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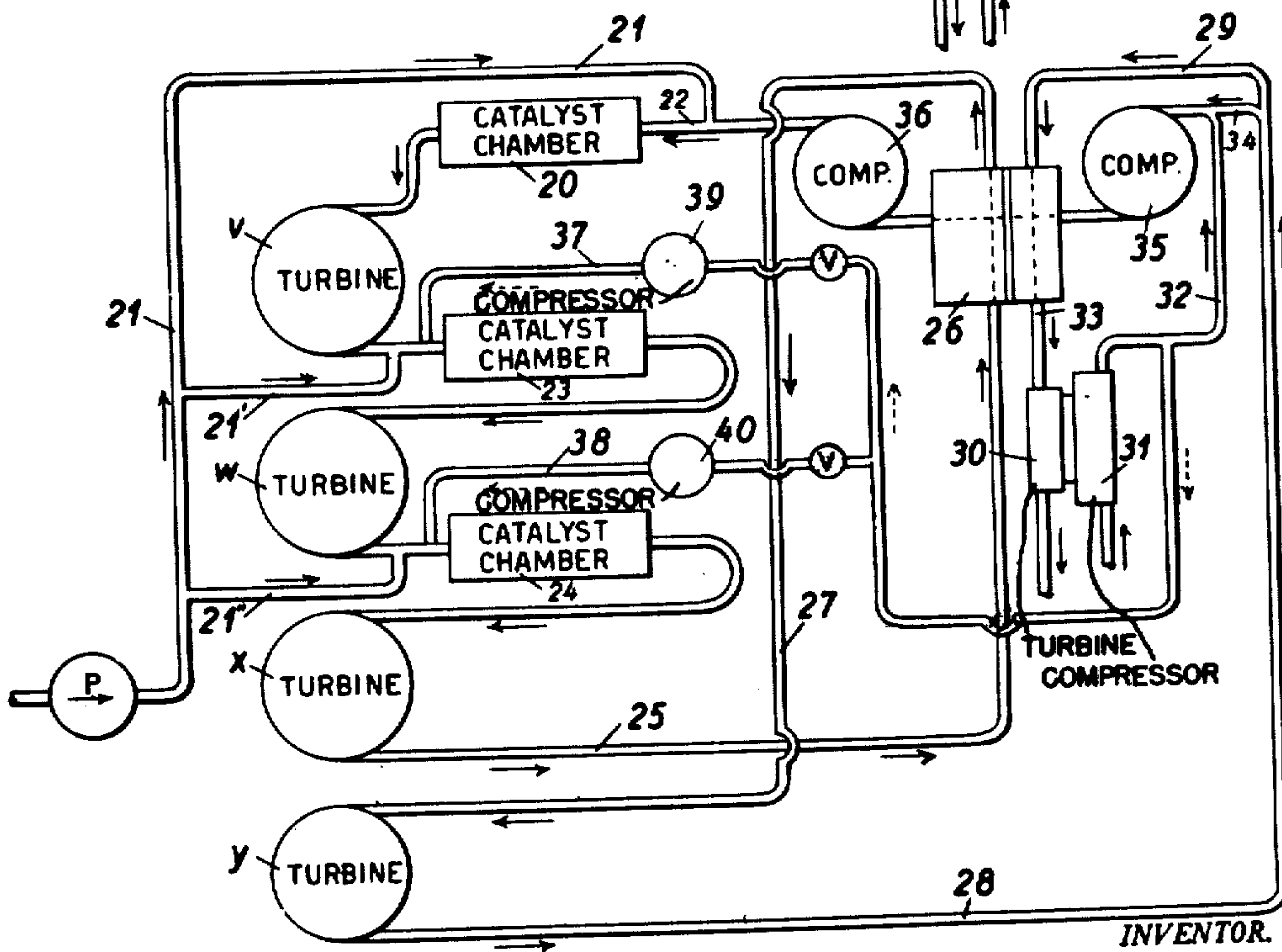
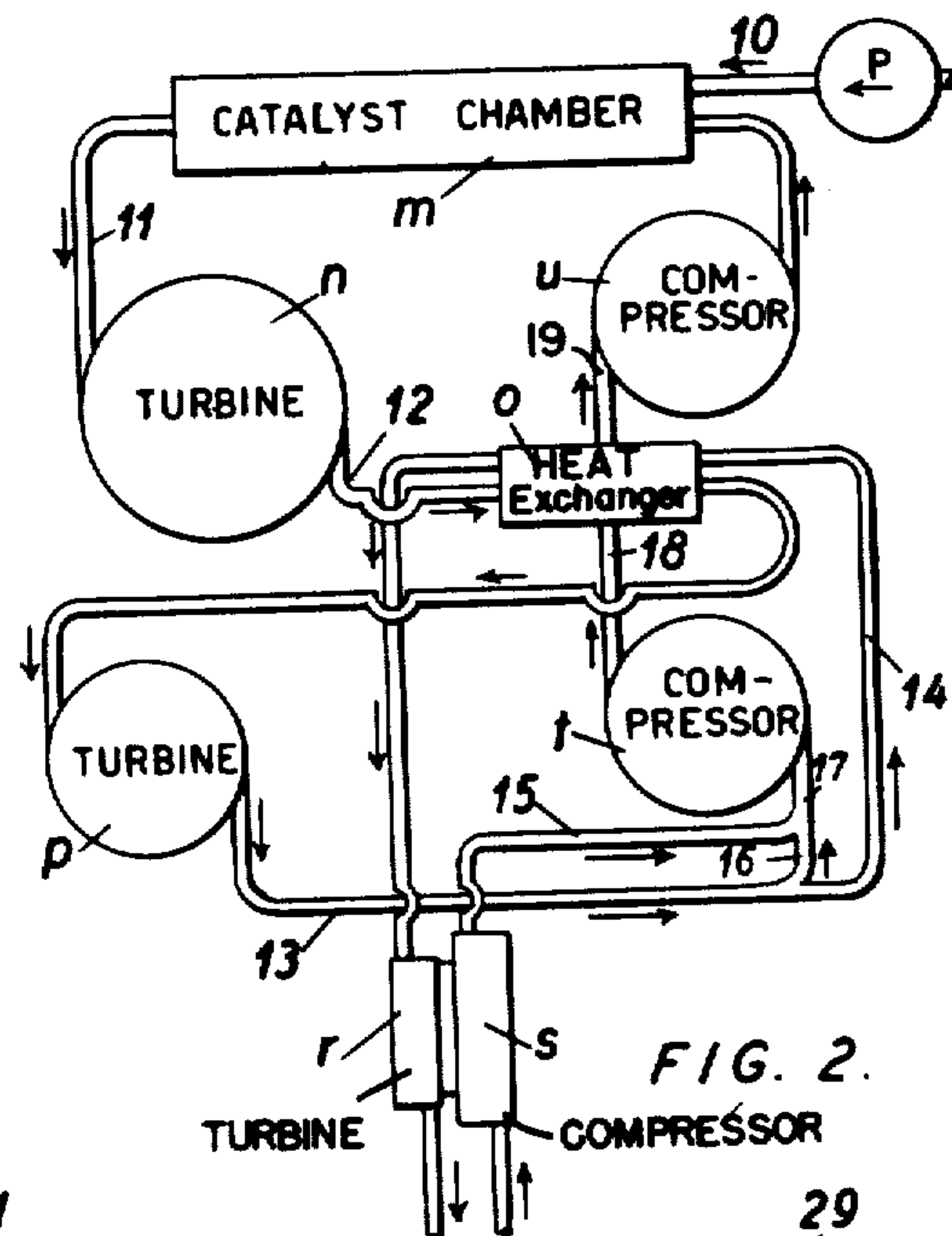
