hydrogen. The evaluation of the respective fuel cells of Examples 52-154 and 52-156 involved D<sub>2</sub>O as water to moisture the anode and H<sub>2</sub> as hydrogen gas, and analyzed exhaust gas at the anode by gas chromatography. The evaluation resulted in detection of D<sub>2</sub> gas in an amount that was five times as large as the amount of the molecular metal complex (10 mg) expressed by Chemical Formula (133).

**[0242]** The evaluation further involved H<sub>2</sub>O as water to moisture the anode and D<sub>2</sub> gas as hydrogen gas, and ana-

lyzed exhaust gas at the anode by gas chromatography. The evaluation resulted in detection of H<sub>2</sub> gas in an amount that was five times as large as the amount of the molecular metal complex (10 mg) expressed by Chemical Formula (133). The above gas chromatography analysis was made in reference to B. Kure, T. Matsumoto, K. Ichikawa, S. Fukuzumi, Y. Higuchi, T. Yagi, S. Ogo, Dalton Trans., 2008, 4747-4755.

**[0243]** During measurements of the above isotope exchange reaction, measurements of electromotive forces were also made. Even in the case where the isotope exchange reaction occurred, the respective electromotive forces had the same measured values as in Examples 52-154 and 52-156 (Table 14).

#### Reference Example

**[0244]** To study the functions as an electrode catalyst for the anode and as an electrode catalyst for the cathode, measurements of the electromotive forces were made by using, as each of the anode and the cathode, a carbon cloth to which platinum carbon (manufactured by Takana Kikinzoku Kogyo K.K.) was applied.

**[0245]** A membrane electrode assembly (MEA) was produced by providing, on both of the hydrogen electrode side and the oxygen electrode side, carbon cloths to each of which platinum carbon TEC10V50E (manufactured by Takana Kikinzoku Kogyo K.K.) was applied so that a polymer membrane (Nafion [Registered Trademark] NRE212, manufactured by DuPont) was sandwiched by these carbon cloths. The membrane electrode assembly thus obtained was incorporated into a fuel cell (manufactured by Toyo Corporation). In this manner, a fuel cell was produced. Hydrogen and oxygen were supplied to the fuel cell thus produced, and an electromotive force of the fuel cell was measured. The result of the measurement is shown in Table 15 (Ref-175).

**[0246]** Note that the fuel cell thus produced was configured such that each of the hydrogen electrode (anode) and the oxygen electrode (cathode) contains Vulcan (manufactured by Cabot Corporation) and Nafion (Registered Trademark) functioning as an ionomer. Specifically, 10 mg of platinum carbon and 60 mg of Vulcan were added to 100 mg of a Nafion (Registered Trademark) solution (Nafion perfluorinated ion-exchange resin, 5 wt % soln in lower aliphatic alcohols/H<sub>2</sub>O mix [product name], manufactured by Aldrich), and the mixture was dispersed by the ultrasonic vibration machine. Then, the resultant solution was applied to a carbon cloth.

TABLE 15

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electromotive force/V	Maximum current/A cm <sup>-2</sup>
56 - 166	Yes	Yes	No	Chemical Formula (137)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.7	0.001
56 - 167	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (137)	No	Yes	Yes	0.6	0.001
56 - 168	Yes	Yes	Yes	Chemical Formula (137)	Nafion	Nafion NRE212	Nafion	Chemical Formula (137)	No	Yes	Yes	0.4	0.001
57 - 169	Yes	Yes	No	Chemical Formula (138)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.6	0.001

TABLE 15-continued

	Carbon cloth	Vulcan	Conductive polymer	Hydrogen electrode	Ionomer	Polymer membrane	Ionomer	Oxygen electrode	Conductive polymer	Vulcan	Carbon cloth	Electro-motive force/V	Maximum current/A cm <sup>-2</sup>
57 - 170	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (138)	No	Yes	Yes	0.5	0.001
57 - 171	Yes	Yes	Yes	Chemical Formula (138)	Nafion	Nafion NRE212	Nafion	Chemical Formula (138)	No	Yes	Yes	0.3	0.001
58 - 172	Yes	Yes	No	Chemical Formula (139)	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.3	0.001
58 - 173	Yes	Yes	Yes	Pt	Nafion	Nafion NRE212	Nafion	Chemical Formula (139)	No	Yes	Yes	0.3	0.001
58 - 174	Yes	Yes	Yes	Chemical Formula (139)	Nafion	Nafion NRE212	Nafion	Chemical Formula (139)	No	Yes	Yes	0.2	0.001
Ref - 175	Yes	Yes	No	Pt	Nafion	Nafion NRE212	Nafion	Pt	No	Yes	Yes	0.95	1.6

## INDUSTRIAL APPLICABILITY

[0247] A fuel cell electrode catalyst of the present invention is an economical fuel cell electrode catalyst which can be used in place of platinum as a simple substance or a platinum alloy and has easy-to-control catalytic power. Therefore, the fuel cell electrode catalyst of the present invention, a fuel cell electrode including the fuel cell electrode catalyst, a fuel cell including the fuel cell electrode catalyst, and an electric power generation method using the fuel cell electrode catalyst is applicable to electric vehicles, household power sources, portable power sources, and the like each of which includes the same. Thus, the present invention is very useful.

