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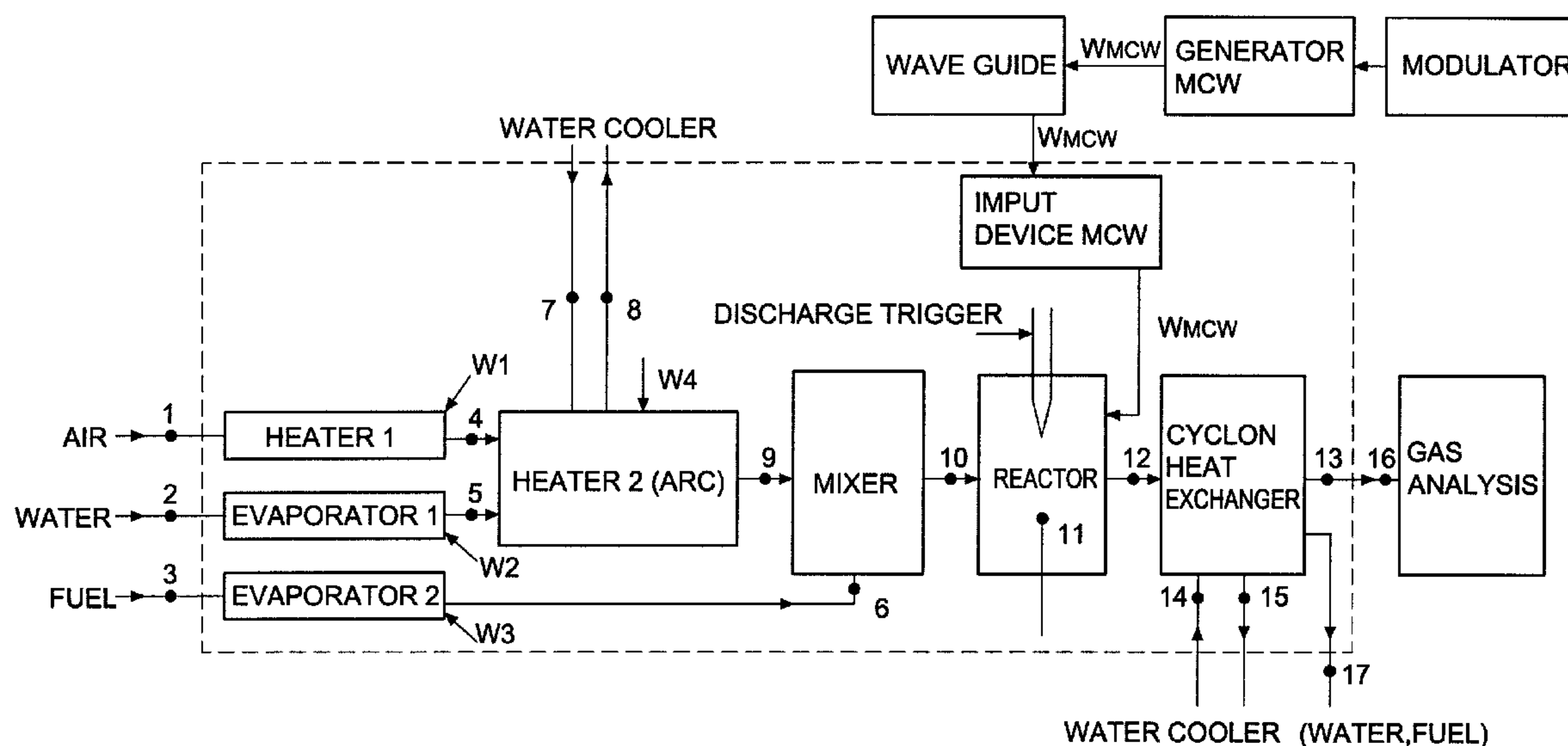
(71) Demandeur/Applicant:
DAVID SYSTEMS TECHNOLOGY, S.L., ES

(72) Inventeurs/Inventors:
VLADIMIR, FATEEV, ES;
POTAPKIN, BORIS, ES;
JIVOTOV, VICTOR K., ES;
BLACH VIZOSO, RICARDO, ES

(74) Agent: FETHERSTONHAUGH & CO.

(54) Titre : TRANSFORMATEUR DE PLASMA DE COMBUSTIBLES FOSSILES EN GAZ RICHE EN HYDROGENE

(54) Title: PLASMA TRANSFORMER FOR THE TRANSFORMATION OF FOSSIL FUELS INTO HYDROGEN-RICH GAS



(57) Abrégé/Abstract:

The invention relates to a device for the production of hydrogen-rich gas from fossil fuels. The device comprises a heater, a mixer and a MCW plasma reactor which are combined in series, as well as an MCW energy source. A pseudo-corona periodical impulse discharge at atmospheric pressure is produced in the reactor and initiates a low temperature plasma-catalytic fuel transformation process. The device enables to carry out the transformation reactions with steam, with steam-air and partial oxidation of fossil fuels for the production of a hydrogen-rich gas with high specific productivity (volumetric ratio) and with a minimum consumption of electric energy. Prior heating of the reagents provides a large part of the energy which is required by thermodynamics. Part of the thermal energy is recovered at the outlet of the plasma reactor. The device can be sufficiently compact in order to be used in internal combustion engines of transport vehicles. The device can be used also in stationary systems for the production of hydrogen-rich gas (power generating plants, etc.). Other fields related with the invention are the construction of microwave plasma equipments (plasma reactors) and the construction of vehicle engines. The present invention relates to the process for converting fossil fuels into hydrogen-rich gas (synthesis gas) through the use of plasma which is generated by microwaves with the addition of oxygen (or air) and with the possibility of water addition.

ABSTRACT

The object of the invention by DAVID is a device for production of hydrogen-rich gas from fossil fuels. The device comprises a heater, a mixer and a MCW plasma reactor combined in series, as well as a MCW energy source. A pseudo-corona impulse-periodic discharge at atmospheric pressure is performed in the reactor, which provides a plasma-catalytic fuel conversion process at a low temperature. The device allows to perform reactions of steam conversion, steam-air conversion and partial oxidation of fossil fuels in order to obtain a hydrogen-rich gas with a high specific productivity (volumetric ratio) and a minimal consumption of electric power. Preheating of reagents provides a substantial amount of the energy required by thermodynamics. Part of the heat energy is recuperated at the plasma reactor outlet. The device may be sufficiently compact to be installed in internal combustion engines of transport vehicles. The device may also be used in stationary systems for production of hydrogen-rich gas (electrical power generation stations, etc.). Other fields related to the invention are the construction of microwave plasma devices (plasma reactors) and construction of motor vehicles.

The present invention relates to the conversion process of fossil fuels into hydrogen-rich gas (synthesis gas) by means of a plasma generated with microwaves with addition of oxygen (or air) and the possible addition of water.

PLASMA CONVERTER OF FOSSIL FUELS
INTO HYDROGEN-RICH GAS

OBJECT OF THE INVENTION

The object of the present invention relates to a plasma converter of fossil fuels into hydrogen-rich gas.

Said converter comprises a heater, a mixing chamber, a reactor, all of these combined in series, and a microwave (MCW) power source for the reactor, such that the converter can receive traditional fossil fuels and convert them into a hydrogen rich gas, in order to increase the efficiency of an internal combustion engine.

Background of the invention

The invention relates to the production of a hydrogen rich gas from hydrocarbons. Hydrogen is attractive as a fuel, as an additive for internal combustion engines, as its presence can significantly change the chemical properties of the fuel and substantially reduce the pollution caused by combustion products [the effect of adding hydrogen to the fuel is to increase the efficiency of an internal combustion engine by 10-50%. See Mishchenko, et al., Proc. VII World Hydrogen Energy Conference, Vol 3 (1988), Belogub, et al., Int. J. Hydrogen Energy, Vol 16. 423 (1991), Varde, et al., Hydrogen Energy Progress V., Vol 4 (1984), Feucht, et al., Int. J. Hydrogen Energy, Vol 13. 243 (1988), Chuveliov, et al., In.: Hydrogen Energy and Power Generation, T. Nejat Veziroglu, Ed., Nova Science Publisher, New York, N. Y. (1991), Das Int. J. Hydrogen Energy, Vol 16. 765 (1991). Related patents are United States Patents

numbers 5887554. 5425332. 5437250 and World Patent n° PCT/US98/18027.

In similar devices the energy for the conversion process can be provided by either pre-heating the gas mixture or by exothermal reactions (such as total or partial oxidation of hydrocarbons), or electrical heating. Additionally, in a first and second case plasma may be used as a catalyst for the chemical processes (plasma treatment of preheated reactants). See V. D. Rusanov, K. Etivan, A. I. Babaritskii, I. E. Baranov, S. A. Demkin, V. K. Jivotov, B. V. Potapkin and E. I. Ryazantsev, The Effect of Plasma Catalysis by the Example of Methane Dissociation into Hydrogen and Carbon, Dokl. Akad. Nauk, 1997. vol 354. n° 1 pages 213 to 215; and A. I. Bararitskii, M. A. Deminskii, S. A. Demkin, K. Etivan, V. K. Jivotov, B. V. Potapkin, S. V. Potekhin, V. D. Rusaov and E. I. Ryazantsev, The Effect of Plasma Catalysis in Methane Decomposition, Khim. Vys. Energ., 1999. vol. 33. n° 1. pages 59 to 66.

It is generally acknowledged that the best substitute for fossil fuels is gaseous hydrogen (H_2). Currently existing technologies have encountered a number of technical and economic obstacles for using hydrogen. Hydrogen is a highly flammable substance, requiring complex and costly storage systems. In addition, the creation of a world-wide hydrogen distribution network implies economic costs and a time scale which are beyond the means of even developed countries.

Availability of a chemical miniplant which, in an economically viable manner, converts fossil fuels and alcohols in the amounts required to obtain a synthetic hydrogen-rich gas is the key to the large scale use of hydrogen as a fuel, both in fuel cells and in internal combustion engines

(ICE).

There are four key elements which must be fulfilled:

- **The first** is "the speed with which the converter can be started".
Currently, the most efficient converter requires 5 to 10 minutes to start up.
- **The second** is "the instantaneous response": the speed with which a car responds when a driver steps on the accelerator pedal.
- **The third** is that "the consumption of thermal and electric power" needed to meet the requirements of the conversion process must be low and within parameters which allow compensation by the energy generated by the ICE or by the fuel cell which uses the converter.
- **The fourth**, in the case that converters can be improved, is to obtain a "commercially viable price" for the converter.

A gasoline engine responds in milliseconds; a converter which reacts slowly would give rise to a slow car which would be rejected by drivers.

Fuel converters and hydrogen storage

In 1992 Arthur D. Little initiated a program in conjunction with a DOE study to develop options in addition to the on-board reformation of methanol as a means of hydrogen supply to fuel cell vehicles. Phase 1 of this program includes an analysis of multifuel reformers, on-board hydrogen storage technologies and hydrogen infrastructure requirements. Phase 2 will involve the development and testing of a 10

kW reformer and a 1 kg capacity hydrogen storage unit.

Alternatives for the direct supply of hydrogen to the fuel cell include: liquefied hydrogen, compressed hydrogen, absorption on carbon and hydride storage.

Liquefied hydrogen has been tested in several vehicles since the 1970's in the United States and other countries. The volumetric and weight density of liquefied hydrogen when used with a fuel cell is the same as or better than diesel fuel used with an internal combustion engine. Its drawbacks are a high liquefaction energy, handling problems and an inevitable boil-off gas release.

Compressed hydrogen is the simplest on-board technology to conceive and could benefit from recent advances with composite materials and cost improvements from progress in natural gas vehicles. High-pressure tanks constructed with advanced materials could provide reasonable weight performance but only marginal volumetric performance. Technical issues to be resolved include cylinder permeability, tank design standards for higher pressures and hydrogen compressor design for refueling.

Several companies are developing multi-fuel processors with different processes, such as:

- Steam Reforming (SR): This process basically involves a catalytic conversion of methane and water (steam) to hydrogen and carbon dioxide through three main stages. Several companies, namely **Haldor-Topsoe (USA-Denmark)**, **Howe-Baker Engineers (USA)**, **IFI/ONSI (USA)**, **Ballard Power Systems (Canada)** and **Chiyoda**

(Japan) have worked on the design and construction of this system.

- Partial Oxidation (PO): An exothermic process by which hydrogen and carbon dioxide are produced from hydrocarbon fuels (gasoline and others) and oxygen (or air). PO processes have a number of important advantages over SR processes. Companies such as **Arthur D. Little (EPYX), Chrysler Corp. and Hydrogen Burner Technologies (all USA)** have announced plans to develop PO converters.

The EPYX PO converter comprises the following steps:

1.- Vaporization of fuel (gasoline) by applying heat, 2.- Combination of the vaporized fuel with a small amount of air in a Partial Oxidation reactor, producing hydrogen and carbon monoxide, 3.- Steam over carbon monoxide reaction with a catalyst to convert most of the carbon monoxide into carbon dioxide and additional hydrogen, 4.- In the preferential oxidation stage, injected air reacts with remaining carbon monoxide over catalyst to form carbon dioxide and steam, leaving hydrogen-rich gases.

- Autothermal Reforming (AR): In this exothermic process, hydrocarbon fuel reacts with a mixture of water and oxygen. The energy released by the hydrocarbon oxidation reaction drives the steam reforming process. Companies such as **Roll-Royce/Johnson-Matthew (UK) and International Fuel Cell/ONSI (USA)** are working on the development of the AR process.
- Thermal Decomposition (TD): (or pyrolysis, cracking) of hydrocarbon fuel produces hydrogen and clean carbon. The energy requirement

per mole of hydrogen produced from methane is somewhat less than for SR process. The technical-economic assessment of hydrogen production by SR, PO and TD processes indicates that the cost (in \$/1000 m³) of hydrogen produced by TD (57) is lower than for the SR (67) and PO (109) processes.

There is another concept in plasma assisted conversion of hydrocarbons, in which cold non-thermal plasma is used as a source of active species in order to accelerate the chemical reactions. The energy requirements of the process in this case can be met through thermal energy (low temperature), so that the plasma acts as a catalyst.

Plasma can be produced through the action of either very high temperatures, strong electric fields or strong magnetic fields. In a discharge, free electrons gain energy from an imposed electric field and lose this energy through collisions. The plasma of a glow discharge is characterized by high electron temperatures and a low gas temperature, electron concentrations of about 10⁹ to 10¹² cm³ and an absence of thermal equilibrium that makes possible a plasma in which the gas temperature can be near ambient, to obtain a plasma in which the electrons are sufficiently excited to cause the rupture of molecular bonds.

A broad spectrum of reactions has been observed to take place in plasmas. These include reactions between electrons and molecules, ions and molecules, ions and ions, and electrons and ions. Different types of discharge have been available in the past 20 years. The availability of radio-frequency and microwave generators has focused attention in recent years on the use of electrode-less discharges.

In a cold nonthermal plasma only charged particles (electrons, ions) gain energy from the applied electric field, while neutral particles remain at almost room temperature. Cold nonthermal plasma can be created by an electric glow discharge normally operated at reduced pressure. (Glow discharged plasmas are well suited for promotion of chemical reactions involving thermally sensitive materials. Relatively little basic experimental work has been published on the structure/performance correlation between the monomer, resulting polymer and selection/rejection properties of the plasma polymerization surface-modified membranes. The power used for preparing membranes ranges from 30 to 150 W, with polymerization time from 60 to 3000 s.

The electrical power needed to maintain the plasma state can be transmitted to the gas by resistive coupling with internal electrodes, by capacitive coupling with external electrodes or by inductive coupling with an external coil, or in the case of microwave discharge by means of a slow wave structure. Because of the many different reactive species in a plasma, it has not been possible to completely explain the mechanisms of the chemical reactions in a plasma.

It is well known that fossil fuels and methods currently employed to obtain usable energy (electricity, mechanical motion, etc.) are very inefficient. The most efficient internal combustion engines used for everyday transport attain peak efficiencies of 32%. This implies that 68% of the energy available from the fuel is not utilized to obtain mechanical energy (movement) and is thus wasted. There are many reasons for this, mainly the limit imposed by the principles of thermodynamics, which is set (for a four-stroke engine using gasoline) at 43%. However, the best engines we use still fall far short of their maximum efficiency. In addition

to this poor utilization of one of our most valuable natural resources, the amount of pollution generated by burning (oxidizing) fossil fuels has already become an escalating problem affecting the whole of our biosphere.

MPCR proposes a better solution to the utilization of fossil fuels, as this is a system which is able to reform/convert fossil fuels into another fuel, a synthetic fuel (SF) by a chemical process which requires little energy and does not yield undesirable by-products. The improved fuel is characterized by being more environmentally friendly as well as suitable for more types of energy conversion processes which may, in addition, be more efficient.

MPCR will have extensive commercial implications. Lower emissions of pollutants should spur environmental protection agencies such as the EPA of the United States and California's Air Resources Board to adopt the zero emission standards, already required by California, making the use of a process similar to that proposed by DAVID mandatory within the decade. That, in turn, would stimulate rapid and widespread use of such a system in such high vehicle-density nations as the U.S. and Canada.

Similar environmental efforts are already underway in Europe, where the European Union's executive arm, the European Commission, is drafting mandatory emission standards for the automobile industry that are much tougher than the industry is willing to accept.

The success of **MPCR** implies that we can still employ fossil fuels, but in a more efficient way, which is also more environmentally friendly. This will extend the duration of our planet's reserves and greatly reduce the

environmental problems that arise from burning hydrocarbons. Furthermore, this technology is directly applicable on a world-wide scale as the distribution networks of fossil-derived fuels like gasoline, methane, ethanol, propane, butane, diesel, etc. already exist.

No microwave plasma fossil fuel conversion system has been patented to date such as the applicants'. The DAVID patent differs from the known ones in the application of a special type of discharge (frequency, voltage, etc.) the process conditions (reaction time, flows of the reactants, etc.) and the special construction of the device (shape of electrodes, reactor, etc.).

The main difference between the **MPCR** and other technologies patented to date is the formation in the **MPCR** of a specific cold plasma, with electron temperature higher than the gas temperature. This plasma is achieved through a combination of a special microwave discharge in electrodes of a special design. With this new process, which is the object of our invention, a drastic reduction of the energy input needed by current conversion processes is possible.

The two components of the synthetic fuel (SF), H_2 and CO, produced through the non-equilibrium cold plasma process, are good fuels for an internal combustion engine. In the case of an ICE fueled by SF the emissions of CO_2 and NO_x are 90% less than fueled by gasoline, in the case of a fuel cell a membrane for separation of CO will be needed (or a special catalytic type converter).

The sulfur (and its typical compounds) content in liquid fuels are partially evaporated and take part in the **MPCR** Process. In the case of an ICE fueled by SF, the emissions will be less high oxides but more sulfur

compounds in a lower oxidation state (lower emissions of sulfur alkalenes and hydrogen sulfide, which are easier and cheaper to remove with existing catalytic converters).