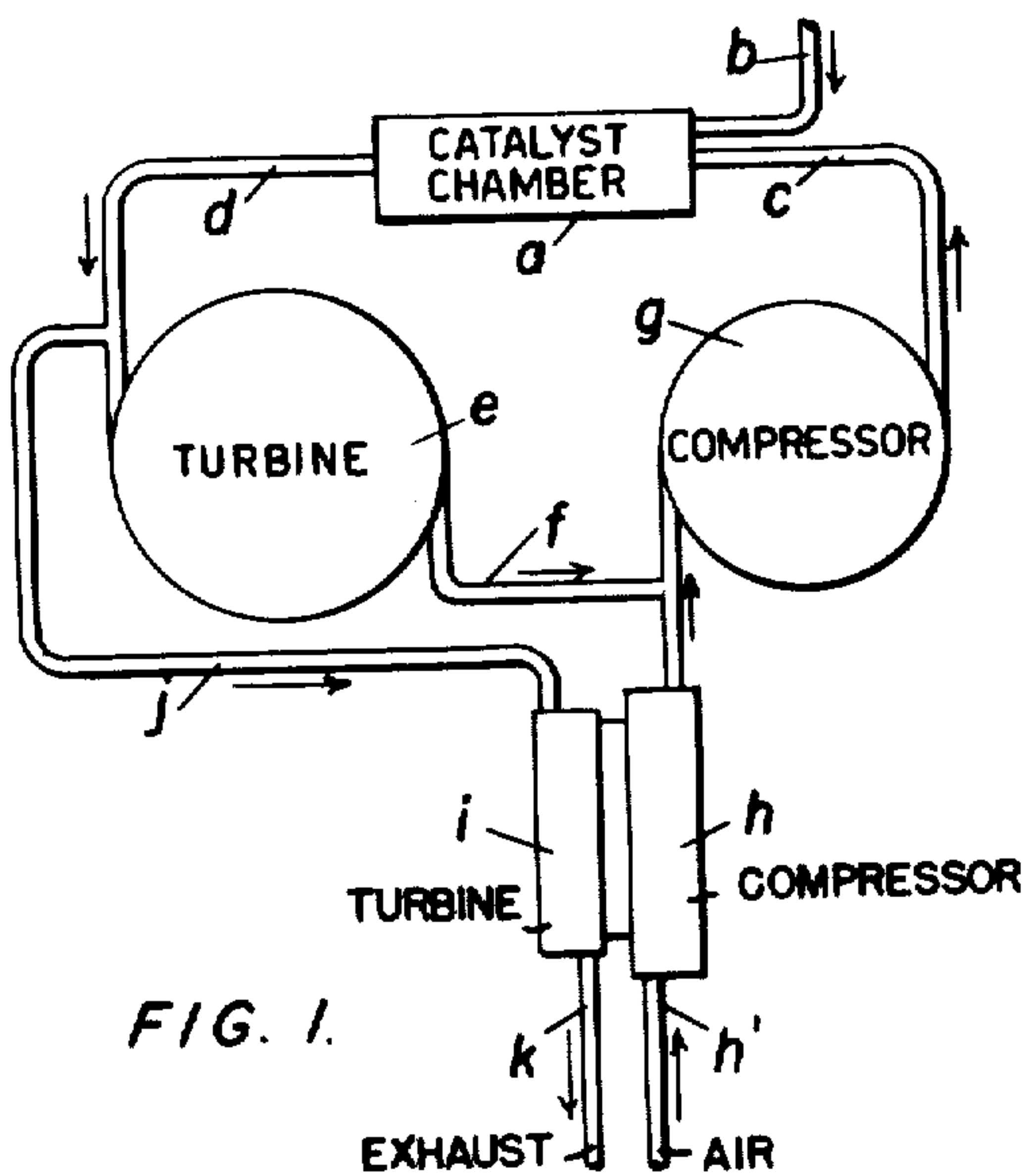
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2,624,172