1-13. (canceled)

14. An electric power generation method comprising:  
oxidizing a fuel through use of a fuel cell electrode catalyst and  
reducing an oxidant through use of the fuel cell electrode catalyst;

the fuel cell electrode catalyst including one or more molecular metal complexes;

each of the one or more molecular metal complexes being a metal complex (i) having a molecular weight of 2000 or less, (ii) not having a layered structure, and (iii) including a total of one or more but not more than three metal atoms and/or metal ions to each of which three or more but not more than six ligands coordinate;

each of the one or more molecular metal complexes being a metal complex other than a porphyrin derivative, in a case where (i) said each of the one or more molecular metal complexes includes one metal atom or one metal ion and (ii) four ligands coordinate to the one metal atom or the one metal ion.

15. An electric power generation method comprising:  
oxidizing a fuel through use of a fuel cell electrode catalyst;

the fuel cell electrode catalyst including one or more molecular metal complexes;

each of the one or more molecular metal complexes being a metal complex (i) having a molecular weight of 2000 or less, (ii) not having a layered structure, and (iii) including a total of one or more but not more than three

metal atoms and/or metal ions to each of which three or more but not more than six ligands coordinate;

each of the one or more molecular metal complexes being a metal complex other than a porphyrin derivative, in a case where (i) said each of the one or more molecular metal complexes includes one metal atom or one metal ion and (ii) four ligands coordinate to the one metal atom or the one metal ion.

16. An electric power generation method comprising:

reducing an oxidant through use of a fuel cell electrode catalyst;

the fuel cell electrode catalyst including one or more molecular metal complexes;

each of the one or more molecular metal complexes being a metal complex (i) having a molecular weight of 2000 or less, (ii) not having a layered structure, and (iii) including a total of one or more but not more than three metal atoms and/or metal ions to each of which three or more but not more than six ligands coordinate;

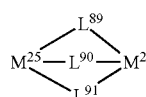
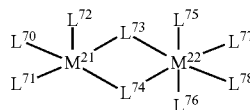
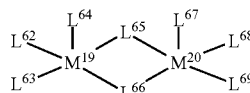
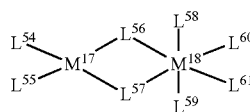
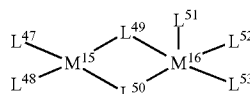
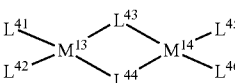
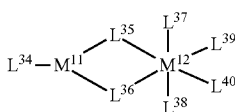
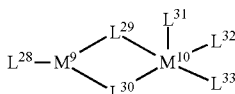
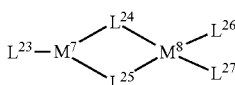
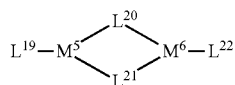
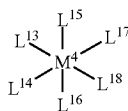
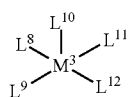
each of the one or more molecular metal complexes being a metal complex other than a porphyrin derivative, in a case where (i) said each of the one or more molecular metal complexes includes one metal atom or one metal ion and (ii) four ligands coordinate to the one metal atom or the one metal ion.

17. The electric power generation method as set forth in claim 14, wherein:

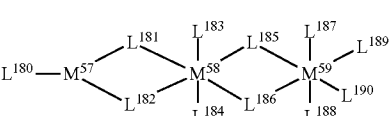
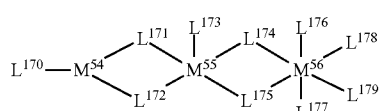
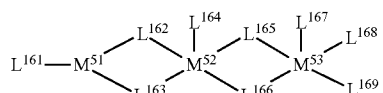
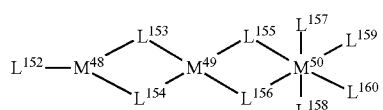
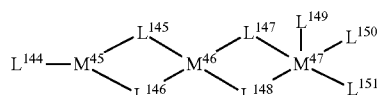
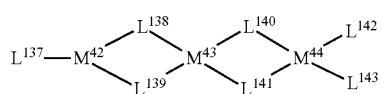
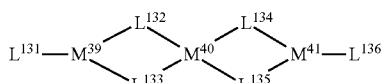
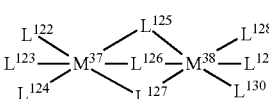
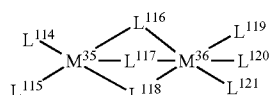
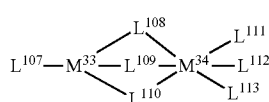
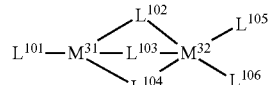
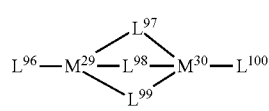
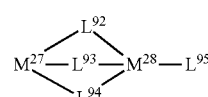
the one or more molecular metal complexes include one or more molecular metal complexes selected from the group consisting of molecular metal complexes expressed by the following General Formulae (1) through (73):