The key to the success of the **MPCR** system lies in the fact that the synthetic fuel (SF) can be obtained on-line from a fossil derived fuel and at a low energy cost. Because SF can be used more efficiently, the overall efficiency of the system is improved. The energy efficiency of the Plasma Catalytic Reactor/Reformer (**MPCR**) is between 80% and 90%, depending on the method used to measure the efficiency. The SF is more environmentally friendly, whether it is oxidized in an ICE or with a fuel cell, providing the added (and very important) benefit of greatly reducing emissions.

In the case where the **MPCR** is used by an ICE, the immediate startup of the engine is one of the main issues to be resolved.

This point can be resolved by the use of an ICE adapted to operate with gaseous fuel (SF).

The main features of existing prototypes of ICE for SF operation are:

The gasoline feed fuel system is complemented with an injection system with a modified controller, based on the principle of the "Timed Admission Port Injection System" appropriate for hydrogen spark ignition fuelled engines.

The SF supply system is based on the use of an electronic control assembly that transforms the output signals from the sensors of engine

cycle parameters determining the optimum air-to-fuel ratio. A very simple technique for mounting the injectors in the ICE for the SF allows them to be installed without changing the cylinder head.

The modified ICE is an economical (low cost) way of adapting the standard ICE to run with SF while maintaining the normal gasoline feed.

The above solution would imply that the startup of the engine will be with gasoline with an addition of 5% synthetic fuel produced by the **MPCR** and stored in a 10 liter deposit, bypassed automatically to SF (after a very short period of time) when the **MPCR** reaches the required production of SF. The hydrogen addition will reduce emissions during the ICE startup operation.

In the case when the **MPCR** is utilized by a fuel cell, the initial running operation until the **MPCR** starts to produce the necessary hydrogen for the cell fuel operation can be the electric energy accumulated in the batteries. In this case, the batteries should provide electric energy for the **MPCR** (electric energy and thermal energy through electric energy).

Analysis and Estimations of Possible Plasma Assisted Conversion Performed by DAVID

Thermal Plasma Variants

1.1 On-board installation with steam conversion of 5% gasoline into synthetic gas.

The installation consists of an arc plasmatron integrated with a chemical

reactor, heat exchanger, internal combustion engine and electricity generator for the plasmatron. Fuel is vaporized and heated to 1000°C as it passes through the heat exchanger. Heating to higher temperatures can result in fuel decomposition and resinous precipitations at relatively cold walls of the fuel supply channels. At the same time, development of a heat exchanger with a working temperature higher than 1400°C is an extraordinarily complex problem which can lead to significantly higher system costs. Fuel vapors heated in the heat exchanger are directed into the arc plasmatron. Preliminary heated steam is also supplied into the arc plasmatron. Cold water is used for cooling the plasmatron walls. During this process water is heated and vaporized; steam is heated to 1300°C and directed towards the plasmatron. In the plasmatron water and fuel vapors gain the energy required for heating up to 2400°C and carrying out the steam conversion chemical reaction, and after they are well mixed they enter the chemical reactor. In the reactor the vapors are converted into syn-gas, which exits at a temperature of 1400°C, the temperature decreasing as a result of the endothermic reaction which takes place. Excess heat is removed by water cooling of the chemical reactor walls. Hot syn-gas passes through the heat exchanger, releasing heat to the fuel and steams, and after cooling down to 400°C enters the internal combustion engine. The generator for the plasmatron electrical power supply is driven by the internal combustion engine.

Listed below are approximate installation parameters estimated on the base of thermodynamic calculations. The installation is calculated for an internal combustion engine with 50 kW power.

1. Arc plasmatron with chemical reactor:

Power	2.5 kW
Steam flow rate	0.2 l/sec.

- 13 -

Gasoline flow rate	0.03 l/sec.
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Dimensions:	
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diameter	0.1 m
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length	0.3 m
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Weight	5 kg.
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2. Heat exchanger

Hot gas flow rate (1400°C)	0.6 l/sec.
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Cold gas flow rate	0.23 l/sec.
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Passed Heat flux	0.65 kW
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Dimensions:	
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diameter	0.25 m
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length	1.0 m
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Weight	15 kg.
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3. Generator

Power	2.5 kW
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Dimensions:	
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Diameter	0.2 m
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length	0.25 m
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Weight	15 kg.
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4. Internal combustion engine

Power	50 kW
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Gasoline flow rate	2.2 l/sec.
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Syn-gas flow rate	0.6 l/sec.
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Production of syn-gas requires:	
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Gasoline flow rate	0.12 g/sec.
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Water flow rate	0.15 g/sec.
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1.2 On-board installation with partial oxidation of 5% gasoline by

oxygen from air

As in the previous case, the installation consists of an arc plasmatron with a chemical reactor, heat exchanger, internal combustion engine and electricity generator. The partial oxidation reaction is exothermic, so that the plasmatron power can be reduced two-fold. Total gasoline flow rate will increase only a few percentage points. Since partial oxidation is carried out by oxygen from air, the syn-gas will be diluted by nitrogen by approximately 50%. Additionally, water is not involved in the process, so that cooling of the plasmatron and chemical reactor walls should take place by standard engine cooling systems. The plasmatron power essentially reduces engine power, so a high load of the cooling system is not required.

Approximate installation parameters:

1. Arc plasmatron with chemical reactor:

Power	1.5 kW
Steam flow rate	0.7 l/sec.
Gasoline flow rate	0.043 l/sec.
Dimensions:	
diameter	0.1 m
length	0.3 m
Weight	5 kg.

2. Heat exchanger

Hot gas flow rate (1400°C)	1.1 l/sec.
Cold gas flow rate	0.75 l/sec.
Passed heat flux	1.7 kW
Dimensions:	
Diameter	0.3 m
length	1.0 m

Weight 20 kg.

3. Generator

Power 1.5 kW

Dimensions:

Diameter 0.15 m

length 0.25 m

Weight 12 kg.

4. Internal combustion engine

Power 50 kW

Gasoline flow rate 2.2 g/sec.

Syn-gas flow rate 0.6 l/sec.

Production of syn-gas requires:

Gasoline flow rate 0.18 g/sec.

Water flow rate 0.7 g/sec.

2.1 On-board installation with steam conversion of gasoline into syn-gas

The installation is meant for syn-gas production from gasoline with a subsequent use of an electrochemical generator (ECG) for generating electricity. The installation consists of an arc plasmatron where gasoline and steams are heated, a chemical reactor where steam conversion takes place, and a heat exchanger where the hot syn-gas dissipates its thermal energy to the fuel and steams. As in case 1.1 the steams and gasoline vapors are heated and thoroughly mixed in the plasmatron and directed to the plasmatron. In the reactor the syn-gas is formed and its temperature lowered due to the endothermic chemical reaction. With the

aid of water cooling the syn-gas temperature is lowered to 1400°C, at which temperature it is directed to the heat exchanger. Thermal energy of the sun-gas in the chemical reactor is quite enough to evaporate all the water required for the reaction. In the heat exchanger the water and gasoline vapors are heated up to 1000°C by the thermal energy of the syn-gas, subsequently entering the plasmatron.

1. Arc plasmatron:

	Power	45 kW
10	Steam flow rate	3.9 l/sec.
	Gasoline flow rate	0.54 l/sec.
	Dimensions:	
	Diameter	0.1 m
	length	0.3 m
15	Weight	5 kg.

2. Chemical Reactor

	Dimensions:	
	diameter	0.15 m
	length	0.2 m
20	Weight	8 kg.

3. Heat exchanger

	Hot gas flow rate (1400°C)	12 l/sec.
	Cold gas flow rate	4.4 l/sec.
25	Passed heat flux	13 kW
	Dimensions:	
	diameter	0.3 m
	length	1.0 m
	Weight	20 kg.

4. Consumption

Gasoline	2.4 l/sec.
Water	3.1 l/sec.

2.2 On-board installation with partial oxidation of gasoline by oxygen from air

As in the previous case, the installation is meant to produce syn-gas for a subsequent use in an ECG. The basic installation blocks consist of an arc plasmatron, a chemical reactor and a heat exchanger. As in case 1.2, as partial oxidation of gasoline is an exothermic reaction the plasmatron power may be reduced by almost 40%. However, at the same time gasoline flow rate is increased 30%. Furthermore, obtained syn-gas is half-diluted by nitrogen. The absence of water in the process requires a separate system for the plasmatron walls and the chemical reactor. The cooling system should be capable of relieving 40 kW of thermal power.

Approximate parameters of the installation:

1. Arc plasmatron:

Power	28 kW
Air vapor flow rate	14 l/sec.
Gasoline vapour flow rate	0.86 l/sec.
Dimensions:	
Diameter	0.1 m
length	0.2 m
Weight	3 kg.

2. Chemical reactor

Dimensions:

diameter	0.15 m
length	0.2 m
Weight	8 kg.

3. Heat exchanger

Hot gas flow rate (1400°C) 22 l/sec.

Cold gas flow rate 14.9 l/sec.

Passed heat flux 34 kW

Dimensions:

Diameter 0.3 m

length 1.0 m

Weight 20 kg.

4. Consumption

Gasoline 3.6 g/sec.

Air 14 g/sec.

3.1 Stationary installation for a refueling station with steam conversion of gasoline into syn-gas.

The design of the installation is identical to case 2.1, but calculated for 10000 m³ of syn-gas per hour. It should be mentioned that the excess thermal power in the chemical reactor ($W \approx 1.5$ MW) required for the fast running of the steam conversion reaction should be relieved by water cooling, and may be employed for technical purposes of the station (such as car washing).

Approximate installation parameters:

1. Arc plasmatron:

Power 13 MW
Steam flow rate 965 l/sec.
Gasoline vapour flow rate 135 l/sec.

Dimensions:

diameter 0.3 m
length 1.5 m

Weight 50 kg.

2. Plasmatron power supply

2.1 Transformer

Dimensions: 7.0 x 5.0 x 6.0 m
Weight 50000 kg.

2.2 Control console

Dimensions: 2.0 x 2.0 x 1.0 m
Weight 150 kg.

3. Chemical Reactor

Dimensions:

diameter 0.5 m
length 1 m

Weight 100 kg.

4. Heat exchanger

Hot gas flow rate (1400°C) 3000 l/sec.

Cold gas flow rate 1100 l/sec.

Passed heat flux 3.3 mW

Dimensions:

diameter 1.5 m
length 5.0 m

Weight 2500 kg.

4. Consumption

Gasoline	0.6 kg./sec.
Water	0.8 kg./sec.

3.2 Stationary installation for a refueling station with partial conversion of gasoline by oxygen

The installation design differs from the prototype described in case 2.2 by a greater productivity and the use of oxygen as oxidant. At a productivity of 10000 m³ of syn-gas per hour, the installation should consume 0.74 m³ of oxygen. If oxidation were performed by air, approximately 3 m³ of oxygen would have to be heated to 2400°C, hence requiring 9 MW of additional power. Even if half of this power is recuperated, power losses clearly exceed expenditures for oxygen gained from air: with currently available technology expenditures for oxygen gained from air are 1.5 MJ/m³. Therefore, the power required for a 0.74 m³/sec extraction of oxygen is equal to only 1.1 MW. A further obvious advantage of using pure oxygen is the absence of nitrogen in the syn-gas.

Approximate installation parameters:

1. Arc plasmatron:

Power	0.5 MW
Steam flow rate	740 l/sec.
Gasoline vapour flow rate	214 l/sec.
Dimensions:	
diameter	0.2 m
length	0.4 m
Weight	20 kg.

2. Plasmatron power supply

2.1 Transformer

Dimensions: 2.0 x 2.0 x 1.5 m

Weight 5000 kg.

2.2 Control console

Dimensions: 2.0 x 1.0 x 1.0 m

Weight 100 kg.

3. Chemical reactor

Dimensions:

diameter 0.5 m

length 1 m

Weight 100 kg.

4. Heat exchanger

Hot gas flow rate (1400°C) 2800 l/sec.

Cold gas flow rate 9540 l/sec.

Passed heat flux 4.0 MW

Dimensions:

diameter 1.5 m

length 5.0 m

Weight 2500 kg.

4. Consumption

Gasoline 0.92 kg./sec.

Water 0.74 kg./sec.

Consideration of the above system shows that its implementation implies certain problems. Firstly, there is a very high temperature gas mixture in the plasmatron and in the chemical reactor, which requires use of special heat-resistant materials and essentially restricts the resources of similar

systems. Secondly, installations with steam conversion of total fuel require considerable expenditures of electrical power. Approximately half of the total syn-gas produced by the installation must be fired to cover these expenditures. It would be interesting to consider similar systems based on non-equilibrium plasma-chemical processes such as plasma catalysis. It should be mentioned that all installation designs mentioned below are based on preliminary experiments with natural gases and alcohols, so that additional research is required for use with gasoline.

Plasma Catalysis Variants

1. On-board installation with 5% fuel and steam pre-heating and subsequent treatment by MCW discharge

Exhaust gases of internal combustion engines have temperatures of about 800°C. Thermodynamic calculations show that this temperature is high enough to carry out a steam conversion reaction for a considerable part of the gasoline. However, kinetics restrictions do not allow conversion to take place in a reasonable amount of time. The MCW impulse periodic discharge treatment of methane previously heated to 800°C increases the degree of methane conversion up to three-fold, even though only 10% of the average discharge power of the MCW consists of preliminary heating. The methane conversion degree attains the thermodynamic equilibrium value.

The installation consists of an internal combustion engine whose heat is used to heat gasoline vapors and water vapors. The vapors enter the chemical reactor, where they are treated by MCW periodic discharges.

Under the influence of the discharges a considerable part of the gasoline-steam mixture is converted into syn-gas, which along with the unreacted hydrocarbon vapors enters the internal combustion engine. It should be mentioned that this scheme does not require the total conversion of the gasoline-steam mixture. A presence of only 10% hydrogen in the fuel mixture considerably improves engine operation, reducing toxic emissions and enhancing engine efficiency.

Approximate installation parameters:

1. Internal combustion engine:

Power	50 kW
Gasoline flow rate	2.2 g/sec.
Syn-gas flow rate	0.6 l/sec.
Production of syn-gas requires:	
Gasoline flow rate	0.12 g/sec.
Water flow rate	0.15 g/sec.

2. Chemical reactor

Reaction zone temperature	800°K
Gasoline vapors flow rate	0.03 l/sec.
Steams flow rate	0.2 l/sec.
Dimensions:	
diameter	0.05 m
length	0.1 m
Weight	0.5 kg.

3. MCW generator

Generation frequency	9 GHz
Average radiation power	25 W
Impulse power	25 kW

Dimensions:

Magnetron with waveguide channel 0.15x0.15x0.4m

Power supply	0.5x0.13x0.6 m
--------------	----------------

Weight:

Magnetron with waveguide channel	6 kg.
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Power supply	10 kg.
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2. On-board installation with partial oxidation of 5% gasoline and water addition for steam conversion

If the gasoline conversion degree in the previous scheme is insufficient, the temperature of the chemical reaction may be increased up to 1000°K in order to partially oxidize the gasoline by air. To economise thermal energy a heat exchanger is installed between the chemical reactor and the engine. The heat exchanger allows to recuperate heat from the syn-gas exhausted from the reactor.

Approximate installation parameters, assuming complete heat recuperation.

1. Internal combustion engine:

Power	50 kW
-------	-------

Gasoline flow rate	2.2 g/sec.
--------------------	------------

Syn-gas flow rate	0.6 l/sec.
-------------------	------------

Production of syn-gas requires:

Gasoline flow rate	0.15 g/sec.
--------------------	-------------

Water flow rate	0.075 g/sec.
-----------------	--------------

Air flow rate	0.37 l/sec.
---------------	-------------

2. Heat exchanger

Hot gas flow rate (1400°C)	0.9 l/sec.
----------------------------	------------

Cold gas flow rate	0.5 l/sec.
--------------------	------------

Passed heat flux	0.35 kW
------------------	---------

Dimensions

diameter	0.3 m
----------	-------

length	1.0 m
--------	-------

Weight	20 kg.
--------	--------

3. Chemical reactor

Reaction zone temperature	1000°K
---------------------------	--------

Gasoline vapour flow rate	0.035 l/sec.
---------------------------	--------------

Steam flow rate	0.1 l/sec.
-----------------	------------

Air flow rate	0.37 l/sec.
---------------	-------------

Dimensions:

diameter	0.05 m
----------	--------

length	0.1 m
--------	-------

Weight	0.5 kg.
--------	---------

4. MCW generator

Generation frequency	9 GHz
----------------------	-------

Average radiation power	25 W
-------------------------	------

Impulse power	25 kW
---------------	-------

Dimensions:

Magnetron with waveguide channel	0.15x0.15x0.4m
----------------------------------	----------------

Power supply	0.5x0.13x0.6 m
--------------	----------------

Weight:

Magnetron with waveguide channel	6 kg.
----------------------------------	-------

Power supply	10 kg.
--------------	--------

3. On-board installation with partial oxidation of gasoline by air and water additions for steam conversion.

The installation is meant for on-board automobile production of syn-gas to be used in an ECG. It consists of a chemical reactor in which steam

conversion of gasoline takes place at the expense of the partial oxidation energy. In order to accelerate the reaction a microwave generator is used. The microwave radiation is directed into the reactor, where chemically active particles are generated under the influence of said radiation. Active particles which participate in chain processes essentially accelerate the conversion of gasoline. The heat exchanger is used to recuperate heat from the generated syn-gas.

Below are shown the parameters for an installation with a productivity of 40 m³ of syn-gas per hour. As air is used for the partial oxidation, the syn-gas will be one-third diluted with nitrogen.

1. Chemical reactor.

Reaction zone temperature 1000°K

Gasoline vapors flow rate 0.7 l/sec.

15 Steams flow rate 1.9 l/sec.

Air flow rate 7.4 l/sec.

Dimensions:

diameter 0.15 m

length 0.5 m

20 Weight 5 kg.

2. Heat exchanger

Hot gas flow rate (1000°C) 17 l/sec.

Cold gas flow rate 10 l/sec.

Passed heat flux 16 kW

25 Dimensions:

diameter 0.3 m

length 1.0 m

Weight 20 kg.

3. MCW generator

Generation frequency 2.46 GHz

Average radiation power 600 W

Impulse power 600 kW

Dimensions:

Magnetron with waveguide channel 0.35x0.15x0.5m

Power supply 0.5x0.22x0.6 m

Weight:

Magnetron with waveguide 10 kg.

Power supply 25 kg.

4. Stationary installation for syn-gas production via partial oxidation of gasoline with water addition and microwave treatment of reagents

The installation scheme differs from the previous one only in the productivity and exchange of air for oxygen. The amount of water is chosen so that under stoichiometric conditions the temperature in the chemical reactor is 1000°K.

The contents of the installation, its approximate parameters and reagent flow rates are shown for a productivity of 10000 m³ syn-gas per hour.

1. Chemical reactor

Reaction zone temperature 1000°K

Gasoline vapors flow rate 0.18 m³/sec

Steams flow rate 0.44 m³/sec

Air flow rate 0.42 m³/sec

Dimensions:

diameter 0.5 m

length 2 m
Weight 100 kg.