PROCESS OF GENERATING POWER INVOLVING CATALYTIC OXIDATION

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2 SHEETS—SHEET 1



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## UNITED STATES PATENT OFFICE

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## PROCESS OF GENERATING POWER INVOLVING CATALYTIC OXIDATION

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25 Claims. (Cl. 60—39.04)

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The object of my invention is to provide a radically new system of generating power which, for a given consumption of fuel, will yield a power output greatly in excess of heretofore known power systems. Another object of the invention is to effect the reaction required, that is, fuel oxidation, to produce the motive fluid for the driven engine regardless of the oxygen content in the fuel gases mixture in such manner as to be outside the limits of inflammability of gases and vapors, thereby eliminating the problems of detonation, explosion and combustion. Another object of the invention is to provide a motor fuel which will function in engines of a compression much higher than those that are now operable with existing fuels. Another object of the invention is to avoid the presence of free oxygen in any part of the power plant beyond the locus of fuel oxidation. Another object of the invention is to maintain at a minimum the power required to introduce fuel and atmospheric air into the power plant. The invention may be embodied in many different constructions. By way of illustration I have in the accompanying drawings (Figs. 1, 2, 3 and 4) diagrammed four different power plants, all embodying my invention and all effective to secure the main advantages thereof.

A simplified embodiment of the invention is shown in Fig. 1 in which *a* is the chamber containing the oxidizing catalyst; *b* the line for supplying fuel, which may be any hydrocarbon fuel, to the catalyst chamber; *c* the line for admission to the chamber *a* of recirculated exhaust motive fluid as hereinafter explained; *d* the line conveying the products of oxidation (the motive fluid) to the driven engine, which is shown as a turbine *e*; *f* a line for passage of exhaust gases from the turbine to a compressor *g*, which also receives air from a compressor *h* connected with an air supply line *h'*; the compressed fluid from compressor *g* passing through line *c* to the catalyst chamber. A part of the motive fluid in line *d* is bypassed through line *j* to a turbine *i*, which drives the compressor *h*. *k* is the exhaust line from the turbine *i* to the atmosphere.

In the catalyst chamber the fuel and oxygen (the latter admitted to the chamber *a* mixed with recirculated exhaust motive fluid) react and the latent energy is transformed into available energy. The products CO<sub>2</sub>, H<sub>2</sub>O, N, leaving the catalyst chamber *a* through line *d* may be at a temperature of (say) 600° C. and at a pressure of (say) 12 atmospheres. The part of these products directed through line *j* to the turbine *i* is calculated to compress fresh air in compressor *h*

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to a pressure equal to that of the exhaust from the turbine *e*, or (say) 3 atmospheres. The exhaust gases from the turbine *e* at a temperature of (say) 300° C. and the air from the compressor *h* at a temperature (say) of 180° C. are compressed in compressor *g*, say to 12 atmospheres, sufficient to give the fluid flowing through line *c* to the catalytic chamber a temperature of (say) 420° C. The catalytic reaction in the catalytic chamber raises the temperature of the outflowing motive fluid to (say) 600° C. The assumed pressures and temperatures above specified are merely illustrative and may be widely departed from. Thus, the oxidation temperature in the catalyst chamber will vary with the catalyst used and is permissibly variable with any given catalyst.

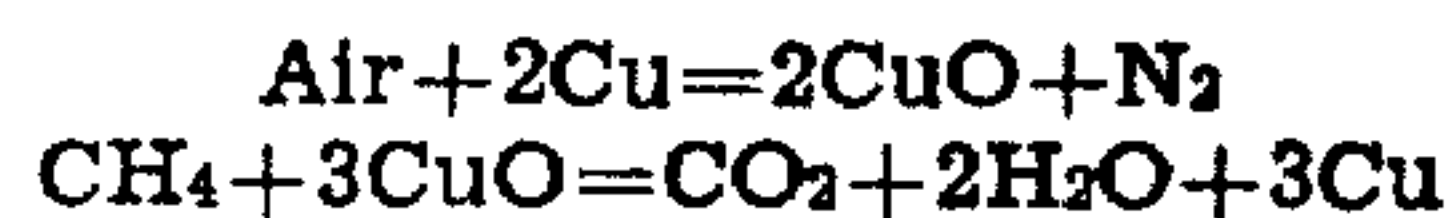
It will be understood from the above description that the catalyst is both a reducing and oxidizing catalyst. An oxidizing catalyst causes an element or compound to combine with oxygen. A catalyst which removes oxygen is a reducing catalyst. A catalyst which gives up its oxygen is in a state of reduction. Let it be assumed that copper is the selected catalyst. The following equations illustrate how the catalyst is reduced while giving up oxygen to yield the products CO<sub>2</sub> and H<sub>2</sub>O:



The following equation explains the removal by the catalyst of the oxygen from the air and from the oxidized products, not expended in power generation, entering the catalyst chamber:



It will thus be understood that reliance is had both on compressed air and the catalyst to supply the required oxygen; that is, the compressed air furnishes molecular oxygen to the catalyst, which in turn furnishes atomic or mono molecular oxygen to the fuel. The following simplified equation will clarify the above statement:



The preceding applies to the well known oxidation catalysts such as platinum, silver, copper, etc., which give unstable oxides in atmospheres and at temperatures contemplated in the invention.

It should perhaps also be explained that in a gas turbine the heat energy of the gases is, through expansion, first changed into kinetic



energy and this in turn to work by impulses produced by gas jets upon the periphery of a revolving wheel. During the expansion the gases give up heat, which produces the work, and consequently this amount of energy is "expended energy." Whatever heat is left in the expanded gases leaving the turbine is what accurately may be called "unexpended energy." This explanation is made in order that there may be no doubt of the meaning of the expressions, occurring hereinafter, "unexpended energy of the products of combustion" and "oxidized products whose energy is not expended in power generation."

From the above description it will be understood that important features of the invention are:

(1) The catalytic oxidation of fuels to  $\text{CO}_2$  and  $\text{H}_2\text{O}$ ; the removal of heat from these products of oxidation to produce the energy required to drive the turbine; (2) the recirculation of the oxidized products (as hereinbefore described, the recirculation of the exhaust fluids from the turbine) to the catalyst to control its temperature and particularly to maintain it at the temperature at which it remains active; (3) the recirculation being in such proportion that the mixture will be outside the limits of inflammability of gases and vapors under operating conditions.