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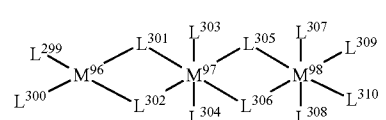
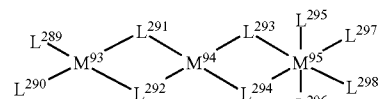
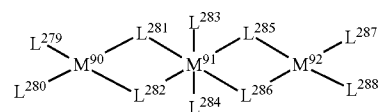
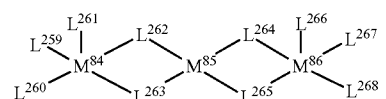
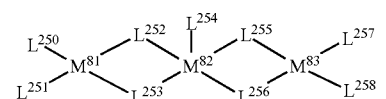
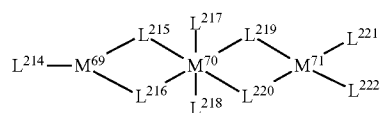
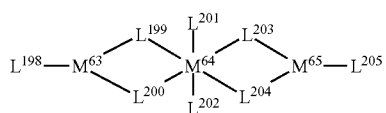
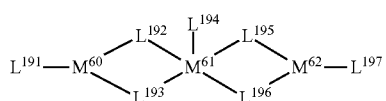
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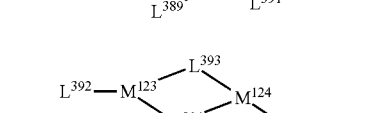
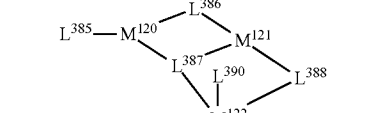
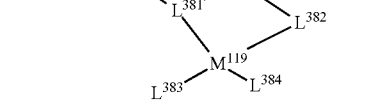
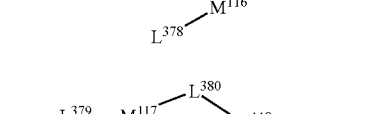
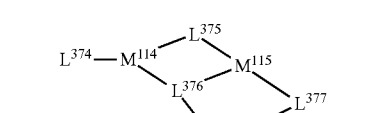
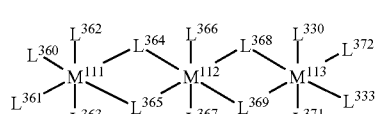
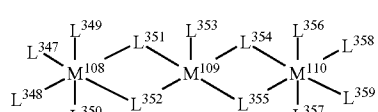
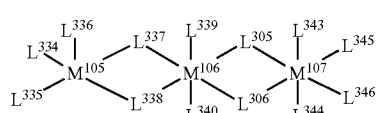
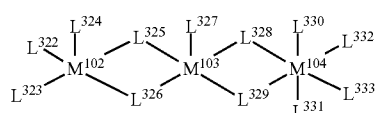
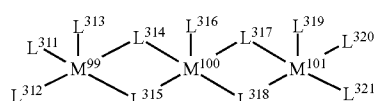
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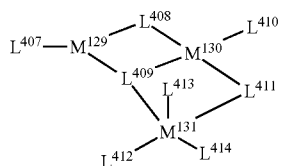
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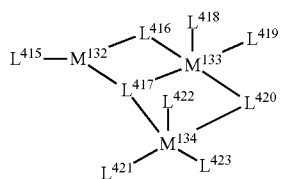
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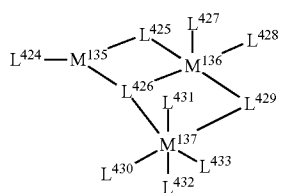
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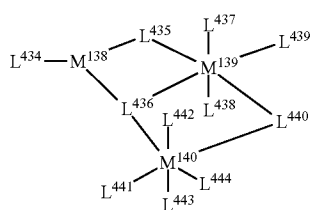
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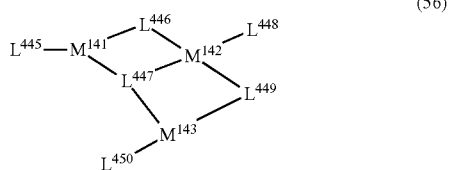
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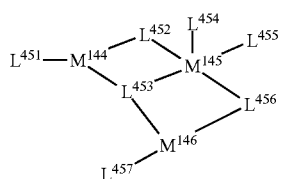
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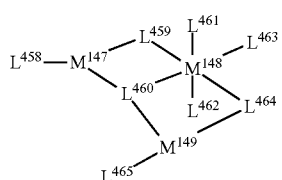
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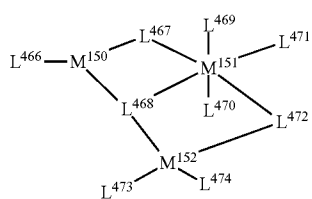
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(57)