2. Heat exchanger

Hot gas flow rate (1000°C) 2.8 m³/sec
Cold gas flow rate 1 m³/sec
Passed heat flux 2.6 MW

Dimensions:

diameter 1.5 m
length 5.0 m

Weight 2500 kg.

3. MCW generator

Generation frequency 915 MHz
Average radiation power 200W

Large-dimension equipment contents:

- a) Power and high-voltage transformers;
- b) Rectifier and power regulators;
- c) Generator blocks with magnetrons;
- d) MCW channels;
- e) Control console.

Installation of the power unit requires 150 m² of open space. Another unit is placed in a covered enclosure of area 70 m².

Impulse power 600 kW

Dimensions:

Magnetron with waveguide channel 0.35x0.15x0.5m

Power supply 0.5x0.22x0.6 m

Weight:

Magnetron with waveguide channel	10 kg.
Power supply	25 kg.

5. Stationary installation for syn-gas production via partial oxidation of gasoline with water addition and microwave treatment of reagents at low temperature. Cases of total conversion and partial conversion with outlet gas separation by a membrane block.

Due to the similarities with the technological scheme of point 4, the parameters and dimensions of the installations will be similar to those calculated in said point 4. In the calculation it was proposed that the steam-oxygen conversion reaction has a very high selectivity (only CO and H₂ can be formed as products). This provides a low process temperature. Two similar calculations were performed, the first at a temperature of 500°C, in which the temperature provides a practically complete conversion in these conditions; in the second calculation a lower temperature was employed (400°C) at which the conversion degree is only of 74%. However, in order to provide a pure syn-gas flow the use of a separation block is proposed. Estimations of the plasmatron power, the membrane block power and the mass flow rates are in the corresponding tables of appendix 5.

Main Results and Conclusions

1. Studies conducted by DAVID have shown that plasma-assisted hydrocarbon conversion processes are very attractive and might be a suitable base for new technologies of hydrogen and hydrogen-rich gas production. Even in the case of thermal plasma applications compact, easy to control and easy to start reformers can be designed. In addition, non-thermal catalysis applications can provide both significant reductions in energy consumptions and low process temperatures.
2. The comparative analyses performed show that for the case of thermal plasma, the following variants can be chosen as the most promising ones:
 - On-board installation for partial oxidation of 5% gasoline to improve the efficiency of a conventional diesel or gasoline engine.
 - Compact stationary installation for on-line hydrogen production based on plasma assisted partial oxidation of gasoline.The main disadvantages of the thermal plasma approach are a rather high energy consumption and a high operation temperature.
3. The above analysis shows that the plasma catalysis approach is quite promising as a solution for the aforementioned problems. IN addition, partial oxidation under plasma catalysis can provide an additional hydrogen yield due to water addition.
4. The most promising variants for plasma catalysis are:
 - On-board steam reforming of part of the gasoline. The engine exhaust heat can be used to meet the energy requirements of the

process.

Partial oxidation of gasoline on-board the car or other vehicle.

5. It should be mentioned that the installation parameters given above are based on theoretical simulation and on experimental results with methane and methanol conversion, so that further theoretical simulations and experiments are required to confirm the data presented.

RESEARCH CONDUCTED BY DAVID ON MICROWAVE-PRODUCED PLASMA CATALYSIS FOSSIL FUEL CONVERSION

Research in conversion of fossil fuels using plasma produced by microwave discharge comprises three basic steps:

1. Discharge modeling to determine the primary discharge parameters, which are essential for chemical reactions in the plasma reactor.
2. Investigation of the role of different chemical mechanisms for fuel conversion in specific discharge conditions.
3. Optimization of the reactor yield.

The first step is closely related to the analysis of available experimental results and should bring about construction of an exhaustive physical model of discharge evolution, in agreement with experimental evidence.

The second step should determine the contributions of the various hydrocarbon conversion mechanisms for predefined discharge conditions through the development of a physical-chemical discharge model. The results of this modeling may be used to improve the specific yield of a reactor by changing discharge parameters.

The physical model of MW discharge evolution should provide primary plasma parameters such as electron and ion concentration, their mean energies, gas temperature as a function of time and their spatial distributions. It is useful to subdivide discharge evolution into three different stages:

1. initial non-equilibrium stage in which there is strong deviation between electron and gas temperatures throughout the active reactor volume;
2. quasi-equilibrium discharge stage in which there are filaments with quasi-equilibrium plasma;
3. afterglow discharge stage in which plasma recombination occurs together with diffusion spreading and surface charge recombination at the reactor walls.

Since microwave discharge is also strongly non-uniform, it can be divided into three different spatial domains:

1. Streamer head with a high value of the reduced electric field, which is responsible for streamer propagation along field lines;
2. Streamer channel with relatively low field which at first ensures quasi-stationary characteristics of channel plasma, until some instability in the streamer channel destroys this quasi-stationary state;
3. The "coat" near the streamer channel with a low electron concentration due to radiation emission from the channel.

These qualifications are made in accordance with available experimental results and common theory of filamentary discharges. The existence of theoretical models and experimental data for the different temporary-spatial intervals is compared. The streamer head has barely been studied experimentally, due to the short time and spatial intervals, but

streamer head parameters can be obtained from streamer velocity and radius by means of plane front propagation theory. This theory is valid for our case as the thickness of the streamer front is sufficiently smaller than the streamer radius. The plane front model was developed for methane, water and hydrogen plasma and produced the initial electron concentrations in the streamer channel after the front. Additionally, the model gives the value of the quasi-stationary field in the channel. These values can be compared to the experimental data available for the electric field intensity and electron concentrations. As the electron concentration in the channel given by plane front theory is relatively small (n_e about $3 \cdot 10^{14}$ $1/\text{cm}^3$), it is quite difficult to measure this quantity from spectroscopic studies. However, the aforementioned value for n_e agrees with the estimation of $n_e < 10^{15}$ $1/\text{cm}^3$ made from an analysis of hydrogen line spreading. It should be mentioned that hydrogen plasma is better suited to experimental measurements due to its more precise structure and well-known kinetic and drift parameters, not only for its ground state but also for the required excited states. This is why hydrogen plasma is used in the first step as a convenient sample environment for discharge modeling.

Electric field intensities in the channel (H_2 - 100 Td, CH_4 - 90 Td) derived from plane front theory and the quasi-stationary assumption are in good agreement with experimental measurements for both hydrogen (≈ 30 kV) and methane (≈ 20 kV) in normal conditions. The deviation in the case of hydrogen plasma may be due to impurities in the bulk gas, such as 1% water. Electron temperatures corresponding to these field intensities are about 2 eV. An alternative way of determining this quantity is to analyze the population of excited hydrogen states using line intensities. To perform these studies a kinetics model was developed for the hydrogen

level population, taking into account impact excitation and de-excitation, spontaneous radiation and ionization processes, including the plane front wave results and calculation of the electron energy distribution function (EEDF). The model shows that the population of excited hydrogen states is strongly in non-equilibrium with respect to electron temperature: T_{ex} were approximately 0.3 to 0.4 eV for the desired levels, while T_0 was about 2 eV. These results are in good agreement with the experimentally observed T_{ex} which is about 0.3 eV, and coincide with previous kinetics calculations for hydrogen.

The rate of gas heating in plasma can determine the onset of a state of quasi-equilibrium due to the ionization heat instability in the streamer channel. The rate of gas heating was determined by solving the kinetic equation for the electron energy and finding the contribution of each elementary process involved in gas heating, taking into account energy conservation given some degrees of freedom. For example, one could expect vibrational energy to be stored without relaxation in translational and rotational degrees of freedom, at least at low temperatures. Simulations give a temperature increase of about 100 K in the first 100 ns. This value is enough to initiate ionization-heating instability in the channel if pressure relaxation occurs quite rapidly. The characteristic hydrodynamic time is about 100 ns for hydrogen and somewhat greater for methane. Thus, ionization instability in the streamer channel seems to be responsible for channel thermalisation in about 100 ns in hydrogen, as experiments show a strong rise in gas temperature and electron concentrations after 200 ns in hydrogen and 400 ns in methane. As could be expected, the electron concentration in the quasi-equilibrium state is determined from the condition that the thickness of the skin layer is about equal to the streamer radius. This

assumption produces electron concentrations of about 10^{16} $1/\text{cm}^3$, which is in reasonable agreement with the experimental value of about $5 \cdot 10^{16}$ $1/\text{cm}^3$. The experimental gas temperature (about 5000 K for methane) is slightly lower than equilibrium temperature for this concentration (about 6000 K) and thus provides the quasi-equilibrium state of the plasma.

The "coat" region near the channel is difficult for performing measurements due to its small electron concentrations. Moreover, electron concentrations in this region depend on impurity concentrations in the gas (which can take part in photo-ionization and association ionization processes). This results in significant restrictions to discharge modeling near the channel.

To determine the kinetics mechanism of fuel reforming in MW discharge several possible mechanisms in discharge conditions were studied. First, thermal dissociation of gasoline with water additions was performed in order to determine the influence of water on gasoline conversion and soot formation. Octane was considered for the gasoline capacity, as it is the highest hydrocarbon present in gasoline. The kinetics scheme was elaborated, consisting of 876 reactions to describe octane oxidation and soot formation. The model contains 85 chemical components, including all hydrocarbons up to C_8H_{18} with isomers and intermediate radicals.

Calculations were made using the WorkBench Code with the Calorimetric Bomb Reactor (CBR) model at $P=\text{const}$ and $T=\text{const}$.

Kinetics curves describing the dissociation of an octane-water mixture at $T=1500\text{K}$ and $P=1$ atm are shown in Figure 1 and Figure 2, and at $T=2100$ K and $P=1$ atm in Figure 3 and Figure 4, at water additions of

89% (Fig 1, Fig 3) and 50% (Fig 2, Fig 4).

Figure 1. Kinetics curves of main concentrations during the dissociation of C₈H₁₈-H₂O (11:89%) mixture at T = 1500 K, P = 1 atm

From Fig. 1 it is clear that the octane conversion process in presence of water, $C_8H_{18} + 8H_2O = 8CO + 17H_2$, can be divided into:

1. fast dissociation of octane with formation of ethylene and methane;
2. slow process of acetylene formation in which the water acts as a catalyst, followed by formation of CO and H₂.

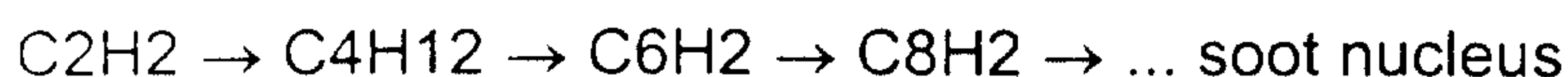
If there is not enough water for the full conversion of octane, the products will be methane (Fig. 2) or acetylene (Fig. 4).

Figure 2. Kinetics curves of main concentrations during dissociation of C₈H₁₈-H₂O (50:50%) mixture at T = 1500 K, P = 1 atm

Figure 3. Kinetics curves of main concentrations during dissociation of C₈H₁₈-H₂O (11:89%) mixture at T = 2200 K, P = 1 atm

Figure 4. Kinetics curves of main concentrations during dissociation of C₈H₁₈-H₂O (50:50%) mixture at T = 2200 K, P = 1 atm

Soot formation during the dissociation of the octane-water mixture at T= 2000 K and P=1 atm is shown in Figure 5 and Figure 6. This model considers a simplified soot formation model suggested by A. V. Krestinin [1]:



Although it is limited to C₈H₂ with further gasification. From the figures, it is clear that if there is not enough water for complete conversion of octane into CO-H₂, soot will be formed.

Figure 5. Soot formation during dissociation of the C₈H₁₈-H₂O (11:89%) mixture at T= 2200K, P = 1 atm.

Figure 6. Soot formation during dissociation of the C₈H₁₈-H₂O (50:50%) mixture at T= 2200K, P = 1 atm.

Figure 7 shows the dependence process time vs. temperature at which it is carried out.

Figure 7. Dependence of process time vs. temperature.

As can be seen in Figure 7, process time is the same as for methane decomposition (see previous report) only for temperatures under 1500 K. The limiting stage is dissociation of methane $\text{CH}_4 \rightarrow \text{CH}_3 + \text{H}$, and at higher temperatures the limiting stage is decomposition of acetylene.

Thus, kinetics results obtained for the thermal mechanisms of fuel conversion determine optimal discharge parameters, and hence the experimental conditions indicated for fuel reforming.

REVIEW OF EXISTING FUEL CONVERSION PATENTS

One of the basic chemical processes used in different aggregates to receive hydrogen-rich gas (h.g.) is steam reforming of hydrocarbons,

such as $\text{CH}_4 + \text{H}_2\text{O} = \text{CO} + \text{H}_2$. This reaction is endothermic, but if oxygen is added to the input mixture the reformation process becomes exothermic. This process can be used to receive h.g., which will be burned in an internal combustion engine or in an on-board fuel cell.

Use of catalysts in a reformation process has been proposed by many authors. A wide range of substances have been patented for their use as catalysts [1.2], as well as suitable designs for reformers [2.3]. We should remark that the important characteristics of a catalytic reformer are a compact shape and not requiring the use of additional equipment. Thermal insulation and heat recycling [3] will provide a high efficiency.

A further way to obtain h.g. based on the steam reformation process is a variant of gaseous hydrocarbon pyrolysis described in [4]. A patented mixture of hydrocarbons and burned oxygen-enriched gas is aggregated after injecting the hydrocarbons in the high temperature mixture obtained to receive an additional amount of hydrogen. The relationship between the amounts of hydrocarbons, steam and oxygen was patented. In the opinion of DAVID the main advantage of this process is the absence of catalysts.

Many authors propose using plasma methods for hydrocarbon fuel reformation. The arc plasmatron was patented as an appropriate design for a reformer [5], in which there is vaporization and pyrolysis of the fuel.

An interesting design for an arc plasmatron is presented in [6]. There exist several chemical processes for fuel reformation in this plasmatron: hydrocarbon pyrolysis leading to hydrogen and solid carbon. The plasmatron design and a continuous mechanical scrubbing of the solid

carbon was patented.

The use of plasma reformation for receiving h.g. which is injected to a car engine when requiring maximum power is patented in [7]. The use of an arc or microwave plasmatron as a reformer is proposed.

The authors of [8] propose adding a turbine to the hydrocarbon fuel reformer plasmatron, which uses kinetic energy and heat from gases in order to obtain additional energy which may be used for the requirements of the plasmatron.

A further group of patents are those which propose using plasma as a stimulator and energy source for an endothermic process of steam reformation of hydrocarbons.

In one of these [9] the gliding arc burns in a reaction volume to stimulate the hydrocarbon reformation process. Exhaust gases are additionally reformed by passing them through a pellet bed.

In another [10] the reaction mixture is heated initially and after passing through the reactor, where high voltage pulse periodic discharges occur and stimulate the steam reformation reaction. There is also a reformer design which may be used for generating h.g., where the h.g. is burned in an on-board SPE fuel cell.

Review of patent literature reveals significant interest by researchers in the problem of obtaining h.g. from hydrocarbons. As the review shows

the largest patent group is those where the authors propose to conduct the hydrocarbon reforming process with a catalyst, where the catalyst is a suitable chemical substance. Most patents disclose plasma hydrocarbon reforming methods. However, in most cases the authors use plasma as an effective heater of reagents. In DAVID's opinion only two patents use plasma as a source of heat energy and as a stimulator of the hydrocarbon reforming process. In the first of these [9] a mixture of oxygen rich gas and hydrocarbons is activated by the gliding arc plasma and moves on a special metallic or ceramic material, where the mixture is finally transformed in to the synthesis gas. But his patent cannot serve as a prototype for our device. The idea used in the second patent [9] is quite similar to the design of our device. IN both cases the mixture of reagents is heated and then treated by the cold plasma. There is no full conversion in such system; part of the hydrocarbons are transformed into carbon dioxide, requiring a membrane with a selected conductivity to obtain hydrogen. This system requires additional gas compression and uses more energy.

literature

N	Patent no.	Author	Country
1	PCT/JP97/02445	Tomura	JP
2	PCT/US96/1590	ISENBERG, Arnold, O	US
3	4	CLAWSON, Lawrence, G	US
4	PCT/US97/1490	Allen, M. Robin	US
5	6	E.M. Rudyak	USSR
6	USSR 632294	N.S. Pechuro	USSR
7	USSR 700935	Cohn	US
8	USSR 203816	Cohn	US
9	USP 5.887.554	CHERNICHOWSKI, M.	Fr

10	USP 5.852.297 PCT/US98/1802 7 PCT/FR97/0239 6	Albin ETIEVANT, Claude	Fr
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Presented and prior systems can generate syn-gas on-board a vehicle or produce it in a stationary device. Both constructions are prior art. As an example see U.S. Patent n° 5887554 in which systems are disclosed for the reformation of fuel into synthesis gas.

Stationary systems require high pressure vessels or cryogenic containers.

A further important example of a converter system is World Patent PCT/US98/18027. In it is disclosed a conversion process for light hydrocarbons (such as CH₄, C₂H₆, C₃H₈, C₄H₁₀ or natural gas) in presence (possible) of water and oxygen (air) by an electric discharge (particle discharge). In the description of the device of this patent one of the energy sources for the conversion process is partial oxidation of hydrocarbons.

The on-board production of hydrogen is described in detail. This group of devices is described for example in U.S. Pat. No. 5143025. In it is disclosed the use of electrolysis to separate H₂O into H₂ and O₂ and addition of H₂ to engine fuel. The hydrogen rich gas production system using interaction of water and C₀ (solid carbon) is developed in U.S. Pat. No. 5159900. In this device partial oxidation of carbon electrodes by water provided by arc treatment is the main source of the H₂ + CO

mixture. In U.S. Pat. No. 5207185 to Greiner et al., the basis of the device is a burner which uses one portion of the hydrocarbon fuel to reform another portion in order to produce hydrogen. The hydrogen is mixed with the fuel to be used in the engine.

Yet another system involves use of the thermal converter to reform one portion of the gasoline into hydrogen rich gas. (See Breshears El, et al., Proc. of EPA 1st Symposium on Low Pollution Power Systems Development, 268 (1973)). Other similar systems use partial oxidation in the presence of catalysts. (See Houseman, et al., Proc. 3rd World Hydrogen Energy Conf. 949 (1980)).

U.S. Patents Nos. 5435332 and 5437250, both to Rabinovich et al., disclose internal combustion engine systems with arc plasmatrons as the means in both.

Currently patented devices for performing plasma assisted fuel conversion use a stabilized plasma discharge in a high or superhigh frequency arc plasmatron of various models, and pulse variants of the arc discharge (railgun, gliding); see U.S. Pat. Nos. 5,425,332; 5,437,250 and 5,887,554. The very high temperature characteristic of these discharges and the resulting thermodynamic weight equilibrium do not allow to fully benefit from the advantages of the plasma fuel conversion method.