What is meant by the expression "outside the limits of inflammability of gases" will be understood by those skilled in the art. However, since the maintenance outside these limits of the reaction required to produce the motive fluid is an important and novel feature of my process, a brief explanation, with quotations from well known publications on the art, may be desirable.

An inflammable mixture of gases and vapors, such as air and gasoline vapors, may be diluted with one of its constituents or with other gases until it is no longer inflammable. The limit of inflammability is the border-line composition; a slight change in one direction produces an inflammable mixture, in the other direction a non-inflammable mixture.

There are two limits of inflammability, a lower and a higher, for each pair of so-called combustible gases and supporters of combustion. The lower limit corresponds to the minimum amount of combustible gas capable of conferring inflammability on the mixture and the upper limit to the maximum amount of combustible gas capable of conferring inflammability on the mixture. For example, for air-gasoline mixtures these limits under atmospheric conditions are 1.3 and 6 per cent. gasoline vapors, respectively. (See Lange's Handbook of Chemistry, "Properties of Inflammable Liquid Gases," page 43, under Gasoline.) Mixtures within these limits liberate enough energy on combustion of any one layer to ignite the neighboring layer of unburned gas and are therefore capable of self-propagation of flame or explosion; others are not. These limits have been obtained through experimental determinations which have shown that below 1.3 per cent. and above 6 per cent. of gasoline vapors by volume in an air-gasoline mixture (e. g. 1 gasoline, 100 air or 7 gasoline, 100 air) there cannot be inflammability nor explosion under atmospheric conditions of temperature and pressure.

In my process the composition of the gas and vapor mixture is not so simple, and conditions of temperature and pressure deviate widely from atmospheric conditions. In determining the limits of inflammability in the mixture existing in my process there must be considered the effect of

the dilution of combustible gas in inert gas (nitrogen) and also  $\text{H}_2\text{O}$  and  $\text{CO}_2$  and the effect of superatmospheric pressure and temperature. A typical example of the composition of the gas and vapor mixture in my process is as follows:

Nitrogen	Percent	76.0	Inert and diluent gases
$\text{H}_2\text{O}$ (steam)	do	9.5	
$\text{CO}_2$	do	8.8	
Oxygen	do	5.3	
Hydrocarbon vapors	do	0.4	

If, for example, with such a mixture, the pressure of the mixture of gas and vapor before entering the catalyst is raised to (say) 30 atmospheres, while the temperature is kept within the range (say) 260 to 320° C., the process operates outside the limits of inflammability of gases and vapors. This low temperature range is not only well below the range of inflammability of gases and vapors, but is well within the range that the catalyst starts to oxidize liquid fuels. In order to produce maximum energy the gases entering the catalytic zone should be maintained at the lowest permissible temperature within the range within which the catalyst starts, and continues to carry, the reaction; the positive energy liberated depending upon the difference between the temperature of the gases leaving the catalytic zone and the inlet temperature to that zone. With the high compression specified, the temperature specified may be maintained by cooling between or after the compression steps, as hereinafter described. It is possible, from the literature of the art referred to below, to calculate the limits of inflammability in the said mixture.

As to the effect of dilution of combustible gas in inert gas, see pp. 7, 8, 9, of the Bureau of Mines Bulletin 279 and also Technical Paper 450 by G. W. Jones published by Bureau of Mines in 1929 under the title "Inflammability of Mixed Gases"; also the paragraphs of Bureau of Mines Bulletin 279,

As to the effect of increase of pressure (which, dependent on the mixture, may widen, or narrow, or not substantially change, the limits of inflammability) see:

Bureau of Mines Bulletin 279, Figure 14, "Effect of Pressure Above Normal on Limits of Methane in Air."

Berl, E., and Werner, G. (The Limits of Combustibility of Inflammable Gas- and Vapor-Air Mixtures at Higher Pressures) Ztschr. angew. Chem., vol. 40, 1927, pp. 245-250.

Bone, W. A., Newitt, D. M., and Smith, C. M. Gaseous Combustion at High Pressures. IX. The Influence of Pressure Upon the "Explosion Limits" of Inflammable Gas-Air, etc., Mixtures. Proc. Roy. Soc., vol A117, 1928, pp. 553-576.

As to the effect of increase of temperature (which widens the limits of inflammability, both reducing the minimum limit and increasing the maximum limit) see: White, A. G. Limits for the Propagation of Flame in Inflammable Gas-Air Mixtures. III. The Effect of Temperature on the Limits. Jour. Chem. Soc., vol. 127, 1925, pp. 672-684.

I have not, however, depended exclusively upon the literature of the art to calculate the limits of inflammability in the mixture of gas and vapor characterizing my process. That my process operates outside such limits has been demonstrated by a great number of experiments and tests.

The embodiment of the invention shown in Fig. 1 does not embody certain highly desirable



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features of my invention, as will be apparent from the description of other embodiments, but it illustrates one of the simplest embodiments of the invention and discloses all features thereof that are necessary to operativeness.

Another embodiment of the invention is shown in Fig. 2, wherein the recirculating medium is subjected to two successive compressions, between which it is cooled, as hereinafter described, by heat exchange with a less advanced part of the recirculating medium. In this drawing *m* is the catalyst chamber; 10 the fuel feed line to chamber *m*; 11 the line for feeding from the catalyst chamber the products of oxidation CO<sub>2</sub>, H<sub>2</sub>O, N—the motive fluid—to a first stage turbine *n* (say) under a pressure of 50 atmospheres at a temperature of 680° C.; 12 a line for conveying exhaust gases from turbine *n* through heat exchanger *o* to a second stage turbine *p* under a pressure of (say) 9 atmospheres, the temperature of the gases leaving turbine *n* being (say) 280° C. and being raised in heat exchanger *o* to 400° C.; 13 a line receiving exhaust gases from turbine *p* at a pressure of (say) 3 atmospheres and at a temperature of (say) 150° C. One fraction of these gases flows by line 14 through heat exchanger *o* to the turbine *r* of a turbo-compressor and exhausts to the atmosphere. The compressor element *s* of the turbo-compressor forces atmospheric air, compressed to a pressure of (say) 3 atmospheres and thereby raised to a temperature of (say) 150° C. through line 15. The exhaust gases from turbine *p* that have not been utilized, as above described, to drive the turbo-compressor, flow from line 13 through line 16 and there unite with air inflowing through line 15, the resultant gaseous mixture flowing through line 17 to a compressor *t*, wherein it is raised in pressure to (say) 25 atmospheres and raised in temperature to (say) 480° C. Thence the flow is through line 18, heat exchanger *o* (wherein the temperature of the gaseous mixture is reduced) and line 19 to a compressor *u*, where the mixture is compressed to (say) 50 atmospheres and again raised in temperature to (say) 480° C., at which temperature and pressure it is admitted to the catalyst chamber *m*.