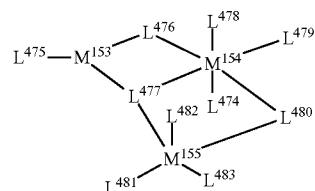


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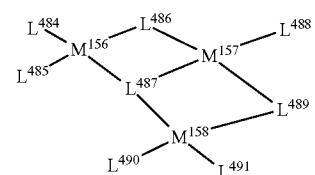


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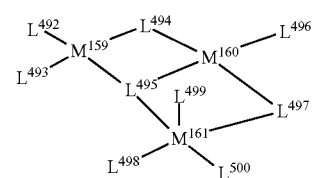
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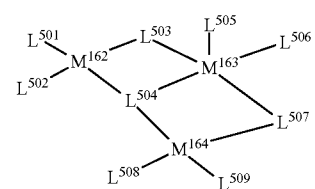
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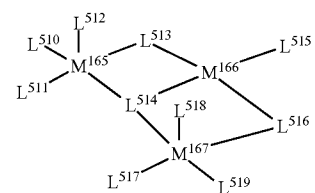
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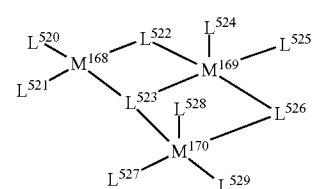
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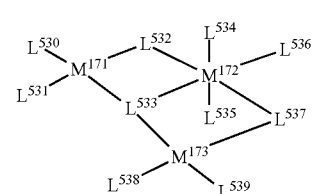
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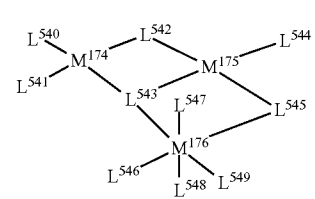
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(65)



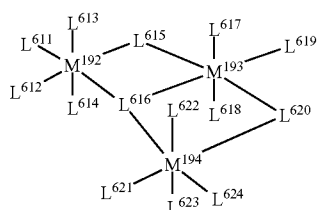
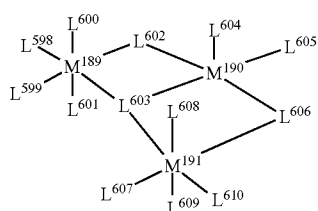
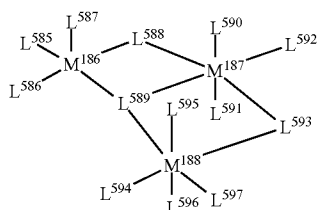
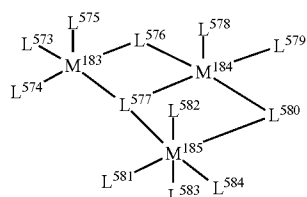
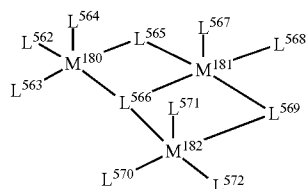
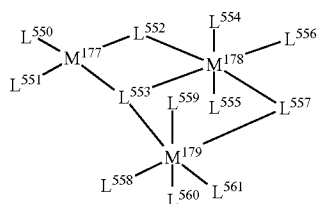
(66)



(67)



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where each of  $L^1$  through  $L^{624}$  independently indicates a ligand, each of  $M^1$  through  $M^{194}$  independently indicates a metal atom or a metal ion, and the molecular metal complex expressed by the General Formula (2) is a metal complex other than a porphyrin derivative.

**18.** The electric power generation method as set forth in claim 17, wherein:

the one or more molecular metal complexes selected from the molecular metal complexes expressed by the General Formulae (1) through (73) include one or more

molecular metal complexes selected from the molecular metal complexes expressed by the General Formulae (5) through (21).

**19.** The electric power generation method as set forth in claim 17, wherein:

the fuel cell electrode catalyst is usable in each of an anode and a cathode.

**20.** The electric power generation method as set forth in claim 17, wherein:

the one metal atom or one metal ion is a metal atom or a metal ion thereof, the metal atom being selected from the group consisting of metal atoms and metal ions of 3A group elements, 4A group elements, 5A group elements, 6A group elements, 7A group elements, 8 group elements, 1B group elements, 3B group elements, and 6B group elements in a periodic table.

**21.** The electric power generation method as set forth in claim 20, wherein:

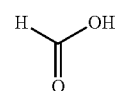
the one metal atom or one metal ion is a metal atom or a metal ion thereof, the metal atom being selected from the group consisting of the metal atoms and the metal ions of the 8 group elements.