DESCRIPTION OF THE INVENTION

The object of the invention is a plasma converter of hydrocarbons into hydrogen-rich gas. The converter comprises a heater, a mixing chamber,

a reactor and a microwave power source connected to the reactor. An impulse-periodic pseudo-corona microwave discharge is used to accelerate the conversion process in the reactor. A pseudo-corona discharge is generated by a set of metal edges introduced in the microwave resonator at the maximum electric field region. As a result, at a specially selected regime (pulse duration, pulse period to pulse duration ratio, specific energy input, temperature at reactor inlet) a plasma-catalytic character of the conversion process is provided. A plasma-catalytic conversion process is characterized by a high productivity and low electric energy requirements at the lower temperature limit. The proposed reactor allows to carry out the conversion process for the fuel (petrol, kerosene, diesel fuel, etc.) with steam, steam-oxygen (steam-air) and partial oxidation with air into a hydrogen rich gas. Most of the energy required to carry out a specific process is supplied to the system as thermal energy from the heater, at the expense of heat recuperation at the reactor outlet, as well as (for steam-oxygen conversion or partial oxidation) at the expense of a partial burning of fuel in the mixing chamber. In the case of steam conversion the heater may include an arc plasmatron. Supersonic nozzles may be used in the mixing chamber which provide effective mixing of the initial reagents in a time under 10^{-3} - 10^{-5} sec.

Modern technology allows to build the proposed device for both a large scale production stationary system and in a compact design for placing in vehicles. Use of the hydrogen-rich gas production from fuel system on-board vehicles avoids the use of on-board hydrogen containers. The combined use on-board of the two devices proposed (use of internal combustion engines adapted for the hydrogen-rich gas and gasoline mixture) significantly reduces emission of pollutants and increases

engine efficiency. The engine performance characteristics are enhanced without any radical changes in engine design. A further application of the proposed equipment is the combination with a fuel cell to generate electricity which is supplied to the vehicle's electric motor.

**DESCRIPTION OF THE DEVICE CONSTRUCTED BY DAVID IN
WHICH THE EXPERIMENTS OF THE INVENTION HAVE BEEN
CARRIED OUT**

5 The experimental setup shown in figure 8 comprises:

A technological block (represented by a dotted line in Figure 1);

A feed system for the reagents (fuel, water, air) ;

A water feeding system

10 Modulator, MCW generator, waveguide

Water and fuel are evaporated in Evaporator 1 and Evaporator 2 at temperatures above their respective boiling points Water is supplied at the inlet of heater 2 (arc plasmatron) and fuel at the mixing chamber inlet.
15 The temperature of the fuel vapour must be high enough to prevent steam condensation during feeding in the mixing chamber.

The air is heated to a temperature above the boiling point of water and steam is supplied at the inlet of heater 2. The air temperature must be
20 high enough to prevent steam condensation in the mixture at the inlet of heater 2.

In heater 2 the steam and air mixture is heated to a fixed average mass temperature which depends on the chosen regime (see tables 2, 3, 4 and
25 5) and is fed at the mixer inlet.

Operation regimes of the technological block (firstly process temperature) are determined by the power change of heater 2 and/or changes in the consumption of initial reagents.

At the mixer all reagents are supplied quickly and after they are supplied to the plasma-catalytic reactor.

5 In the reactor the heated reagent mixture is treated by an impulse-periodic microwave pseudo-corona discharge.

Process products are cooled at the heat exchanger. The condensed phase (nonreacting water and fuel, and in some cases carbon) is
10 separated in the cyclone heat exchanger. The syn-gas obtained is fed to a chromatographic analysis. At point 16 the consumption of gas phase products is determined. Non-reacted water and fuel consumption is necessarily determined at point 17.

15 The discharge trigger and the MCW input device are constructively part of the technological block.

The discharge trigger is a sharp tungsten pivot placed in the reactor in the MCW field to initiate the pseudo-corona microwave discharge.

20 The MCW input device creates an electric field distribution in the reactor with a maximum intensity in the region of the sharp tungsten pivot.

Measurement points (points 4-15) for the main parameters of the
25 technological block are shown in figure 1. Nominal values of technological block parameters (reagent consumption, temperature regime) for the basic regimes of the reaction scheme are given in tables 1, 2, 3 and 4.

1.2. Brief description of the MCW installation

The MCW installation modulator produces a set of periodic voltage pulses essential for the operation of the MCW generator with the MCW input device.

The main parameters of the MCW radiation are:

Radiation impulse duration - 0.1 - 1 mks;

Impulse repetition frequency - up to 1 kHz;

Power in impulse – up to 50 kW;

Average power – up to 50 W;

Radiation wavelength - 3 cm

1.3. Input reagents

Input reagents are fed at the technological block input in normal conditions (points 1, 2, and 3 in figure 1). Cooling water has the following parameters at the input:

Pressure - 3 atm.

Temperature - 15° - 25°C

2. ENGINEERING DEMANDS FOR SEPARATION OF THE TECHNOLOGICAL BLOCK ELEMENTS

2.1 General demands

An arrangement of block elements in a single construction is proposed.

Maximum use will be made of possible collection-distribution of the construction for cleaning elements, replacing elements, modernization of the block and so on.

Figure 9 shows a scheme of the arrangement of the following elements

of the technological block: heater 2 (arc plasmatron), mixer, reactor, discharge trigger, MCW input device and set of thermocouples TC_i (index corresponds to measurement point in the scheme) for block temperature regime control. Pipe diameter is 20 mm.

2.2 Arc plasmatron – heater 2

Plasmatron power is 300W, not considering the efficiency coefficient of the plasmatron, losses, etc..

Working gas – steam, mixture of steam and air.

Pressure – above atmospheric (gas drift at the expense of water and fuel pressure in evaporators 1 and 2). Atmospheric pressure is fixed at the gas duct outlet by removal of gas from the heat exchanger.

Gas consumption at plasmatron entrance:

Regime 1 (without air) – steam 40.55 - 355 cm³/s

Regime 2 (with air) – steam 18.7-40.55 cm³/s plus 14-55 cm³/s from air.

Gas temperature (average) at the plasmatron outlet – up to 3000 K.

Thermocouples TC_4 and TC_5 are incorporated in the plasmatron.

Thermocouple TC_9 is active and measures the radial temperature distribution at the plasmatron outlet – at the mixer inlet. It is possible to remove the thermocouple from the pipe section.

2.3 Mixer

The parameters of one component of the mixture (steam plus air) are set by the arc plasmatron operation regime.

Parameters of the second component of the mixture (fuel vapour):

Consumption:

Regime (without air): 0.025 - 0.22 g/s

Regime (with air): 0.025 g/s

Mixing time is 10^{-4} s.

Gas temperature after mixing is 500 - 1560 K.

Thermocouple TC_6 is incorporated into the mixer. Thermocouple TC_{10} controls the gas temperature after mixing in the center of the pipe. It is possible to remove the thermocouple from the pipe section.

2.4 Reactor with discharge trigger and MCW input device

in the variant shown in Figure 2 the reactor butt-end is closed by a metal wall MC with holes for a spectral diagnosis of discharge and a vacuum packed glass window GW. Wall MC is used to reflect MW radiation in the direction of MCW discharge zone DZ. The distance between MC and the axes of the input device MCW radiation is on the order of 5-10 cm. In this variant the cyclone heat exchanger can interface with the side wall of the reactor as shown in figure 2. in this case the arrangement of the technological block is horizontal. MCW radiation reflection in the direction of the discharge zone from the mixer zone is attained by reducing the pipe cross-section at the mixer output from 20 mm to 15 mm.

The MCW radiation input device is a rectangular waveguide with a cross section of 24 x 11 mm. The wider wall of the waveguide is directed along the pipe and is 150 mm in length. At a distance of 70 mm from the junction of the waveguide and the pipe is placed a hermetizer made from a material transparent to MCW radiation. The between-axes distance of the input device and the discharge zone is on the order of 5 to 10 cm.

Note: For the sake of convenience in figure 2 the MCW input device is arranged in the outlet plane. In the real system the input is not inclined 90° and oriented perpendicular to the outlet plane.

The discharge initiator is a sharp tungsten bar with a diameter on the order of 2 mm. The initiator is active on the pipe radius and may be removed from the pipe section.

Thermocouple TC₁₁ controls the radial temperature distribution in the pipe. The temperature range is 300 to 1560 K. The thermocouple is active on the pipe radius and may be removed from the pipe section.

The distance from discharge zone DZ to the reactor inlet-mixer outlet is minimized and is determined by construction properties of the block elements.

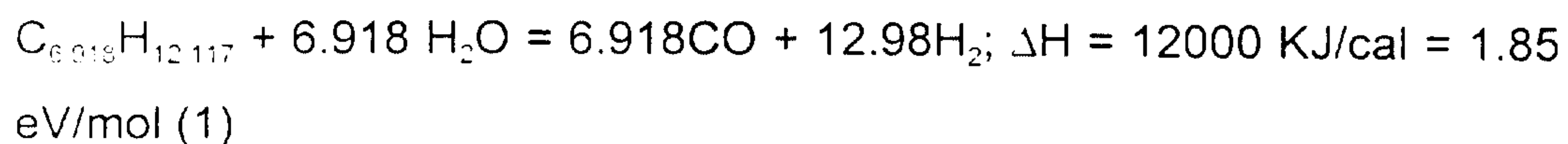
3. Parameters of the technological block

Nominal process parameters have been calculated for the characteristic regimes of experimental investigations in order to determine the reagent consumption rates. These data are used in the project design of the installation.

The two main types of processes which take place in the installation are steam conversion without air (1) and fuel conversion by steam and with partial oxidation of fuel by oxygen from air.

3.1. Technological block parameters for the steam fuel conversion process without air.

In this case the process corresponds to the reaction:



The energy input J to the initial reagents is the main parameter which is varied in the experiment:: $J = W_4/Q$, where W_4 is the thermal power and Q is the consumption of initial reagents. The energy input determines the temperature regime of the process and the value of the equilibrium degree of conversion. Two main regimes are studied experimentally: varying power W_4 under constant initial reagent consumption Q (Table 1) and varying initial reagent consumption Q under constant heating power W_4 (Table 2).

3.2. Technological block parameters for the steam fuel conversion process with air as one of the initial reagents

If air is present in the input reagents part of the fuel will be oxidized by oxygen. As a result the absorbed energy offsets part of the external energy supply. An increase in the proportion of air at the system inlet leads to a reduced heating power W_4 in heater 2. As in the initial regimes (without addition of oxygen), two regimes are considered: regime "e" (100% fuel conversion, see tables 1, 3) and regime "n" (65% fuel conversion, see table 4). Addition of oxygen in these regimes leads to a reduced W_4 power of heater 2 in the regime with conservation of temperature and fuel conversion degree (tables 3, 4).

Key to tables 1.2.

Q – reagent consumption, in (g/s) for the liquid phase and (nm^3/g) for the gaseous phase.

T - temperature

Power W_4 - Power absorbed by the gas heated in heater 2, not considering heater efficiency, losses and the like.

α - estimation of the conversion equilibrium degree in point 12. In this point, together with hydrogen and CO, there is vapors of non-reacting

water and fuel in amounts corresponding to (1). The sum of water and CO concentrations are given as an estimate of the conversion degree.

– At point 9 is shown the average mass temperature at the given section; in practice the radial temperature distribution is measured by a mobile thermocouple.

– The temperature value is given without considering energy costs for dissociation of water molecules; the true temperature is about 3000 K.

J – Energy input (enthalpy) for initial reagents in the specific regime, which ends with the heating and evaporation of the reagents (for purposes of information).

For consumptions of initial reagents (fuel and water) given in table 2 the fuel and water evaporator powers are respectively $W_3 = 5W$ and $W_2 = 80W$.

The main peculiarity of the regimes defined and shown in Table 1 is the variable ratio of average MCW discharge power ($W_{MCW}^{ev} = 50 W$) to heating power W_4 (heating power may range between 50 and 300 W).

Table 2 shows data calculated for regimes with constant heating power $W = 300 W$. The ratio W_{MCW}^{ev} / W_4 is constant and approximately equal to 15%.

When input reagent consumption (water and fuel) varies the power of their evaporators (W_2 and W_3) also vary, as shown in table 2.

Key to tables 3 and 4

– The conversion degree α corresponds to the fuel conversion degree.

Table 1

Points on scheme		1	2	3	5	6	9 ⁽¹⁾	10	11	12		
Parameters	W_4 W	Q air	Q water	Q fuel	Q WATER	Q FUEL	T, K	T, K	T, K	T, K	J (kJ/kg)	α , %
Regimes												
A	48	0	0.032 g/s	0.025 g/s	0.0146 nm ³ /h	0.021 nm ³ /h	1060	701	701	580	4000	18
B	80	0	0.032 g/s	0.025 g/s	0.0146 nm ³ /h	0.021 nm ³ /h	1461	890	890	620	5000	35
C	112	0	0.032 g/s	0.025 g/s	0.0146 nm ³ /h	0.021 nm ³ /h	1829	1039	1039	649	6000	50
D	176	0	0.032 g/s	0.025 g/s	0.0146 nm ³ /h	0.021 nm ³ /h	2500	1269	1269	696	8000	73
E	304	0	0.032 g/s	0.025 g/s	0.0146 nm ³ /h	0.021 nm ³ /h	3760 ⁽¹⁾	1560	1560	800	12000	99

Table 2

Points on scheme	1	2	3			9"	10	11	12		
Parameters	W_4 W	Q air	Q water	Q fuel	W_2 W	W_3 W	T, K	T, K	T, K	J (kJ/kg)	α , %
Regimes											
E	300	0	0.032 g/s	0.025 g/s	80	5	3760 ¹⁾	1560	800	12000	99
F	300	0	0.045 g/s	0.035 g/s	113	7	1367	1367	709	9166	77
G	300	0	0.056 g/s	0.044 g/s	140	9	1264	1264	684	8003	67
H	300	0	0.112 g/s	0.088 g/s	280	18	916	916	615	5173	34
I	300	0	0.168 g/s	0.132 g/s	420	27	759	759	580	4286	20
J	300	0	0.281g/s	0.219g/s	720	44	605	605	530	3569	8

Table 3

Points on scheme		1	2	3	5	6	9 ¹⁾	10	11	12		
Parameters	W_4 W	Q air	Q water	Q fuel	Q WATER	Q FUEL	T, K	T, K	T, K	T, K	J (kJ/kg)	α , % ²⁾
Regimes												
E	304	0	0.032 g/s	0.025 g/s	0.146 nm ³ /h	0.021 nm ³ /h	3760 ¹⁾	1560	1560	800	12000	99
K	265	0.014 nl/s	0.028 g/s	0.025 g/s	0.128 nm ³ /h	0.021 nm ³ /h	3098 ¹⁾	1458	1458	811	7300	100
L	212	0.028 nl/s	0.023 g/s	0.025 g/s	0.105 nm ³ /h	0.021 nm ³ /h	2403	1298	1298	825	4500	100
M	91	0.055 nl/s	0.014 g/s	0.025 g/s	0.064 nm ³ /h	0.021 nm ³ /h	1179	838	838	838	1500	100

Table 4

Points scheme	1	2	3	5	6	9 ¹⁰	10	11	12		
Parameters	W ₄ W	Q air	Q water	Q fuel	Q WATER	Q FUEL	T, K	T, K	T, K	J (kJ/kg)	α , % ²⁾
Regimes											
N	144 0	0.032 g/s	0.025 g/s	0.146 nm ³ /h	0.021 nm ³ /h	2176	116 0	116 0	664	7000	63
O	86 0.014 nl/s	0.028 g/s	0.025 g/s	0.128 nm ³ /h	0.021 nm ³ /h	1390	888	888	651	3900	65
P	32 0.028 nl/s	0.023 g/s	0.025 g/s	0.105 nm ³ /h	0.021 nm ³ /h	697	541	541	642	1500	64

DETAILED DESCRIPTION OF THE INVENTION

The basis of our invention consists of using a superhigh frequency pseudo-corona impulse-periodic discharge at atmospheric pressure, which differs from currently existing devices by:

- ? Low reagent temperature
- ? High weight non-equilibrium scale
- ? Highly energy-efficient generation of chemically active particles in the plasma
- ? Highly efficient use of electrical energy

The device of our invention is meant to carry out plasma-catalytic fossil fuel conversion into hydrogen-rich synthetic gas (mixture of hydrogen and carbon monoxide)

The main processes involved in the fuel conversion are:

- ? Steam conversion (see j below)
- ? Steam-oxygen conversion (k)
- ? Partial oxidation (l)

Before entering the plasma-catalytic reactor area reagents are pre-heated to a temperature which provides a sufficient conversion equilibrium scale for the reactor. As a rule, this temperature is too low to carry out the process in an acceptable time period (kinetic drag). Plasma treatment of preheated reagents allows, by means of chain processes with participation of chemically active particles, to eliminate kinetic limitations and reach the equilibrium values of reagent conversion scales.

The main part of the device object of this invention is the plasma-catalytic reactor (figure 10), in which the preheated reagents are treated by a pseudo-corona impulse-periodic microwave discharge.

The reactor is a metallic pipe (1 in figure 10) with a round section, which in addition is used to transport gas and as a waveguide for propagation of the microwave radiation. The microwave radiation enters the reactor through a standard rectangular waveguide (2) (H01 type wave) through interface orifice (3).

The interface orifice is closed by hermetizer (8) which is transparent to microwave radiation to prevent perturbation of the dynamic parameters of the gas and to insulate the waveguide pipe from the reactor volume. The longer wall of the rectangular waveguide is placed along the axis of the pipe where the H11 wave type is excited in the round waveguide. The electric field E distribution in the rectangular and round waveguide are described in figures 2 and 3.

Reactor diameter is chosen under the condition that no other (higher) wave types are excited at the round waveguide aside from the main wave type H11. The next wave type is E01. Fulfilling this condition leads to the following constraints for the diameter D:

$$l_{\lambda} < l_{cr}^{H11}(D) = 1.705 D \quad (a)$$

$$l_{\lambda} < l_{cr}^{E01}(D) = 1.308 D \quad (b)$$

where:

l : is the wavelength of the microwave radiation in free space

l_{cr} : are the critical wavelengths in the round waveguide for the corresponding wave types

From the above relationships, a condition for the reactor diameter is obtained:

$$0.59 l_0 < D < 0.76 l_0 \quad (c)$$

Heated reagents enter the reactor from mixing block (11 in figure 10) through the reagent inlet element (4).

The mixer consists of a device with three reagent inlet systems. The first inlet system (10) is installed on the system axis. Through it are sent to the mixer, in the different variants of the process and conversion, heated steam (process j) or heated steam-air mixture (k), or heated air (l). The second and third reagent inlets (9 and 10) are concentric supersonic nozzle systems. Use of these systems in the device construction leads to a mixing time of reagents at a molecular level on the order of $10^{-3} - 10^{-4}$ seconds. In the steam-oxygen conversion (k) and partial oxidation (1) variants, fuel oxidation occurs between the second and third reagent inlet systems. The energy produced in this oxidation process heats the reagents additionally.

The reagent inlet system (4) consists of part of the pipe which narrows as it reaches the mixer. It must narrow enough so that the reagent inlet element is beyond limits of wave H₁₁. This is, so that the microwave radiation reflects off this element towards interface orifice (3). This condition leads to the following relationship between the characteristic

transverse dimension of the reagent element and the diameter d:

$$I_0 > I_{cr}^{H11}(d) = 1.705 d \quad (d) \quad (e)$$

Process products exit the reactor through the orifices of plug (5). This plug is meant to reflect microwave radiation towards interface orifice (3).