The embodiment of my invention shown in Fig. 2, like that shown in Fig. 1, represents a simplified embodiment of the invention.

The embodiment of my invention shown in Fig. 3 represents a preferred embodiment of my invention in which, in a multi-stage turbine, catalytic chambers are inserted between stages to superheat the medium coming out of each stage except the last.

From the catalyst chamber 20 (to which fuel is admitted through line 21 and to which recirculated medium, at a pressure of [say] 60 atmospheres and at a temperature of [say] 480° C., is admitted through line 22) the products of oxidation CO<sub>2</sub>, H<sub>2</sub>O, N constituting the motive fluid, at a temperature of 680° C., go to the first stage turbine *v*. The exhaust gases from turbine *v*, at a pressure of (say) 30 atmospheres and at a temperature of (say) 480° C. go to a second catalyst chamber 23, to which fuel is admitted through a branch line 21' from the main fuel line 21 and from which such exhaust gases, at a temperature of 680° C., go to a second stage turbine *w*. The exhaust gases from turbine *w*, at a temperature of (say) 330° C. and at a pressure of (say) 15 atmospheres, go to a third catalyst chamber 24, to which fuel is admitted through another branch line 21'' from the main fuel line 21 and from

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which the exhaust gases, at a temperature of (say) 500° C., go to a third stage turbine *x*; the exhaust wherefrom, at a temperature of (say) 200° C. and at a pressure of (say) 5 atmospheres, flowing through line 25, heat exchanger 26 and line 27 to a fourth stage turbine *y*. The exhaust from turbine *y*, at a temperature of (say) 200° C. and at a pressure of (say) 3 atmospheres, flows through line 28 and thence splits into two streams, one stream going through line 29 and heat exchanger 26 and line 33 to the turbine element 30 of a turbo-compressor and exhausting to the atmosphere, the other stream going through line 34 to a compressor 35. The turbine 30 drives a compressor 31 which compresses atmospheric air to (say) 3 atmospheres, raising its temperature to (say) 150° C., the compressed air going through line 32 to compressor 35, which, as above stated, receives also the exhaust from the fourth stage turbine *y*.

In compressor 35 the recirculating medium to which air has been admitted is compressed to (say) 15 atmospheres, raising the temperature to (say) 480° C., and is discharged therefrom through heat exchanger 26, in which its temperature is reduced to (say) 230° C. Thence the recirculating medium goes to a compressor 36, wherein it is compressed to (say) 60 atmospheres, raising its temperature to (say) 480° C., from which it goes, through line 22, into the first catalyst chamber 20.

In some installations it is more convenient to admit air only to the first catalyst chamber 20. In other installations it may be advisable to admit air to catalyst chamber 23 also, and possibly to both catalyst chambers 23 and 24. Branch air-flow lines 37 and 38 from air-flow line 32 to the catalyst chambers 23 and 24, either to the entrance thereto, as shown, or to any part of such chambers, are therefore provided. These lines, in which are interposed compressors 39 and 40, are usually permissive, but not always necessary. It may be preferred to supply air to only the first catalyst chamber 20 if the amount of oxygen thus supplied is outside the limits of inflammability in the operating condition.

The insertion of catalytic chambers between stages to superheat the medium coming out of each stage except the last has several advantages. One is that the fuel is supplied in proper proportion to each catalytic chamber. Another and more important advantage is that there is less circulating medium for the same catalytic temperature difference between inlet and outlet of fluids. Differences between inlet and outlet temperatures and ratio of recirculation to fresh air can vary over wide ranges.

While Fig. 3 shows an embodiment of the invention that is preferred for general use, the embodiment shown in Fig. 4 may be preferred for exceptional uses and has some special advantages. In this embodiment there are four catalyst chambers, 50, 60, 70 and 80. One chamber 50 at high pressure is receiving recirculated fluid and fuel and discharging H<sub>2</sub>O, CO<sub>2</sub> to a high pressure turbine 51. The next chamber 60 is receiving nothing but is releasing H<sub>2</sub>O, CO<sub>2</sub> through a mono-detender 55 to a low pressure turbine 52, the gases expanding in chamber 60 to a medium pressure. The next chamber 70 is receiving fresh air through a blower, the gases expanding rapidly to atmospheric pressure and discharging to the exhaust. The last chamber 80 is in a period of repressuring from atmospheric pressure to high pressure and is receiving



H<sub>2</sub>O, CO<sub>2</sub> from a second stage compressor at a constant rate through a controlled inlet 58. There is no discharge from chamber 80.

It may be advisable to explain that a monodetender is a two-stage regulator that effects pressure reduction in two stages. It maintains steady pressure and automatically compensates for drop in pressure as the gas or vapor is consumed. Since it is a well-known commercial device, its detailed construction requires no illustration and its specific operation requires no description.

The admission to, and discharge from, the several catalyst chambers is controlled by the valves shown in the drawing, Fig. 4. To avoid applying a multiplicity of numerals to the twenty-eight valves shown, they are all marked 58. The valves which are closed in the cycle just described are denoted by circles enclosing diametric lines, while valves that are open are denoted by open circles. The several catalytic chambers function as above described, namely: the first, 50, on stream for catalytic reduction and discharging motive fluid to the high pressure turbine, the second, 60, discharging motive fluid, with falling pressure, to the low pressure turbine; the third, 70, receiving atmospheric air and discharging to exhaust, and the fourth, 80, repressuring.