**22.** The electric power generation method as set forth in claim 17, wherein:

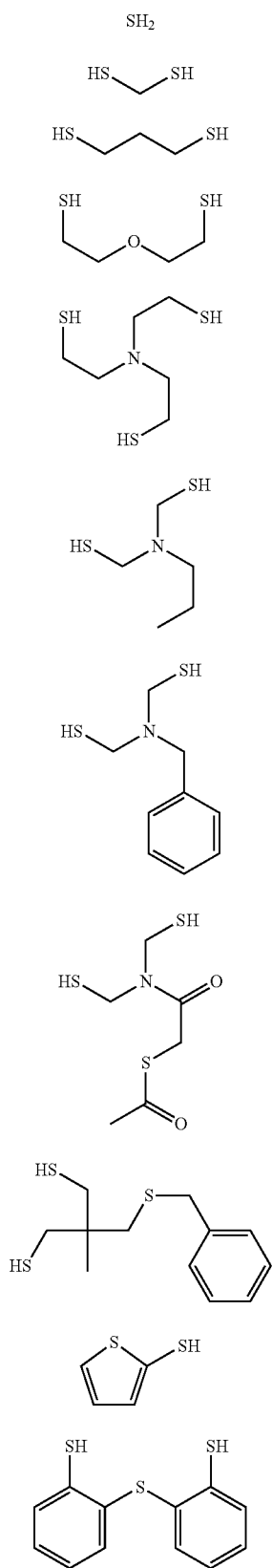
each of ligand atoms of the ligands indicated by  $L^1$  through  $L^{624}$  is independently a hydrogen atom, a carbon atom, a nitrogen atom, an oxygen atom, a phosphorus atom, a sulfur atom, or a halogen atom.

**23.** The electric power generation method as set forth in claim 17, wherein:

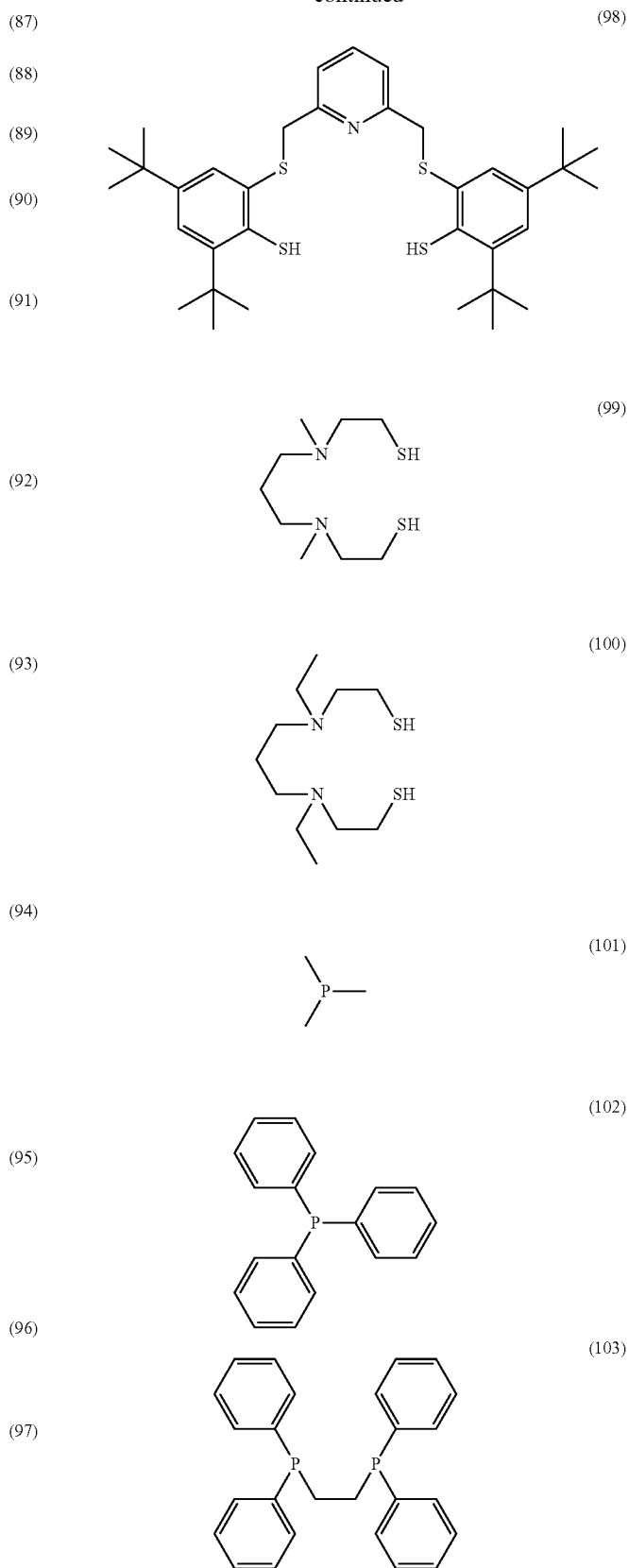
each of the ligands indicated by  $L^1$  through  $L^{624}$  is independently selected from ligands expressed by the following Chemical Formulae (74) through (116):