An alternative organization of the exit of process products from the reactor can be a pipe segment similar to that of the reagent inlet (4) but which narrows in the opposite direction. In both cases the length of the reactor (L in figure 10) must be an integer multiple of the half-wavelengths $l_{wg}/2$ of the microwave radiation in the waveguide:

$$L = n l_{wg}/2 = n l_0 / (1 - (I_0 / I_{cr}^{H11}(D))^2)^{1/2} / 2 \quad (e)$$

The discharge is initiated by a corona element – a sharp metal bar (6) made from a non-melting material introduced in the waveguide. The point of the bar increases the microwave electric field E around it and thus achieves the pseudo-corona effect discharge. This bar is aligned along the force lines of field E inside the waveguide (figure 12). The position of the bar point (H in figure 12) is approximately equivalent to half the radius of the waveguide. In a longitudinal sense (L2 in figure 10) the bar is placed at the point where the stationary wave field in the resonator without discharge has its highest value:

$$L_2 = l_{wg} (n/2 + 1/4) = (n/2 + 1/4) l_0 / (1 - (I_0 / I_{cr}^{H11}(D))^2)^{1/2} / 2 \quad (f)$$

The streamers of the pseudo-corona discharge stage are transformed in the microwave field into the plasma streamer system, and travel as a

microwave streamer, filling the pipe cross section and creating the microwave impulse discharge zone (7 in figure 10). The purpose of the pseudo-corona discharge stage is to generate plasma at atmospheric pressure with a high average electron energy.

The purpose of the microwave streamer stage is to create a plasma formation extended in space for the plasma-catalytic treatment of reagents.

Coordination of the rectangular waveguide (2 in figure 10) and reactor (1) is achieved by choosing the ration between lengths l and L_1 (figure 10). Practically all the microwave radiation is absorbed at the discharge area (7), so that the part of the waveguide to the right of the radiation input orifice (3) operates in the traveling wave regime in presence of the discharge. In this case distance L_1 on the order of an integer multiple of the half wavelengths in the waveguide will be:

$$L_1 = n l_{WG} / 2 = l_0 / (1 - (l_0 / l_{cr}^{H11}(D))^2)^{1/2} / 2$$

(g)

The microwave radiation source operates in an impulse-periodic regime. The radiation impulse duration t_1 is defined as the time required for both discharge stages (pseudo-corona effect and microwave streamer stage) to take place in given conditions.

The impulse repetition period t_2 is found from the optimal relation of the following quantities: lifetime of active particles generated by the plasma in the passive discharge phase, after the superhigh frequency radiation impulse ceases; linear speed of reagents passing through the discharge

zone; discharge energy supply:

$$J_{\text{plasma}} = W / Q \quad (h)$$

where

$$W = W_{\text{PULSE}} \cdot t_1 / t_2$$

W is the average power of the microwave radiation, , W_{PULSE} is the pulse power and Q is the reagent consumption.

The microwave radiation impulse power W_{PULSE} , (h), (i) determines the energy input for the plasma, J_{PLASMA} . In addition, the pulse power depends on the electric field strength in the round waveguide in the absence of plasma, which must be lower than the disruptive discharge and at the same time be high enough to initiate the pseudo-corona discharge stage in the corona element.

The thermal energy supply (energy supply for preheating of reagents) J_{HEAT} must be enough to heat reagents to the required temperature and to compensate energy consumption by the endothermic processes of the system, which lead to the reagent conversion equilibrium scale at the given temperature.

Preheating of reagents may be performed by the following methods:

- heater with independent power supply (e.g. arc plasmatron);
- incineration of part of the fuel in the combustion chamber;
- oxidation of part of the fuel by oxygen in conversion processes involving oxygen (air);
- heat recuperation at the device outlet

Combinations of the above methods are also possible.

The ratio of plasma energy supply to heat supply $J_{\text{plasma}}/J_{\text{heat}}$ is on the order of 1-10%.

Characteristic temperatures for conversion processes and their corresponding reagent conversion scales are given below.

The steam fuel conversion process (j) with a 35% conversion has the following characteristic temperatures: steam heating temperature 1450 K, temperature of the steam-fuel vapour mixture after mixing 890 K, product temperature after process 620 K.

The steam fuel conversion process (j) with a 65% conversion has the following characteristic temperatures: steam heating temperature 2180K, temperature of the steam-fuel vapour mixture after mixing 1150 K, product temperature after process 665 K.

The steam fuel conversion process (j) with a 99% conversion has the following characteristic temperatures: steam heating temperature 3750K (not considering water molecule dissociation processes), temperature of the steam-fuel vapour mixture after mixing 1560 K, product temperature after process 800 K.

The steam-oxygen fuel conversion process (k) with a conversion degree of 65% (water-air molar ratio 2.5) has the following characteristic temperatures: vapour-air mixture heating temperature 1390 K, reagent

temperature after mixing 890 K, product temperature after process 650 K.

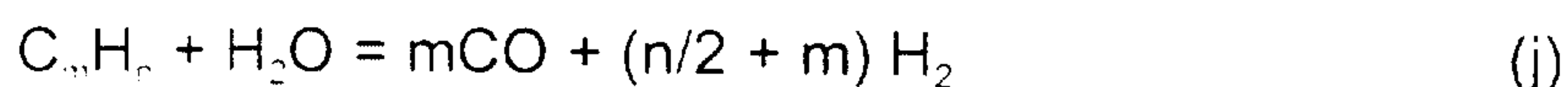
The partial fuel oxidation process (1) with a 100% conversion (fuel-air mole ratio of 1:3.46) has the following characteristic temperatures: heating temperature of the vapour-air mixture 1110 K, reagents temperature after mixing 896 K, products temperature after process 1611 K.

3. EXECUTION AND CHARACTERISTICS OF THE PROCESSES.

The proposed device can perform processes of fossil fuel conversion with steam, steam-oxygen and fuel vapour in hydrogen rich gas, as well as the stimulated partial oxidation of fuel process.

3.1.

The steam fuel conversion process is described by the reaction:



and its realization in the device is schematically represented in figure 13.

The steam is sent to the heater and then to the first inlet of the mixing chamber, while the fuel is sent to the second and third inlets of the mixing chamber. Depending on the chosen regime the ratio of fuel at the second and third mixer inlets can be varied between 0 and 1, and the general steam/fuel molar ratio can vary between 6 and 14.

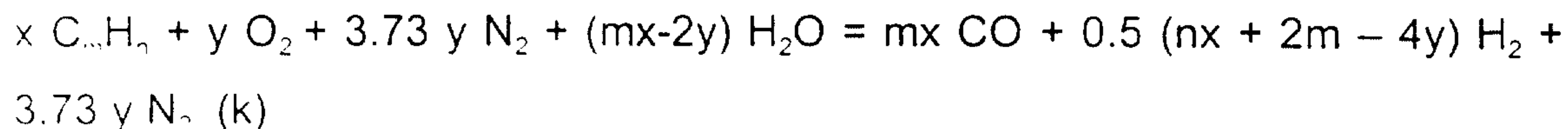
As a heater, as shown in figure 14, can be used a recuperating heat exchanger which uses the heat from the reactor outlet and the arc plasmatron connected in series. The temperature of the steam required for the steam fuel conversion process at the heater outlet is between 1400-3000 K, and the temperature of the reagents at the reactor inlet is between 900-1500 K¹.

The overall energy balance for the plasma catalytic steam conversion process comprises the energy consumed to evaporate reagents (J_{vapor}), to heat reagents and the chemical process. The product composition at the reactor outlet (reagent transformation scale "a") and the energy "A" consumed by the product (hydrogen rich syn-gas) depends firstly on the energy supplied $J_{\text{SUM}} = J_{\text{plasma}} + J_{\text{heat}} + J_{\text{vapor}}$. The relationship is presented in the following table (energy supply J_{SUM} is shown as a ratio of power and weight of liquid reagents).

J_{SUM} , kJ (kg)	a, %	A, eV/mol
12000	96	0.14
9170	77.5	0.19
8000	67	0.19
5170	49	0.28
4290	20	0.31

3.2.

In the steam-oxygen (steam-air) conversion process, for given amounts of fuel (x) and oxygen (y)



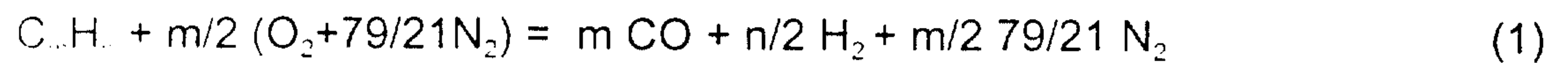
and as shown in figure 15, steam is sent to the heater mixed with air and the fuel is sent to inlets 2 and 3 in a ration of 0.5-2. The temperature at the heater outlet is 500-600 K and at the reactor inlet is 800-1500 °K. The steam / air and steam / fuel molar ratios are within 0.3-2 and 3-7 respectively.

The degree of transformation of reagents into hydrogen rich syn gas depends on the energy supplied to the system, J_{SUM} (see p. 3.1), as well as on the molar ratio of air to fuel "g". The main quantitative characteristics are given in the following table:

	g, %	J_{SUM}, kJ/kg	a,%
20	25	7300	100
	25	3400	65
	42	4500	100
	42	1500	69
25	64	1500	100
	64	850	95

3.3.

In the partial oxidation of fuel process,



as shown in figure 16, air is sent to the heater and fuel to the second and third inlets of the mixing chamber in a ratio of 0.5-2 "g" with an air/fuel molar ratio at the reactor inlet of 8-12.

The temperature required to carry out the partial oxidation of fuel at the heater outlet is in the range 500-600 °K and the temperature at the reactor inlet is between 900-1100 °K.

To ensure the working temperature for the process an energy J_{SUM} must be supplied (see p. 3.1) between 1000-1500 kJ/kg, with which the reagent transformation degree reaches 100%.

REFERENCES IN FIGURES 10 TO 16**FIGURE 10- CONSTRUCTION OF THE DEVICE**

- 1 - round waveguide, chemical reactor;
- 2 - rectangular waveguide;
- 3 - interface orifice;
- 4 - reactor reagent inlet element;
- 5 - reactor product outlet, waveguide plug;
- 6 - initiator bar;
- 7 - plasma catalytic discharge zone;
- 8 - first mixer inlet;
- 9 - cross section of second mixer inlet;
- 10 - cross section of third mixer inlet;
- 11 - reagent mixing chamber.

**FIGURE 11 -COORDINATION OF THE ELECTRIC FIELD
DISTRIBUTION AT THE ROUND AND RECTANGULAR
WAVEGUIDES.**

- 1 - rectangular waveguide
- 2 - round waveguide
- E - microwave electric field vector.

FIGURE 12 – CORONA INITIATOR BAR INLET TO THE WAVEGUIDE

- 1 - round waveguide
- 2 - sharp bar of a rigid metal

3 - electric field force lines at the bar and discharge waveguide. Below is the distribution of the microwave electric field amplitude.

**FIGURE 13 –SCHEME OF THE STEAM FUEL CONVERSION
PROCESS**

1, 2, 3 – First, second and third inlets of reagents into the mixer.

**FIGURE 14- SCHEME OF THE STEAM PREHEATING IN STEAM
FUEL CONVERSION PROCESS**

**FIGURE15- SCHEME OF THE STEAM-AIR FUEL CONVERSION
PROCESS**

1, 2, 3 – First, second and third inlets of reagents into the mixer.

**FIGURE 16- SCHEME OF THE PARTIAL OXIDATION OF FUEL
PROCESS**

1, 2, 3 – First, second and third inlets of reagents into the mixer.

Figure 17- DRAWING OF THE DEVICE

1- Round waveguide, plasma chemical reactor, 2- Rectangular waveguide for entry of microwave radiation to the reactor, 3- Interface orifice, 4- Inlet element of reagents into the reactor, 5- Outlet of reactor products, waveguide connector, 6- initiator bar, 7- Plasma catalytic discharge zone, 8- First mixing chamber inlet, 9- Cross section of the third mixing chamber inlet, 11- Reagent mixing chamber.

CLAIMS

1. Plasma converter of fossil fuels into a hydrogen-rich gas, comprising a heater, a mixing chamber, a reactor, these
5 connected in series, and a MCW energy source for the reactor, which generates impulses with a pulse duration of 0.1 to 1 microseconds and a pulse period to pulse duration ratio of 100 to 1000 in the centimeter or decimeter range of microwaves (X, S bands), using a pseudo-corona impulse periodic MCW discharge
10 at atmospheric pressure at the reactor, which is initiated by a set of metallic pins inserted in the MCW resonator, and where the length dimension of the resonator is approximately several times the wavelength of the MCW radiation, and the metallic pins are arranged in the resonator at the areas of maximum electric field,
15 and where the mixing chamber is provided with an inlet connected to the heater, as well as a second and third inlets for supply of reagents at the various areas of the mixing chamber.
2. Device according to claim 1, in which in order to perform a steam
20 conversion of fuels process steam is supplied to the heater and at the second and third mixing chamber inlets a fuel is supplied in a ratio Q_1/Q_2 of 0 to 1.
3. Device according to claim 2 in which the heater is constructed as a
25 heat exchanger with thermal recuperation of the hydrogen-rich gas produced and with an arc plasmatron connected to the heat exchanger in series.
4. Device according to claim 2 in which in which the steam to fuel

molar ratios are selected within the range 6 to 14.

5. Device according to claim 2 in which the temperature of the steam at the heater outlet is approximately 1400-3000 K, and the temperature of the reagents at the reactor is 900-1500 K.
6. Device according to claim 1 in which to perform the steam-air conversion of fuel process steam mixed with air is supplied to the mixing chamber, and in the second and third inlet of the mixing chamber is supplied fuel in ratios Q_2/Q_3 within the range 0.5 to 2.
7. Device according to claim 2 in which in which the reagent temperature at the heater outlet is approximately 500-600 K and at the reactor inlet is 800-1500 K.
8. Device according to claim 2 in which in which the steam/air and steam/fuel molar ratios at the reactor inlet is chosen within the ranges 0.3-2 and 3-7 respectively.
9. Device according to claim 2 in which to perform partial oxidation of fuels air is supplied at the first inlet of the mixing chamber and fuel at the second and third inlets of the mixing chamber in ratios Q_2/Q_3 within 0.5 to 2.
10. Device according to claim 9 in which the temperature of the reagents in the heater outlet is 500-600 K, and at the reactor inlet it is 800-1500 K.
11. Device according to claim 9 in which the air/fuel molar ratio at the

reactor inlet is 8-12.

- 5
12. Device according to claims 6 and 9 in which the heater is constructed as a heat exchanger with thermal recuperation, which uses the heat from the hydrogen-rich gas produced in the reactor.
13. Device according to claim 2 in which the total flow rate of the reagents Q and the MCW average specific power is selected according to the relation $W/Q = 0.2 - 0.4 \text{ kW*hour/m}^3$.
- 10
14. Device according to claims 6 and 9 in which the total flow rate of the reagents Q and the average value of W is selected according to the relation $W/Q = 0.05 - 0.15 \text{ kW*hour/m}^3$.