These operations proceed until the valve connections are shifted so that catalytic reduction and discharge of motive fluid to the high pressure turbine occurs in chamber 80, while from chamber 50 motive fluid is discharging to the low pressure turbine; chamber 60 receiving air and discharging to exhaust; and chamber 70 repressuring.

These operations proceed until the valve connections are shifted so that the four described fluid flows occur respectively in catalyst chambers 70, 80, 50 and 60.

In the next cycle the valve connections are shifted so that the four described fluid flows occur respectively in catalytic chambers 60, 70, 80 and 50.

A more specific description will now be given of the operation that occurs when the valve connections are as shown in Fig. 4; it being understood that the pressures and temperatures given are merely illustrative.

Catalyst chamber 50 is receiving fuel from line 59 and also recirculated H<sub>2</sub>O, CO<sub>2</sub> through line 61 at a pressure of 22 atmospheres. The products of oxidation, H<sub>2</sub>O, CO<sub>2</sub> and the recirculated H<sub>2</sub>O, CO<sub>2</sub>, at a temperature of 650° C., pass to the high pressure turbine 51. The exhaust from turbine 51, under a pressure of 3 atmospheres and at a temperature of 180° C., passes through heat exchanger 57, wherein the temperature is raised to 400° C., and thence passes to the low pressure turbine 52. At the same time oxidation products and recirculated fluid are going direct from catalyst chamber 60 to the low pressure turbine 52, the pressure in chamber 60 falling to 3 atmospheres. Part of this exhaust, at a temperature of 180° C., from the low pressure turbine 52 goes to the atmosphere; the remainder, at atmospheric pressure, going to a first stage compressor 54, which raises the pressure to 8 atmospheres and the temperature to 480° C. The compressed fluid goes through the heat-exchanger 57 (therein exchanging heat with the exhaust from the high pressure turbine 51) and, being therein reduced in temperature to 200° C., passes to a second stage compressor 53, where-

in the pressure is increased to 22 atmospheres and the temperature to 450° C. The recirculating fluid from compressor 53 is divided into two streams, one going to the catalyst chamber 50 and the other, through a restricted orifice 58, to catalyst chamber 80, the pressure in the latter being thus raised from 3 atmospheres to 22 atmospheres.

Air is admitted to the system solely by opening the air supply line 71 to catalyst chamber 70, the fluid displaced by admission of air exhausting through line 62. Exhaust fluid from the high pressure turbine may be used to furnish the power required to force air into the system, as in the power plants shown in Figs. 1, 2 and 3.

The invention is not limited to the use of any particular catalyst. Any oxidizable material which, when oxidized, effects by contact the oxidation of hydrocarbons or other compounds to CO<sub>2</sub>, H<sub>2</sub>O (or sulfur to SO<sub>2</sub>, SO<sub>3</sub>) at temperatures of about 600° C. and above, functions with total efficiency. Examples of metals which may be used are copper, chromium, vanadium, manganese and molybdenum. Among other elements that will function successfully are silver, nickel, cobalt, iron, magnesium, platinum, tungsten, thorium, lead and zinc. Combinations or mixtures of these elements will give a more active catalyst and will effect oxidation and reduction over the widest range of temperature. For example, copper manganese, finely divided, over an activated alumina support effects oxidation at below 300° C., thereby permitting an easy start of the engine under mild conditions of compression. The same catalyst will reduce easily at 500 to 800° C.

By the term "total efficiency" in the preceding paragraph I mean oxidation of a fuel to CO<sub>2</sub> and H<sub>2</sub>O at temperature below flame or explosion temperature, so as to produce the maximum amount of energy that can be obtained from such fuel. Among catalysts so effective may be mentioned copper or platinum-silver dispersed on activated alumina when controlled as described.

The qualities most desirable in the catalyst may be summed up as follows: (1) It should be physically strong and have a definite hardness. (2) Chemically, it should reduce and oxidize readily between 500° and 800° C. For engine starting it should reduce and oxidize readily at lowest possible temperature. (3) The surface for heat exchange, which should be extensive, is given by the support, which may be inert, but is much preferably active, as, for instance, activated alumina, or activated zirconia or silica gel.

When finely divided all these oxidation catalysts in reducing and/or oxidizing atmosphere release nascent oxygen in atomic stage; and this phenomenon explains the oxidation of gases, when they are outside the limits of inflammability of gases and vapors.

The catalyst is preferably supported in a chamber of the spark-plug porcelain type enclosed in a steel case. The catalysts have an almost indefinitely long life. There is no problem of regeneration.

As above explained, recycling of a large proportion of the formed CO<sub>2</sub> and H<sub>2</sub>O is required to maintain the catalyst within proper temperature limits.

In the foregoing description I have not specified the means for driving any of the compressors except the compressor for forcing air into the system. In the simplified embodiment of the invention shown in Fig. 1, the turbine e mechanical-



ly drives the compressor *g* and the fuel pump (shown in Fig. 2). In the other embodiments the power required to drive the compressors may be taken from either turbine or partly from one turbine and partly from another, in accordance with any arrangement known in the prior art. The driving connections to the several compressors (other than the air blower) are therefore not shown.

While I have specified introducing oxygen into the system by the utilization of air, it will be understood, as of course, that I may utilize any oxygen-bearing gas, including pure oxygen, which is now available at reasonable cost.

In all embodiments of the invention shown in Figs. 1, 2 and 3 there is no free oxygen in the system except between the compressor element of the turbo-compressor and the catalytic chamber. Thus, if the driven element is a turbine, the turbine blades will never be in contact with oxygen. The air is admitted to the recirculating fluid when the latter is at low temperature and pressure. In the embodiment shown in Fig. 4 there is no free oxygen in any part of the system.

The percentage of oxygen to that of the recirculating medium entering the catalytic chamber need be comparatively small. It may not exceed four or five per cent. It may be as little as two per cent. However, it should be understood that the reaction is performed regardless of the oxygen content in the fuel mixture and consequently outside the limits of inflammability of gases and vapors, thus eliminating all problems of detonation, explosion and combustion.