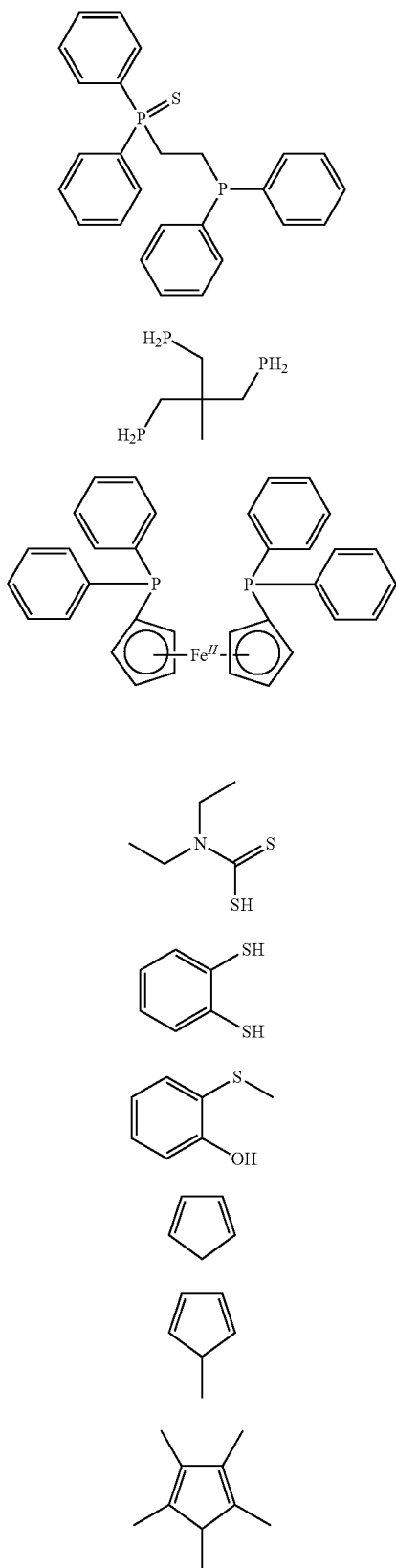
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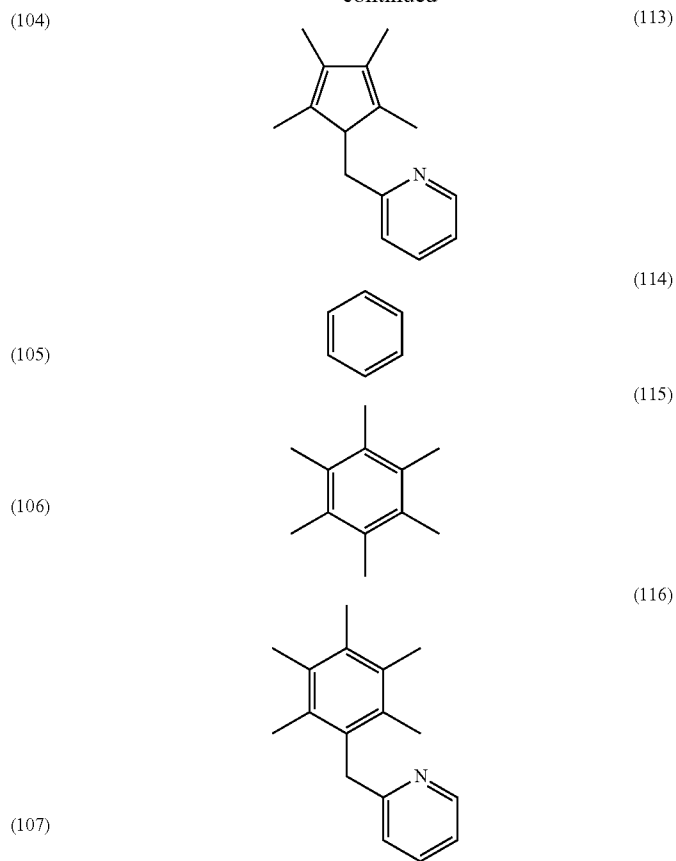
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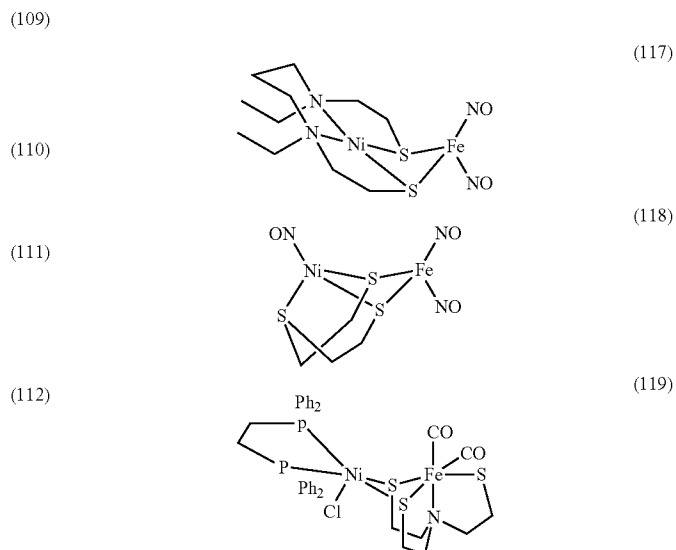