Fetherstonhaugh & Co.
Ottawa, Canada
Patent Agents

1/11

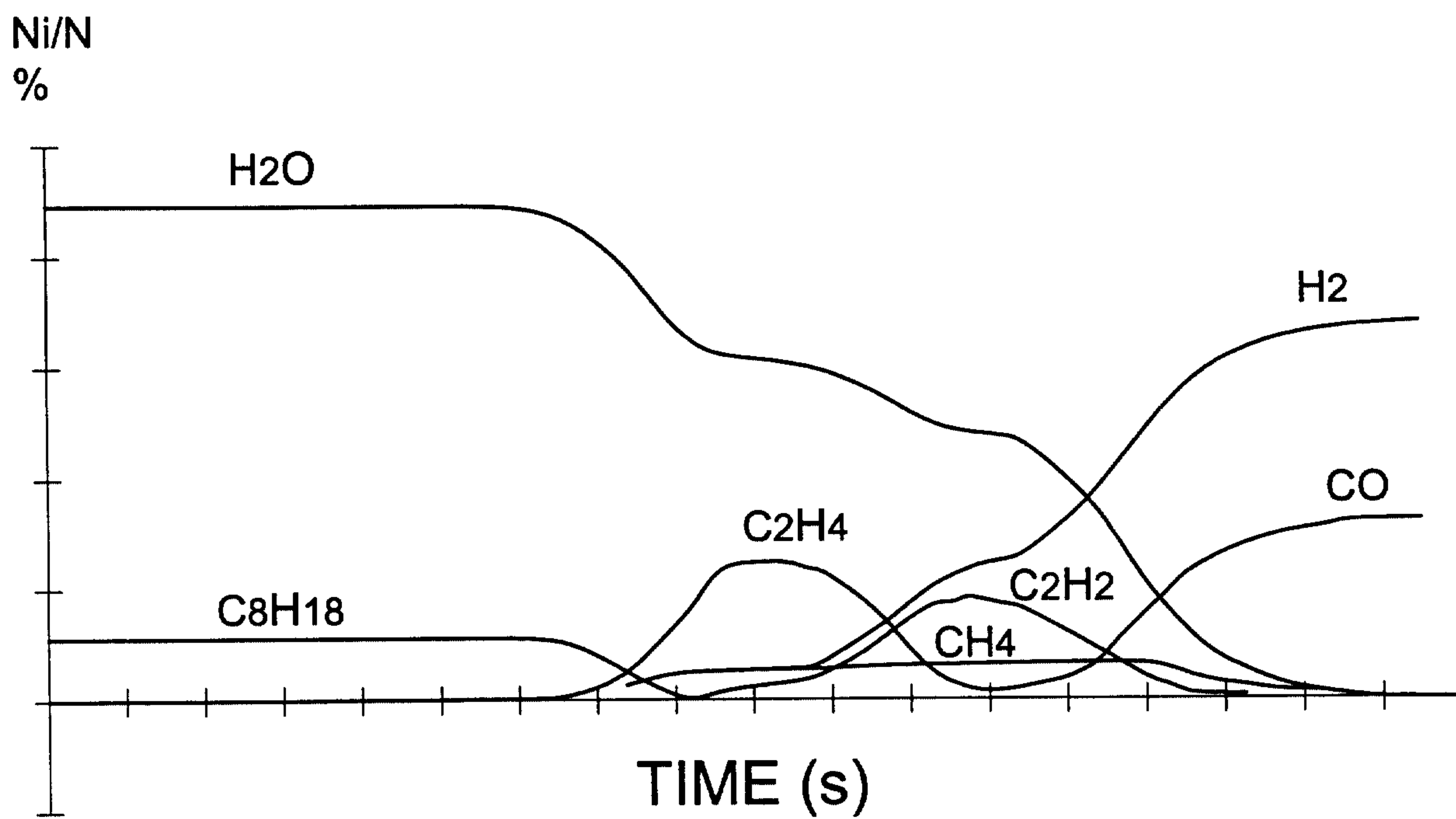


FIG. 1

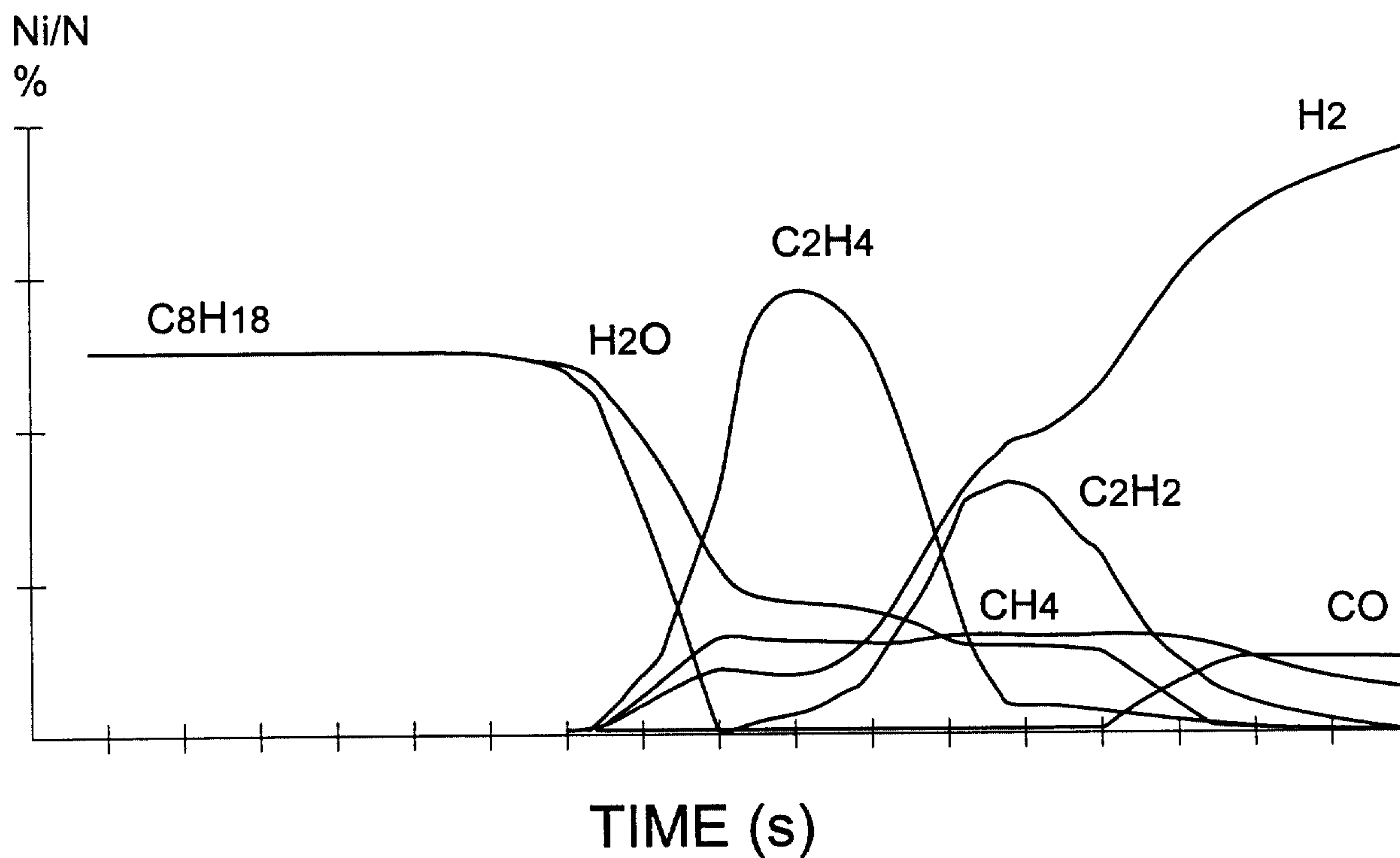


FIG. 2

2/11

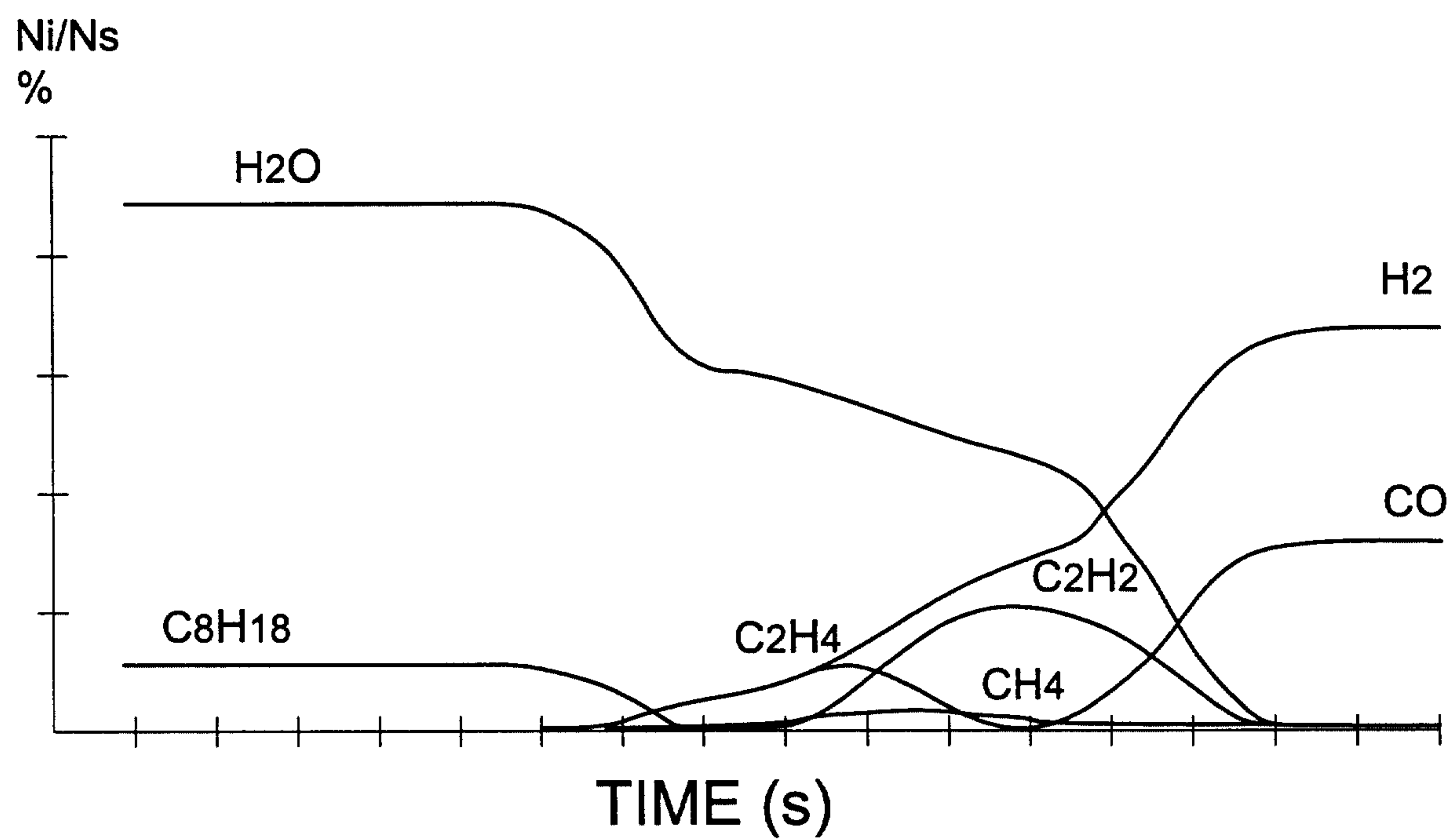


FIG. 3

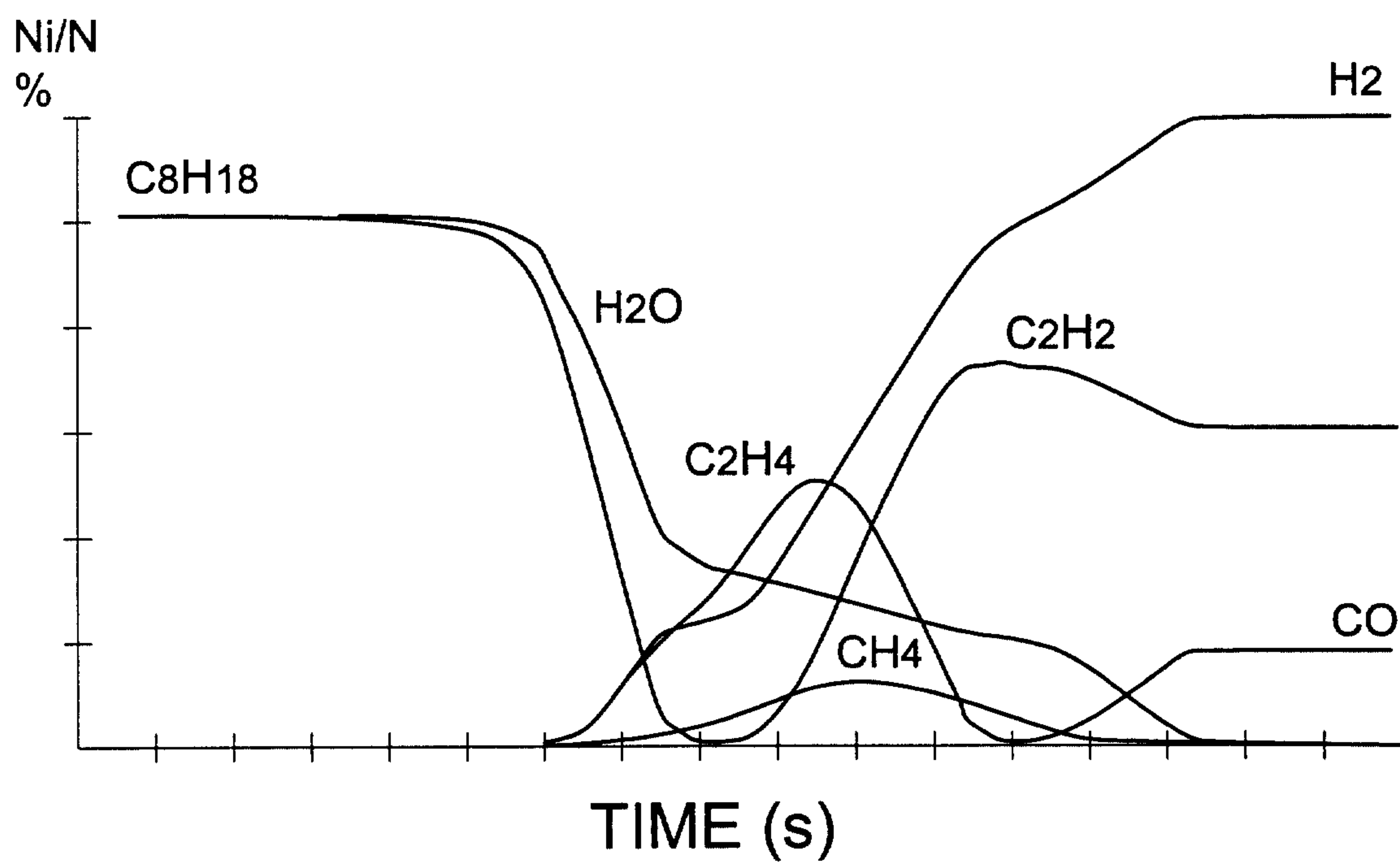


FIG. 4

3/11

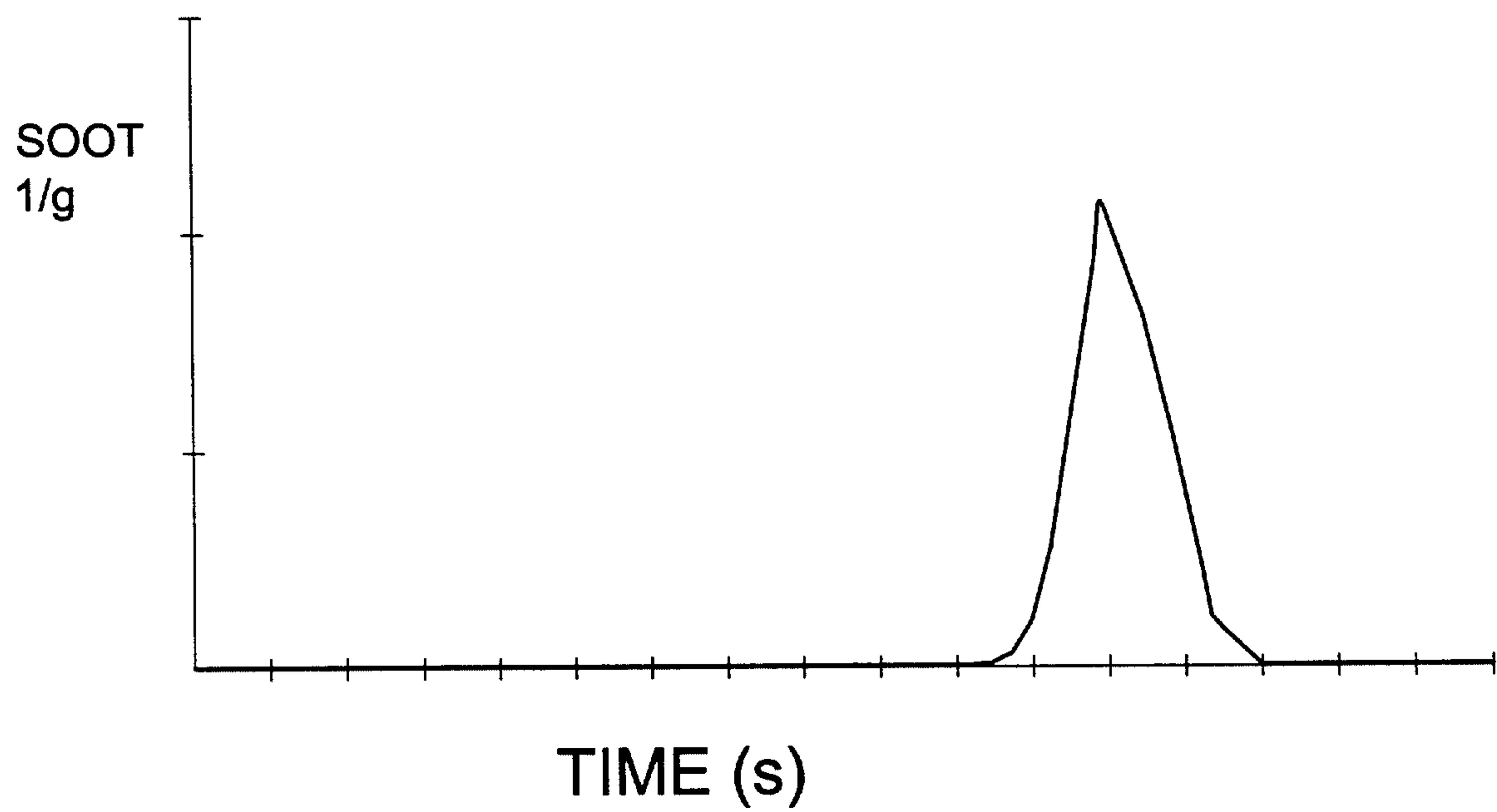


FIG. 5

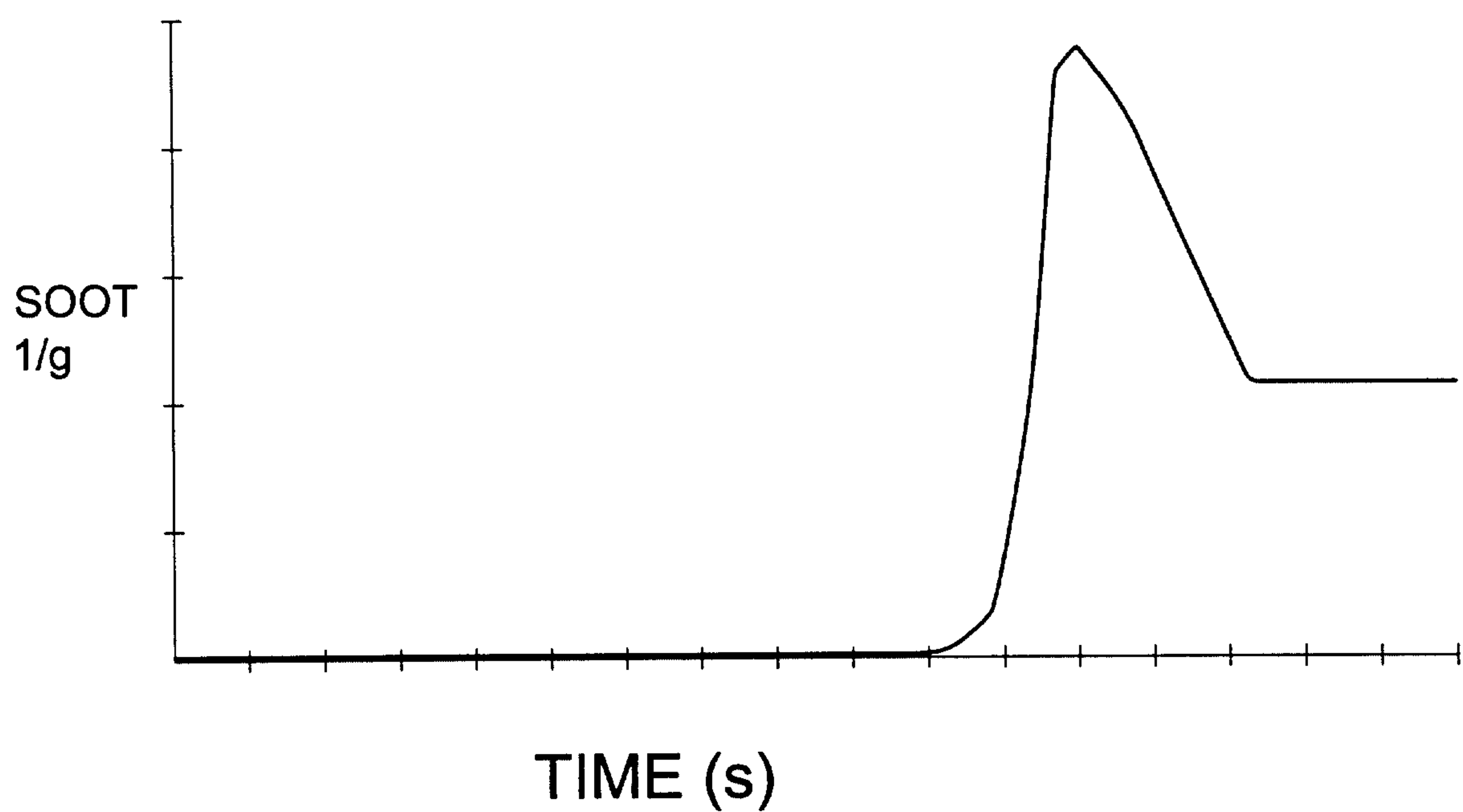


FIG. 6

4/11

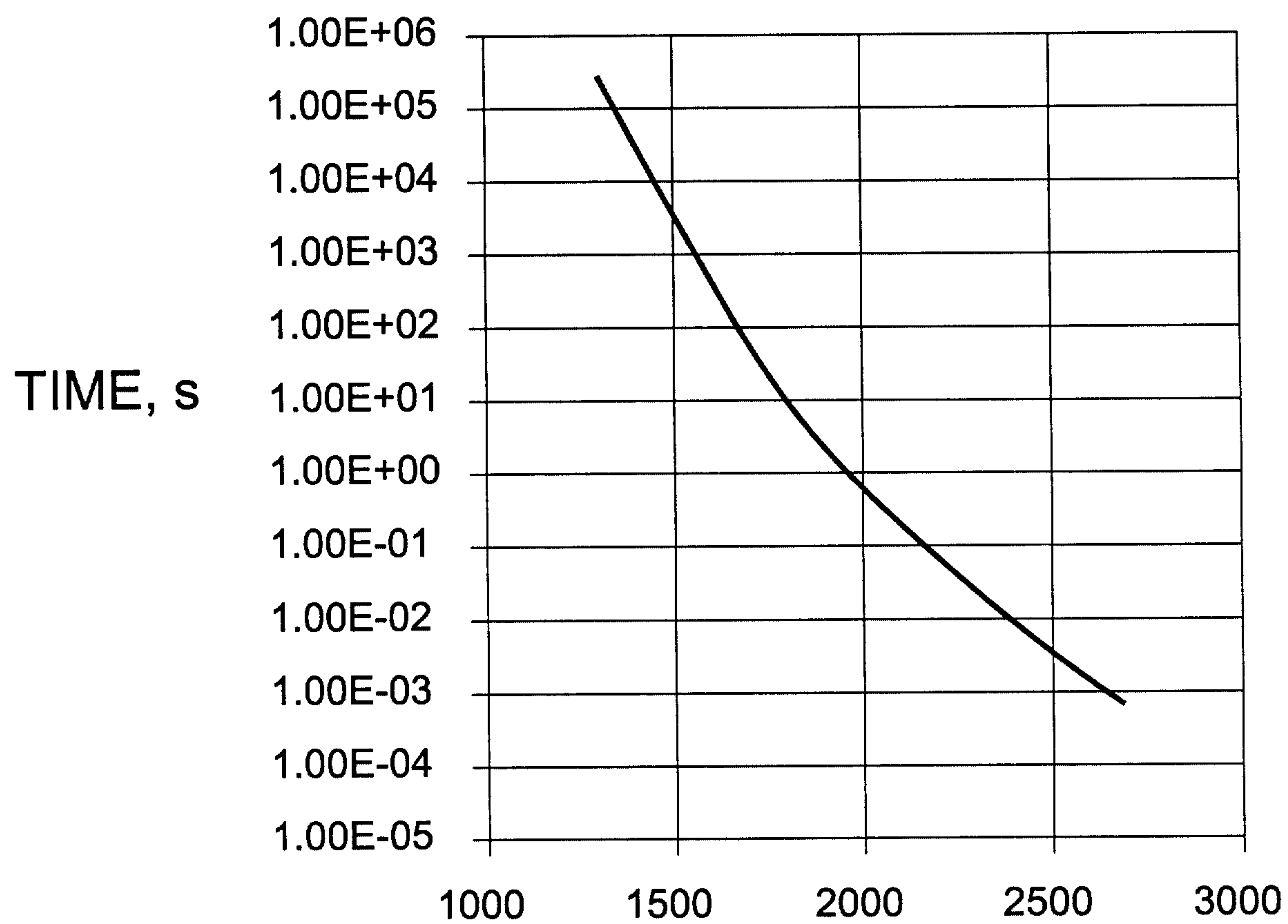
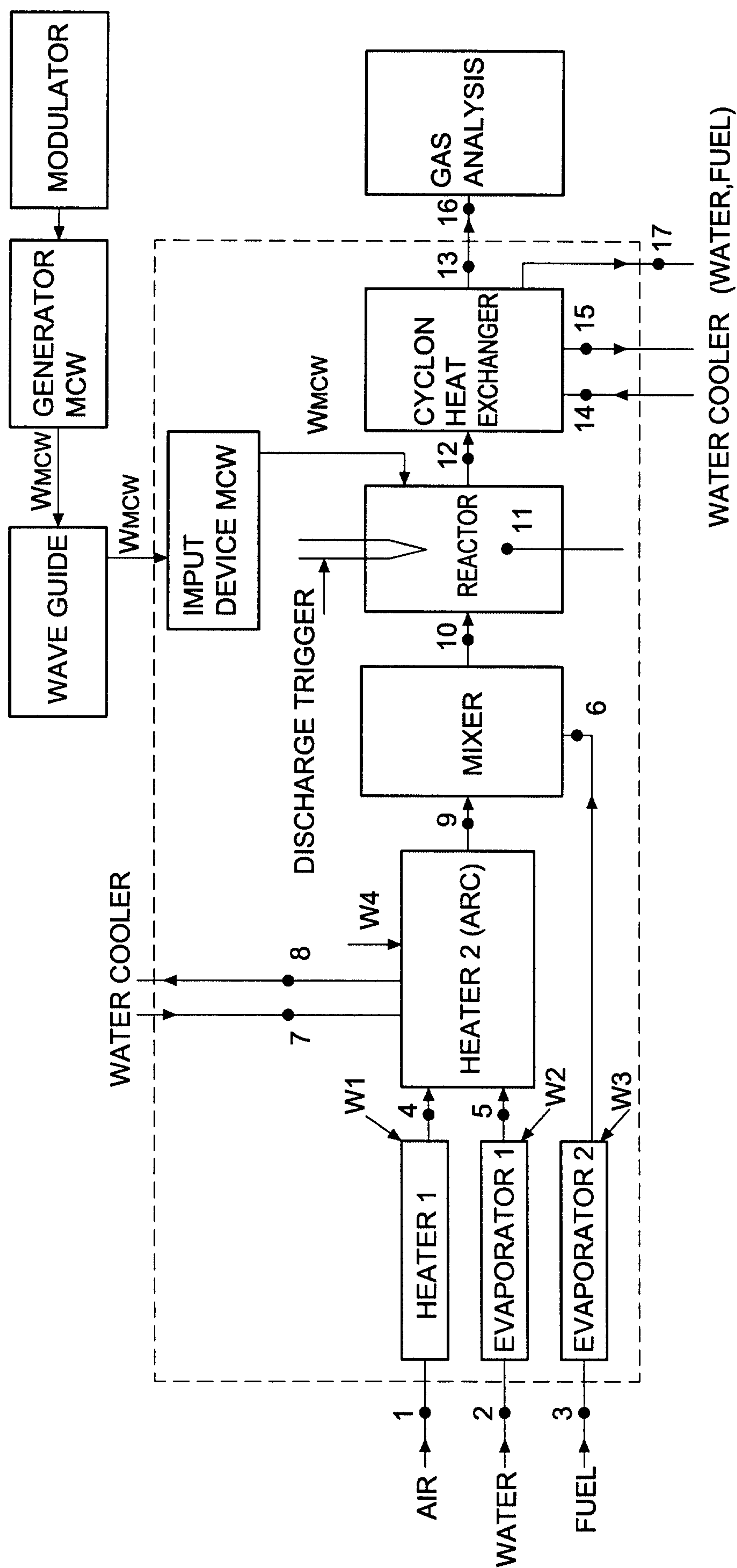