The pumping of the fuel to the system requires no excessive power. The fuel may be in liquid phase, in vapor phase, or in mixed liquid and vapor phase, the only requirement being that if the fuel is in liquid phase or mixed phase the fuel in liquid phase shall be vaporizable, at the temperature maintained in the catalyst chamber to which it is admitted, for good contact with the catalyst.

The net power output for a given fuel consumption in any of the power systems hereinbefore described is greatly in excess of that obtainable in systems heretofore known.

In all the embodiments of the invention shown, the driven engine is shown as a turbine, but it is applicable to an engine of any type. In applications filed by me December 6, 1947, Serial Nos. 790,214 and 790,215, I have illustrated several adaptations of my invention to piston engines.

What I claim and desire to protect by Letters Patent is:

1. The process of generating power which comprises catalytically oxidizing a fuel, utilizing the products of oxidation to generate power, subjecting oxidized products whose energy is not entirely expended in power generation to compression and recirculating such compressed oxidized products to the catalyst in such proportion to the oxygen-bearing gas and fresh fuel that the mixture of recirculated oxidized products, fresh fuel and oxygen-bearing gas will be outside the limits of inflammability under operating conditions.

2. The hereindescribed process which comprises contacting an oxidizable fuel with an oxygen-bearing gas to provide a mixture that is outside the limits of inflammability under operating conditions, contacting said mixture with a catalyst maintained at a temperature sufficiently high to oxidize the fuel in admixture with the gas above specified, utilizing the product of catalytic oxidation as motive fluid to drive the power

transmission element of an engine, and recirculating to the catalyst oxidized products whose energy is not entirely expended in power generation together with fresh oxygen-bearing gas in such proportions as to provide with the oxidizable fuel the non-inflammable gas mixture first above specified.

3. The process defined in claim 2 in which the temperature of the catalyst is maintained by compression of said recirculated oxidized products and fresh oxygen-bearing gas.

4. The process defined in claim 2 in which the specified recirculated oxidized products and fresh oxygen-bearing gas are together subjected successively to compression, cooling and compression.

5. The process defined in claim 2 in which the motive fluid is circulated through a series of power-driven elements at successively lower pressures and in which motive fluid not expended in power generation is, from an element of the series operated at a pressure lower than that of the first element of the series, together with fresh oxygen-bearing gas, conveyed to the catalyst to form the non-inflammable gas mixture first above specified.

6. The process defined in claim 2 in which the motive fluid is circulated through a series of power-driven elements at successively lower pressures, in which an oxidizing catalyst is interposed between two of said elements of the series as well as before the first element of the series, in which an oxidizable fuel is conveyed to the last-named catalyst, and in which fresh oxygen-bearing gas is mixed with the motive fluid flowing toward the last named catalyst to provide the specified non-inflammable gas mixture first above specified.

7. The process of generating power which comprises simultaneously contacting an oxidizing catalyst with a starting fuel and a mixture of a recirculated medium and an oxygen-bearing gas, thereby maintaining the catalyst in reducing and oxidizing condition and effecting oxidation of the starting fuel, utilizing the products from the zone of catalysis as a motive fluid to drive an engine, utilizing a substantial part of the exhaust fluid from the engine as the recirculating medium, and compressing the mixture of oxygen-bearing gas and exhaust fluid from the engine to raise its pressure and temperature, thereby establishing and maintaining the temperature conditions required to effect the oxidizing reaction.

8. The process defined in claim 7 in which part of the motive fluid is utilized to furnish the power required to inject the oxygen-bearing gas into the power plant.

9. The process defined in claim 7 in which part of the motive fluid is utilized to furnish the limited power required to inject the oxygen-bearing gas into the power plant and in which the thus injected oxygen-bearing gas is mixed with the recirculating medium and together subjected to the specified compression.

10. The process defined in claim 7 in which the motive fluid is passed in series through the power driven element in a plurality of stages at successively reduced pressure, in which the oxygen-bearing gas and the exhaust from the last stage are compressed in a plurality of successive compression steps and in which between said compression steps the said oxygen-bearing gas and exhaust are cooled by heat exchange with exhaust fluid.

11. The process defined in claim 7 in which the temperature condition required to effect the oxidizing reaction is established by cooling, as well as compressing, the said mixture.



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12. The process defined in claim 7 in which the temperature condition required to effect the oxidizing reaction is established by cooling, as well as compressing, the said mixture and in which the cooling is effected by heat exchange of the mixture with exhaust fluid.

13. The process of generating power which comprises simultaneously contacting an oxidizing catalyst with an oxidizable fuel, a recirculating medium and an oxygen-bearing gas, thereby maintaining the catalyst in oxidizing condition and effecting oxidation of the starting fuel, utilizing the products of catalytic oxidation and said recirculated medium as a motive fluid, passing the motive fluid through a power driven element in a series of stages at successively lower pressures, contacting the motive fluid exhausting from one stage with an oxidizing catalyst, to which additional oxidizable fuel is admitted, before passing such motive fluid to the next stage to thereby raise the temperature of the motive fluid passing to the latter stage, compressing a substantial part of the exhaust fluid from the last stage to raise its pressure and temperature and utilizing it as recirculating medium admitted as specified to the first named catalyst.

14. The process defined in claim 13 in which oxygen-bearing gas together with exhaust fluid from the last stage are subjected to the specified compression step and utilized for contacting with the first specified oxidizing catalyst to maintain the pressure and temperature conditions required to effect the oxidizing reaction and to provide the required volume of flow of motive fluid to the plural stage power driven element.

15. The process defined in claim 13 in which part of the exhaust fluid from the last stage is utilized to furnish the power required to inject the oxygen-bearing gas into the system, in which the recirculating medium and said oxygen-bearing gas are compressed as specified to raise their pressure and temperature to that at which they are contacted with the first specified catalyst, and in which in the last step therein specified said exhaust fluid is cooled as well as compressed.