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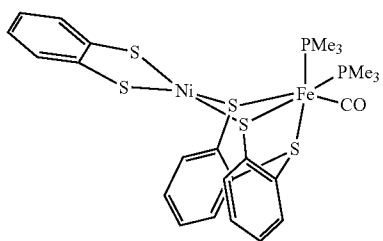


24. The electric power generation method as set forth in claim 17, wherein:

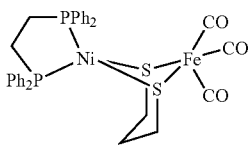
the one or more molecular metal complexes selected from the molecular metal complexes expressed by the General Formulae (1) through (73) are selected from molecular metal complexes expressed by the following Chemical Formulae (117) through (151):



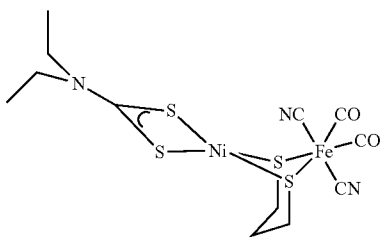
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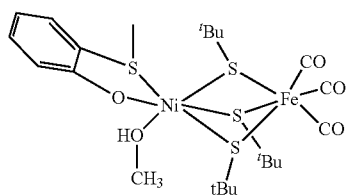
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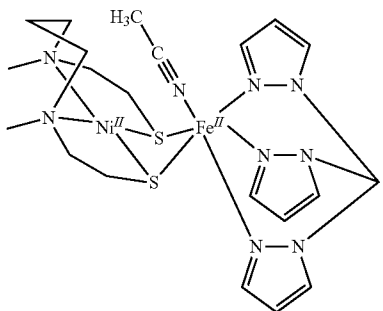
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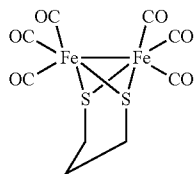
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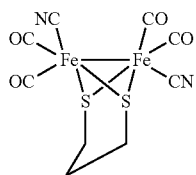
(123)



(124)

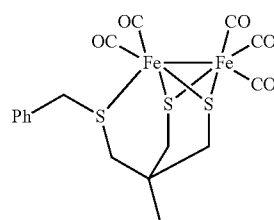


(125)

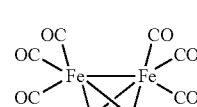


(126)

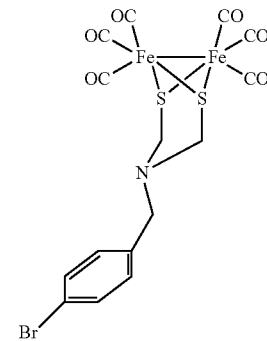
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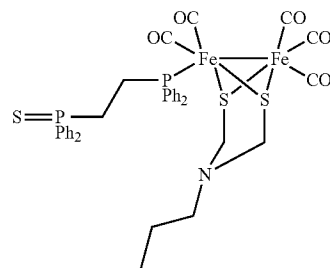
(127)



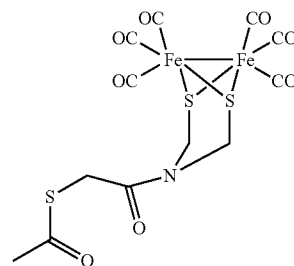
(128)



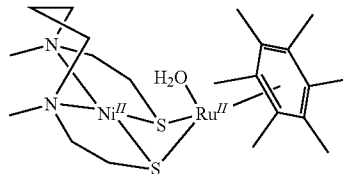
(129)



(130)

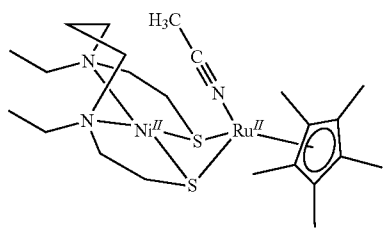
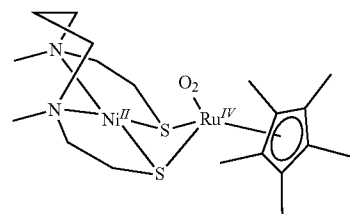
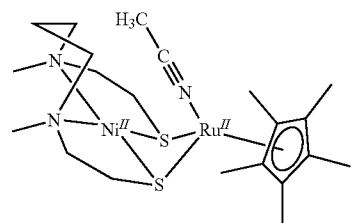
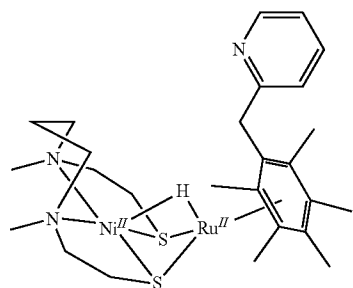
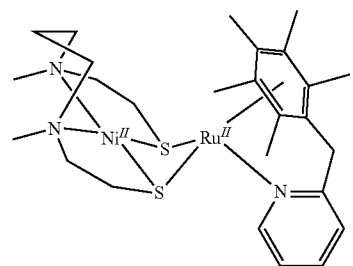
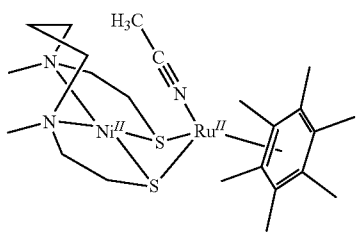