FIG. 7


$$\frac{\infty}{\mathbb{G}} \mathbb{F}$$

6/11

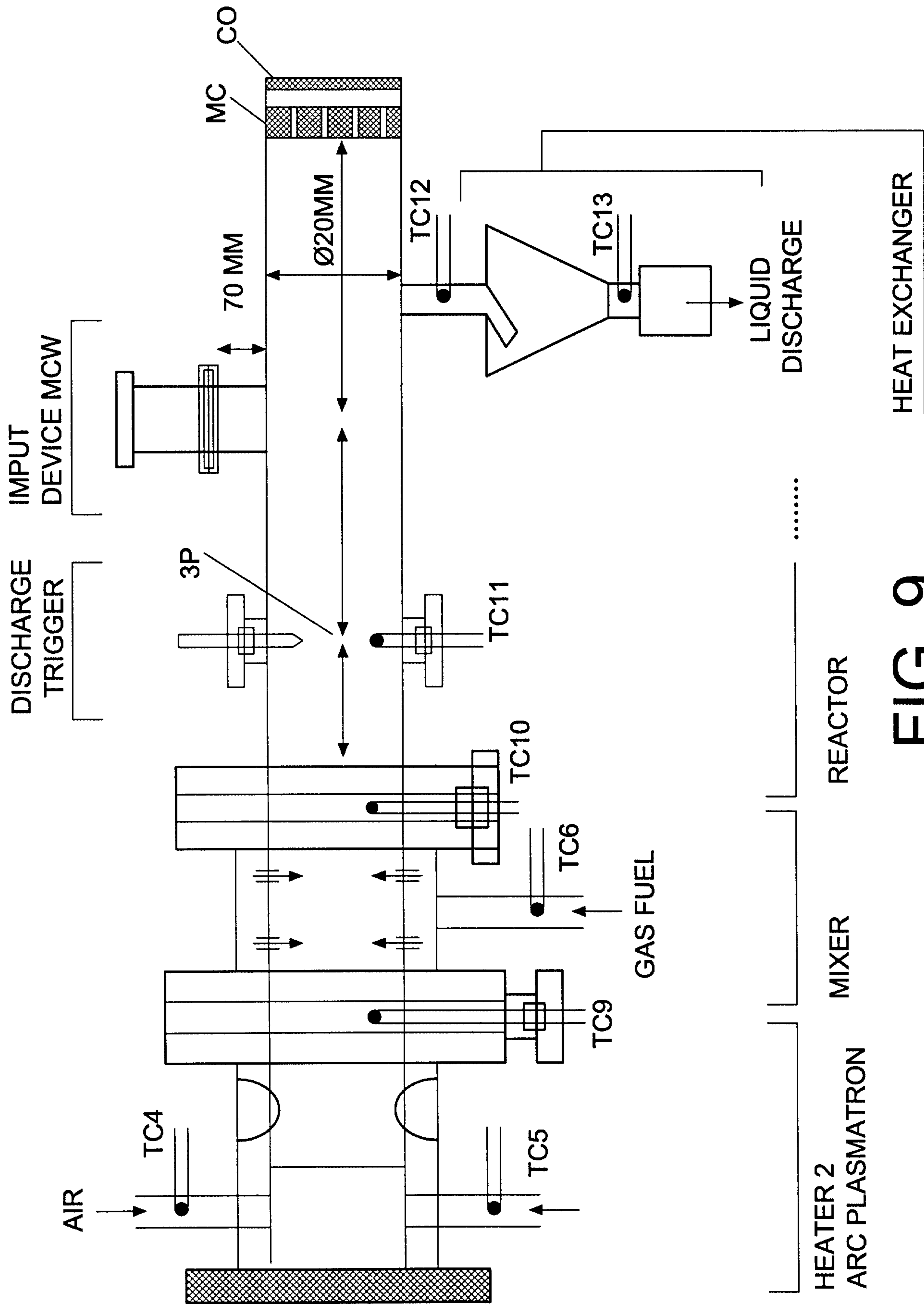


FIG. 9

7/11

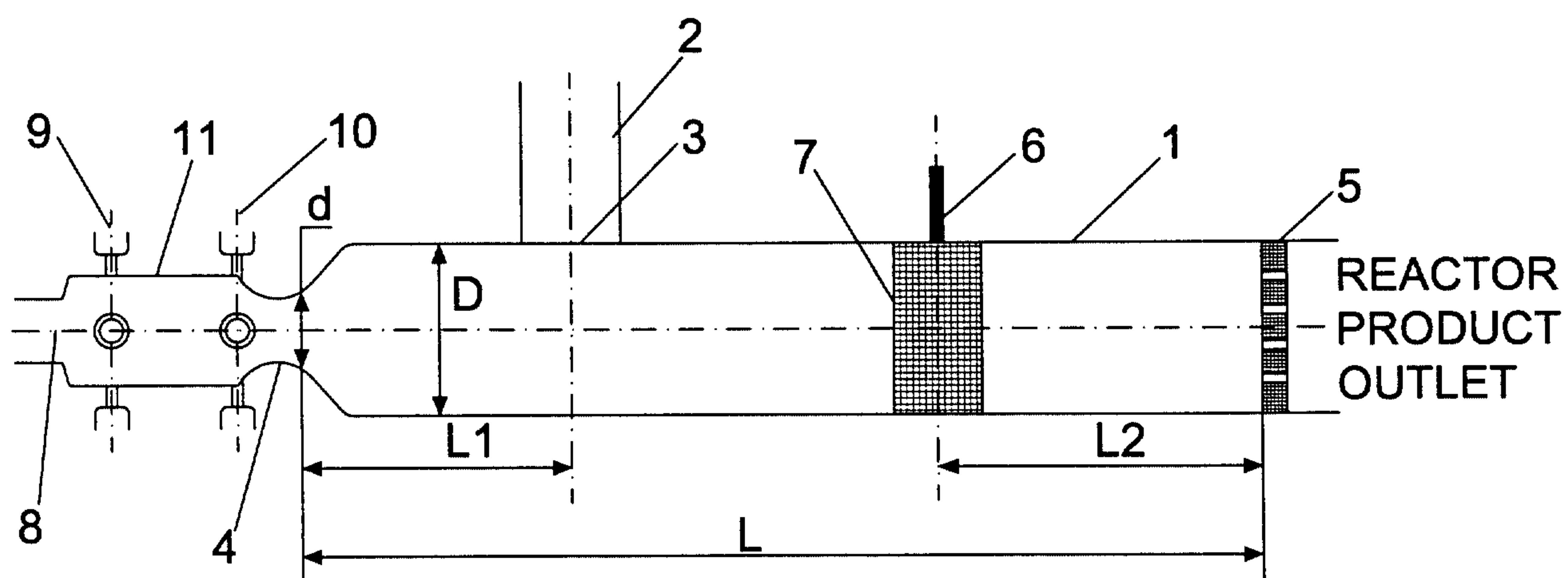


FIG. 10

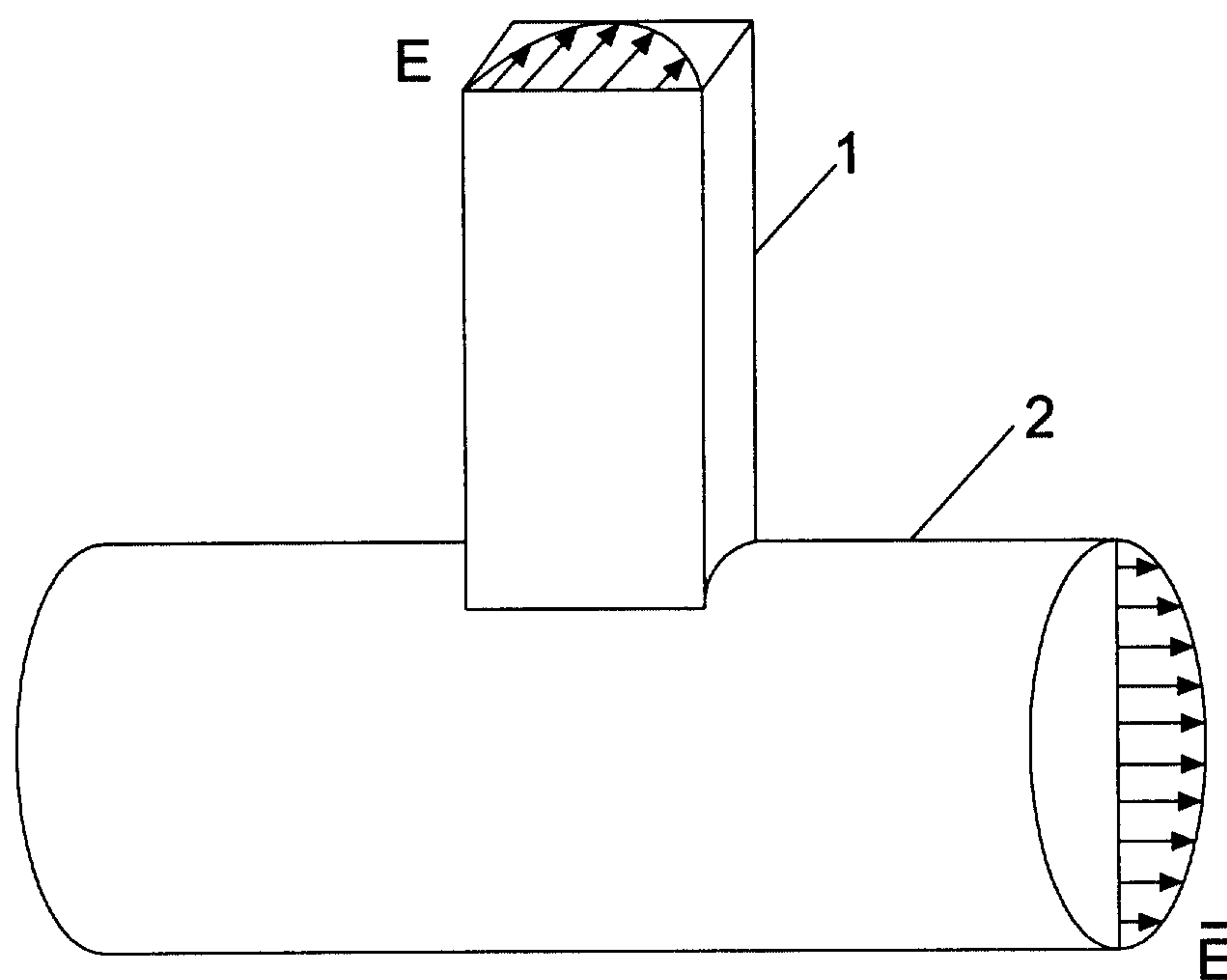


FIG. 11

8/11

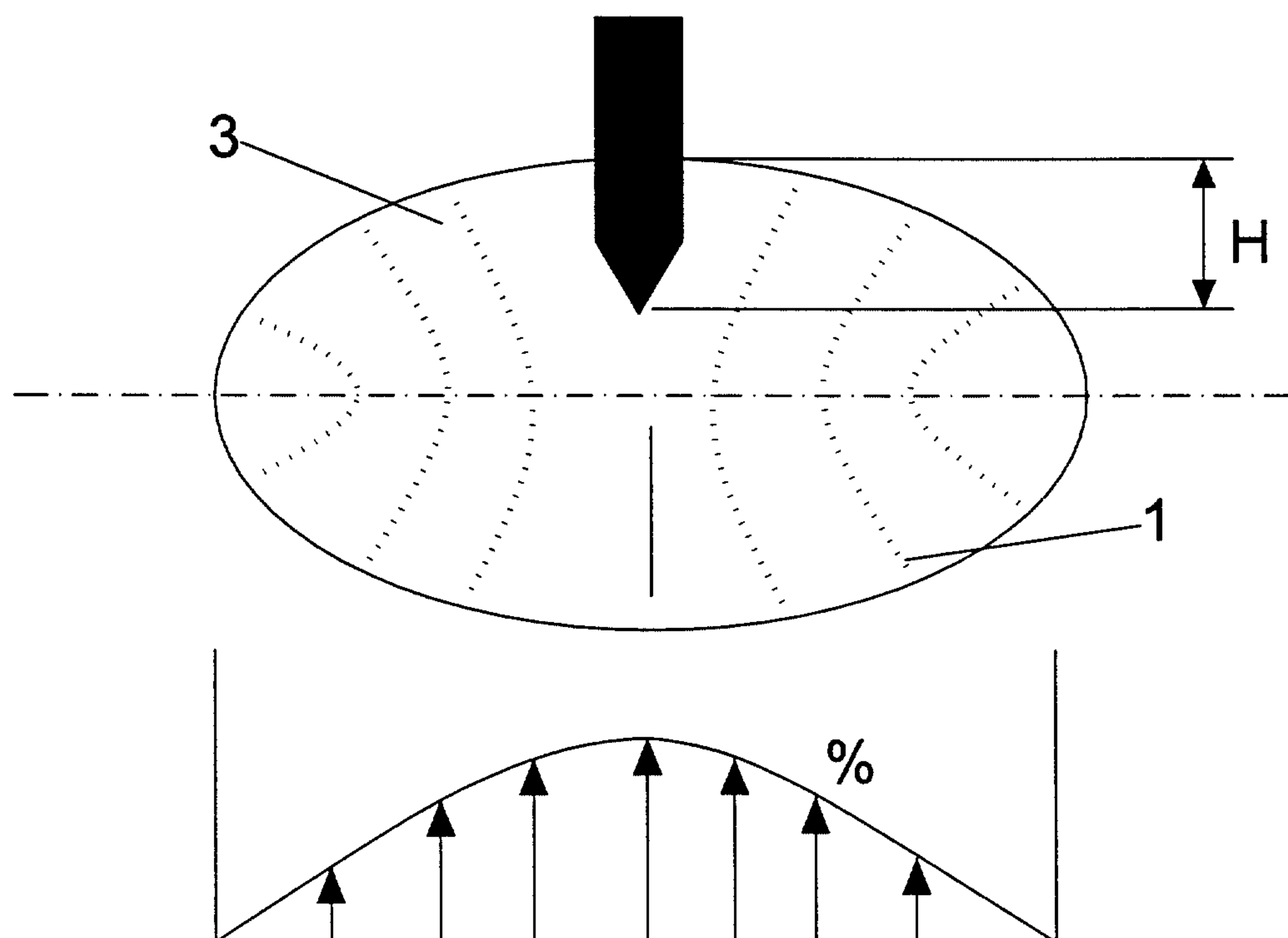


FIG. 12