16. The process defined in claim 15 in which said cooling is effected by heat exchange with motive fluid passing from the next to last stage to the last stage.

17. The process defined in claim 13 in which before the said compression step exhaust fluid from the last stage and oxygen-bearing gas are cooled as well as compressed, and effecting said cooling by heat exchange with motive fluid exhausting from the next to last stage and passing to the last stage.

18. The process of generating power which comprises circulating a medium functioning as a motive fluid successively through a plurality of power-driven elements at successively lower pressures and before each of a plurality of said elements contacting the stream of circulating medium with a catalyst and with an oxidizable fuel, recirculating the stream from the last of said elements to the catalyst preceding the first of said elements, introducing to said stream in the course of its flow, and also to motive fluid flowing between two successive elements, fresh oxygen-bearing gas, the relative percentages of said oxidizing gas and circulating medium flowing to each catalyst being such as to provide with the fresh oxidizable fuel a mixture outside the limits of inflammability under operating conditions, and maintaining each catalyst at a temperature sufficiently high to

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oxidize the fuel contacting with the said gas mixture.

19. In the process of generating power, circulating two parts of a fluid stream containing  $H_2O$ ,  $CO_2$  simultaneously through two catalyst-containing chambers and in each of them maintaining alternately an oxidizing atmosphere and a reducing atmosphere and while one chamber is under an oxidizing atmosphere maintaining a reducing atmosphere in the other chamber, utilizing the stream of oxidized products flowing alternately from the two chambers to generate power and subjecting a stream of such oxidized products whose energy is not entirely expended in power generation to compression to provide the stream passing to the two catalyst chambers as above specified.

20. The process of generating power which comprises catalytically oxidizing a fuel, utilizing the products of oxidation to generate power, returning part of the oxidized products beyond the locus of power generation to the catalyst, introducing to the circuit beyond the locus of power generation the oxygen required to oxidize the fuel, exhausting from the circuit beyond the locus of power generation the proportion of oxidized products whose exhaustion is required to maintain a substantially constant volume of fluid in circuit, and subjecting the fluid beyond the locus of power generation to compression, the proportion of recirculated products and oxygen being so regulated that the mixture of the same with the fresh oxidizable fuel will be outside the limits of inflammability under operating conditions.

21. The process of converting the latent energy of a circulating oxidized fuel medium, comprising carbon dioxide, steam and nitrogen, into available energy for generating power which comprises circulating said medium in an endless stream through a power driven element and thence in contact with a reducing oxidizing catalyst, admitting an oxidizable fuel to said catalyst, supplying air to the endless stream beyond the power driven element, exhausting from the endless stream beyond the power driven element a proportion of said medium required to balance the inflow of air and fuel, subjecting the mixture of said remaining and unexhausted medium and air to compression before admission of the mixture to the catalyst before the admission of fuel, and controlling the relative proportions of added air and said medium so that, with the oxidizable fuel, a mixture is produced that will be outside the limit within which it is possible to produce flame or explosion.

22. The process of generating power which comprises contacting an oxygen-bearing gas with an oxidizable fuel in the presence of a catalyst adapted to effect catalytic oxidation of the fuel while maintaining the proportion of the fuel to oxygen-bearing gas such that the mixture is outside the limits of inflammability under operating conditions, and utilizing the product of catalytic oxidation to generate power.

23. The process defined in claim 22 in which a part of the oxidized fuel whose energy has not expended in power generation is returned to the locus of fuel oxidation, the motive fluid for generating power thereby comprising a mixture of freshly oxidized fuel and a part of said previously oxidized fuel, and, by subjecting the returned oxidized fuel to pressure and, by regulating the proportion returned and its proportion to admitted oxygen-bearing gas, maintaining the specified



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proportion at the locus of fuel oxidation while maintaining the activity of the catalyst.

24. The process of generating power which comprises feeding a stream of recirculating medium at high pressure to a chamber containing an oxidizing catalyst to effect catalytic reduction, thence passing the catalytically oxidized stream as a motive fluid successively through a power driven element in two stages, the first a high pressure stage and the second a low pressure stage, simultaneously flowing motive fluid from a second catalyst-containing chamber to the second of said stages with resultant drop in pressure in such chamber from high pressure to medium pressure, simultaneously admitting an oxygen-bearing gas to a third catalyst-containing chamber while exhausting motive fluid therefrom with resultant drop in pressure to atmospheric, simultaneously subjecting recirculating medium exhausted from the last stage to compression to raise the pressure thereof to high pressure, splitting the compressed circulating medium into two streams, one being the stream admitted to the first named catalytic chamber and the other passing to a fourth catalyst-containing chamber in which the recirculating medium is repressured to high pressure; thereby completing one cycle of operation; then changing the flow of recirculating medium and introduction of the oxygen-bearing gas so that the fourth, first, second and third catalytic chambers function like the first, second, third and fourth catalytic chambers in the first cycle and thus complete the second cycle: then changing the

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flow of said recirculating medium and introduction of the oxygen-bearing gas so that the third, fourth, first and second catalytic chambers function like the first, second, third and fourth catalytic chambers in the first cycle, and thus complete the third cycle: and then changing the flow of said recirculating medium and introduction of the oxygen-bearing gas so that the second, third, fourth and first catalytic chambers function like the first, second, third and fourth catalytic chambers in the first cycle.

25. The process defined in claim 24 in which the exhaust fluid from the second stage is subjected to multi-stage compressions before passing to the two catalyst-containing chambers specified and in which between said compressions the said exhaust fluid is cooled by heat exchange with the motive fluid passing from the exhaust of the first stage to the inlet of the second stage.

EUGENE J. HOUDRY.

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Certificate of Correction

Patent No. 2,624,172

January 6, 1953

EUGENE J. HOUDRY

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows:

Column 1, line 35, for "liquid" read *fluid*;

and that the said Letters Patent should be read as corrected above, so that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 12th day of May, A. D. 1953.

[SEAL]

THOMAS F. MURPHY,  
*Assistant Commissioner of Patents.*