(131)

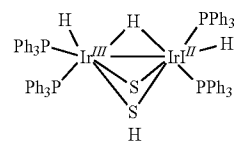
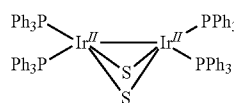
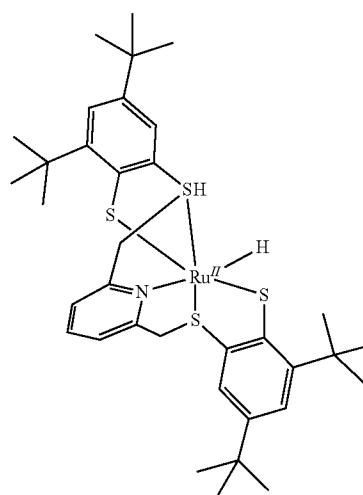
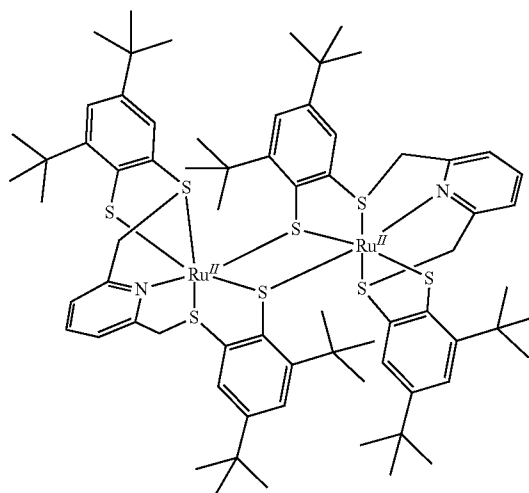
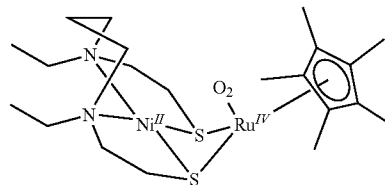


(132)

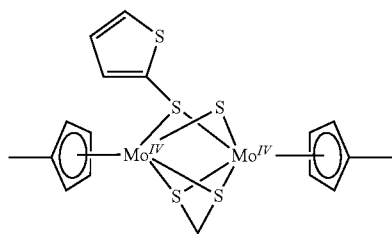
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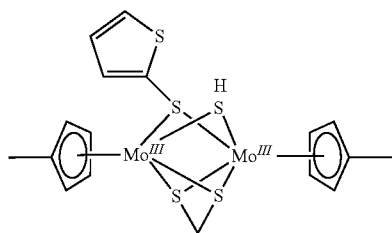
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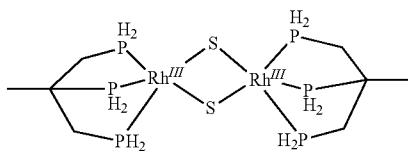
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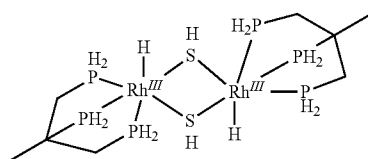
(144)



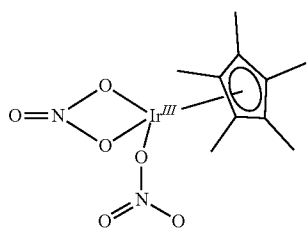
(145)



(146)

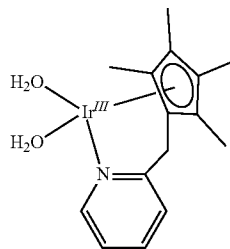


(147)

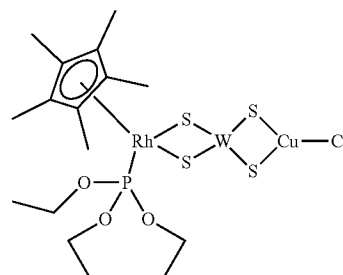


(148)

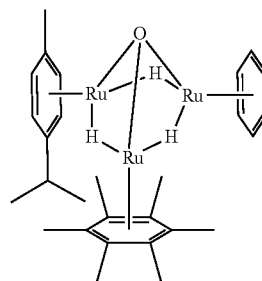
-continued



(149)



(150)



(151)

25. The electric power generation method as set forth in claim 24, wherein:

the one or more molecular metal complexes selected from the group consisting of molecular metal complexes expressed by the Chemical Formulae (117) through (151) are selected from the group consisting of molecular metal complexes expressed by the Chemical Formulae (131) through (138).

\* \* \* \* \*