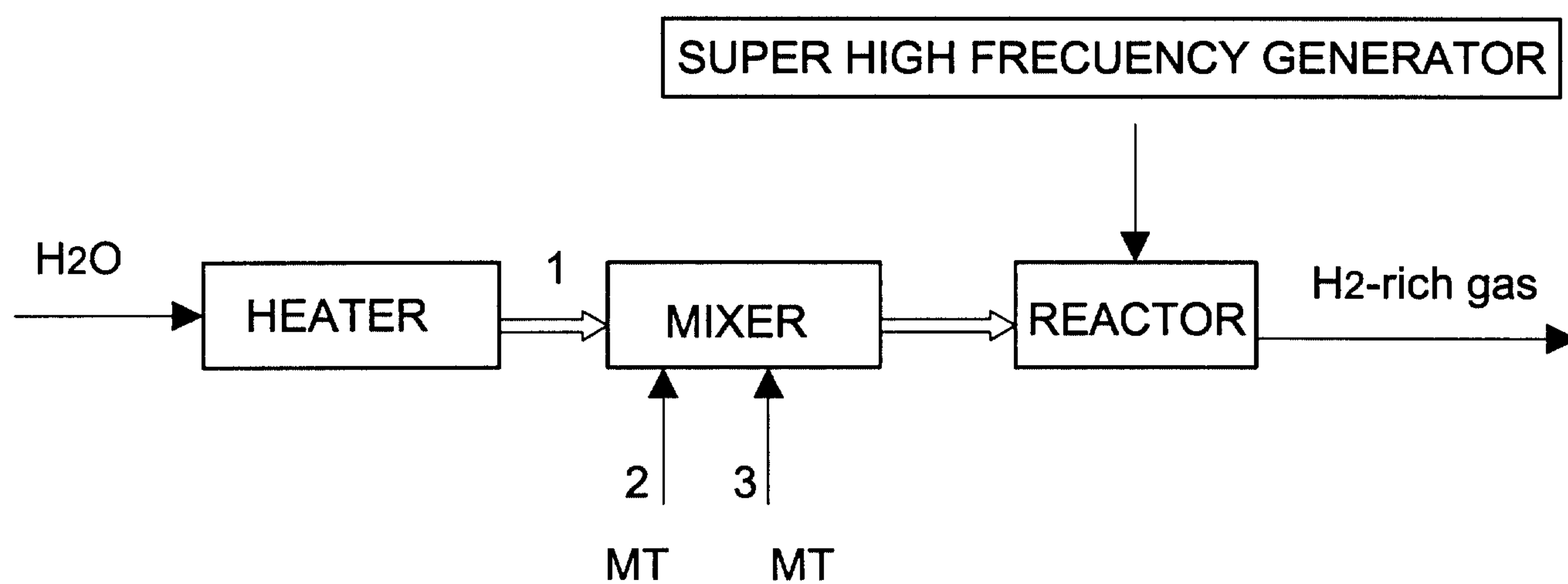


FIG. 13

9/11

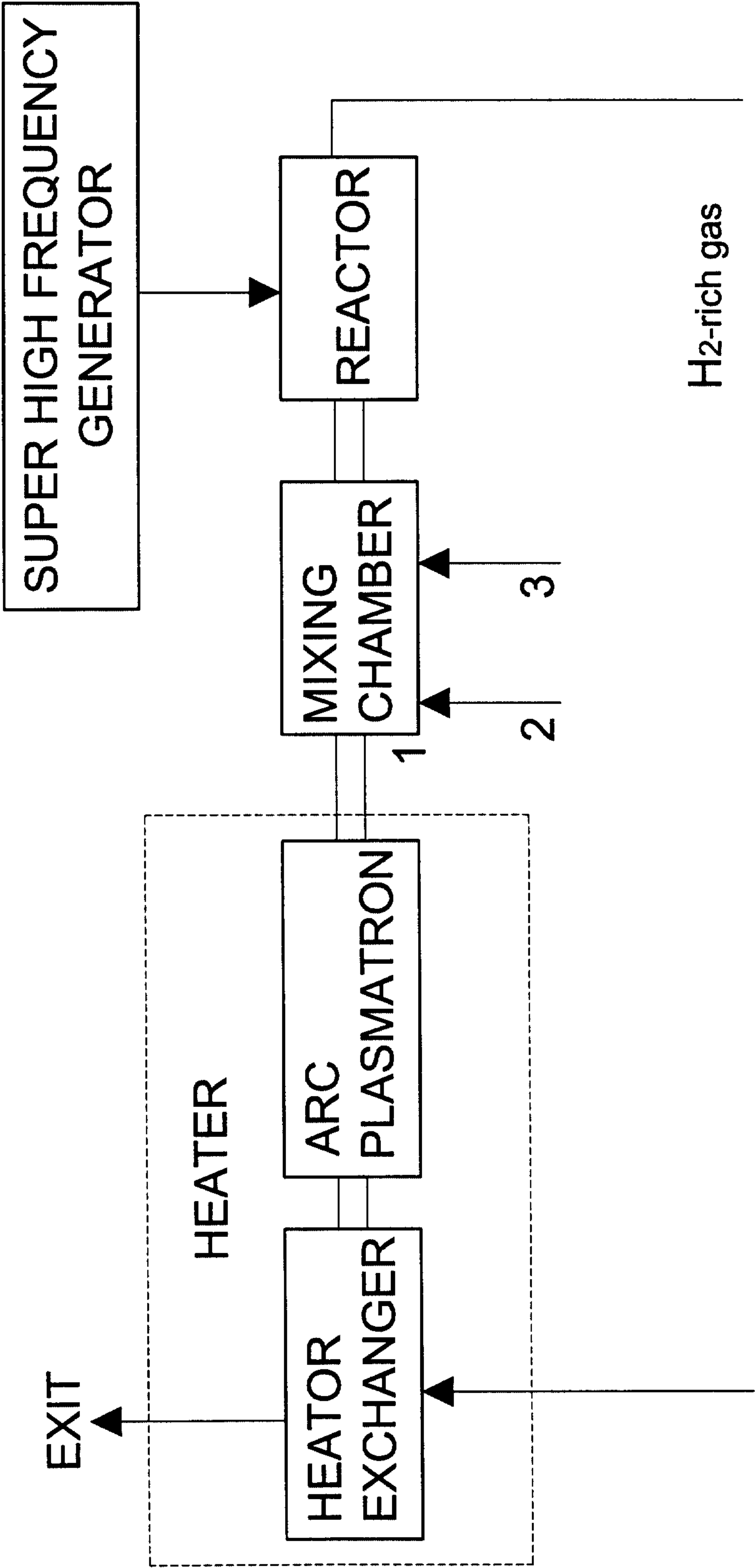


FIG. 14

10/11

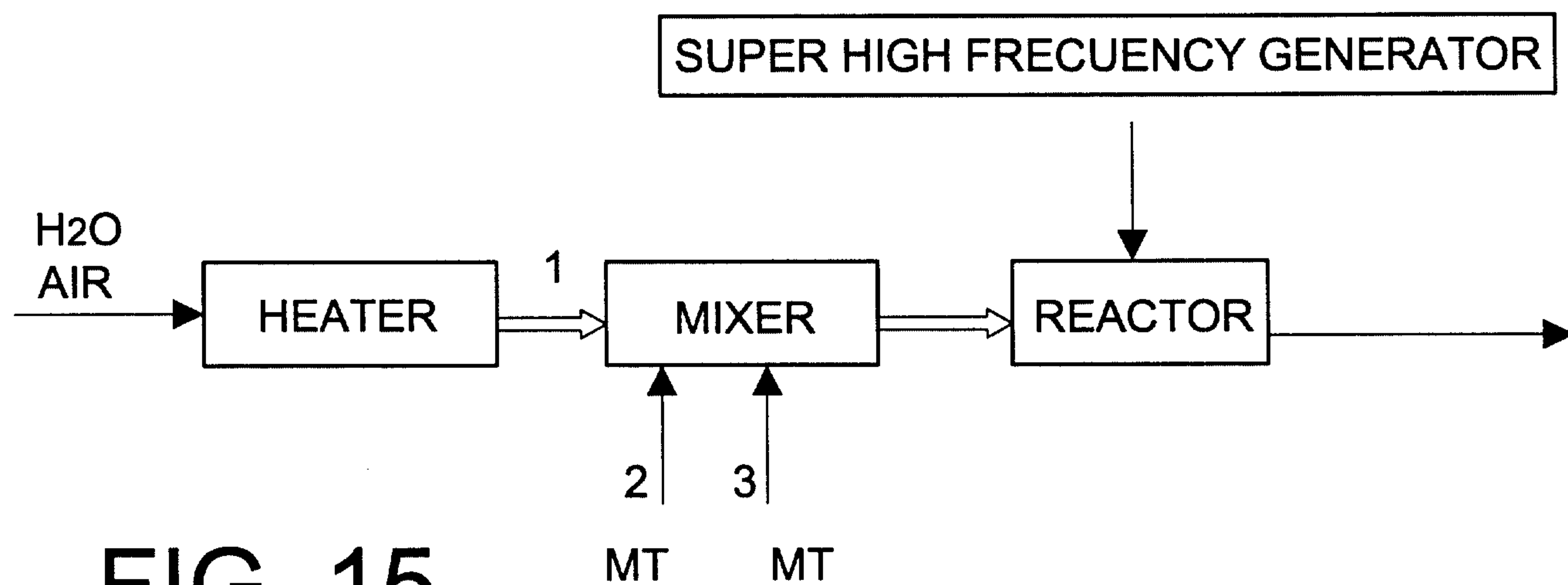


FIG. 15

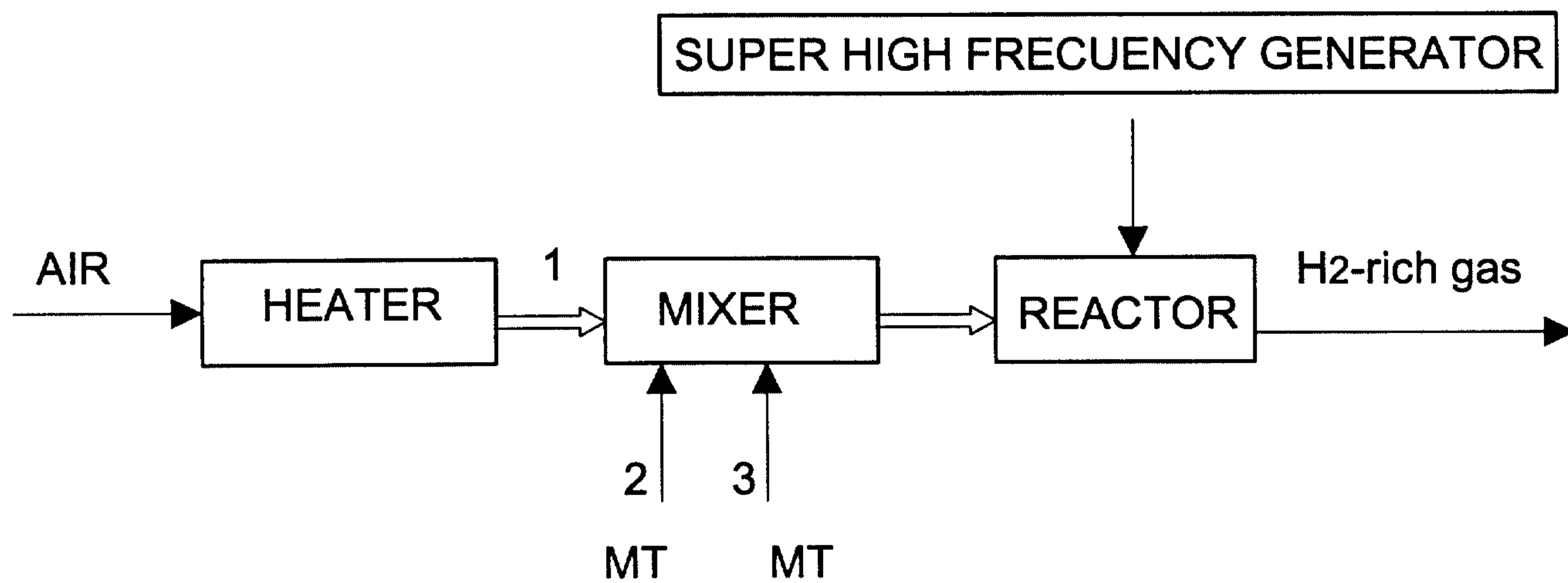


FIG. 16

11/11

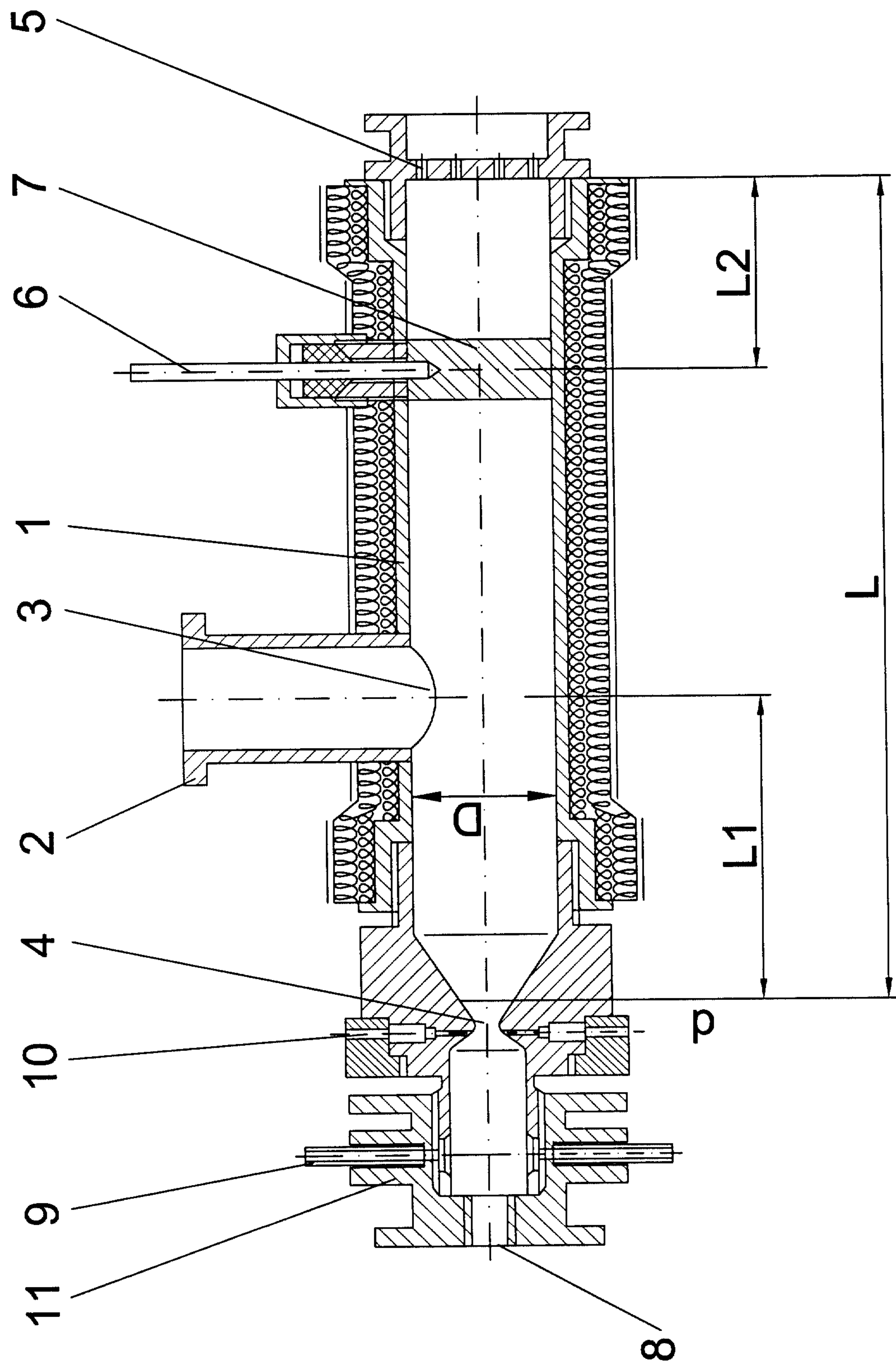


FIG. 17

