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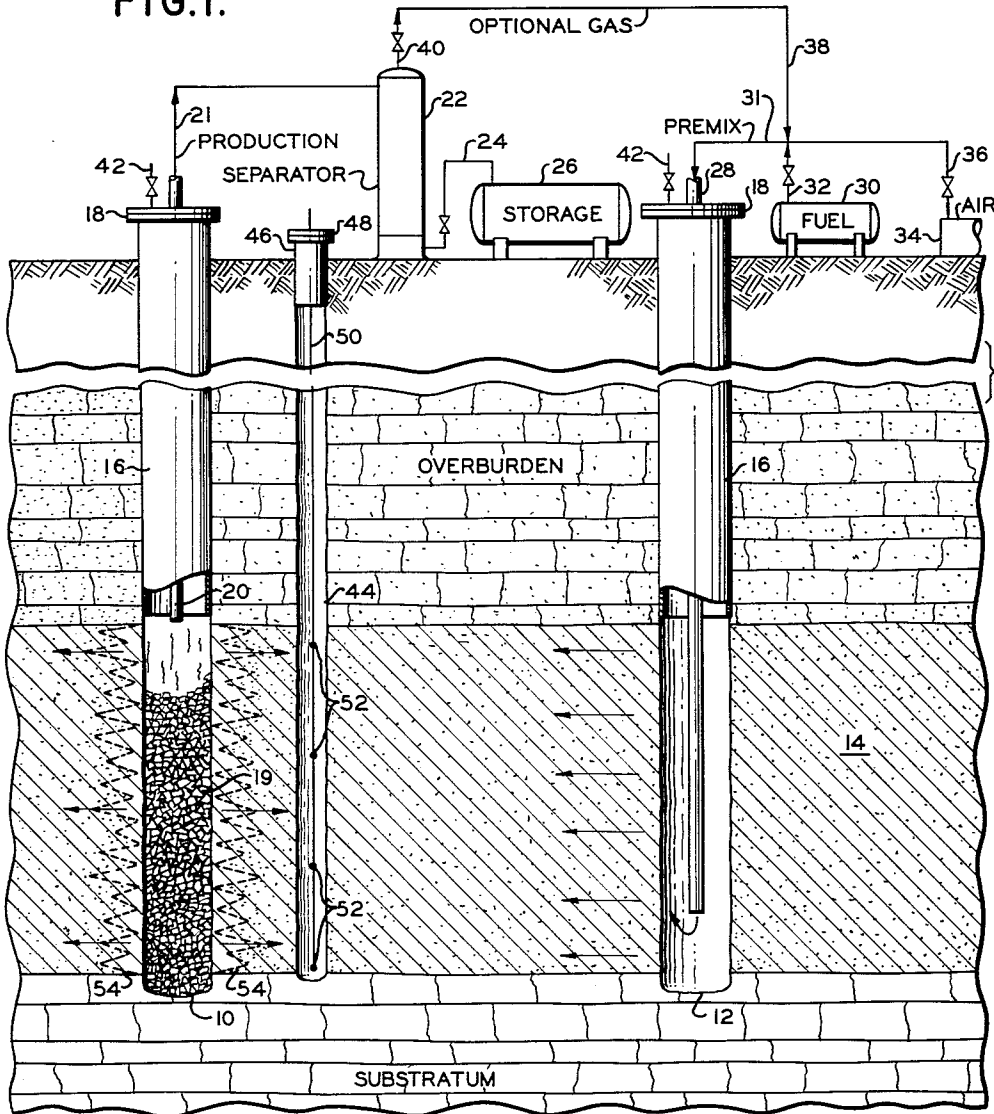
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INITIATION OF COUNTERFLOW IN SITU COMBUSTION

Filed June 11, 1958

2 Sheets-Sheet 1

FIG. 1.



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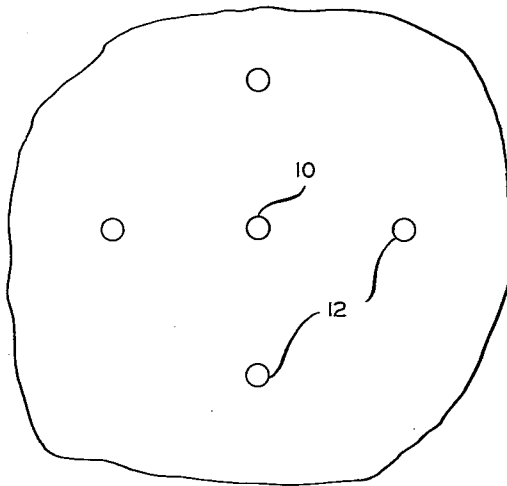


FIG. 2

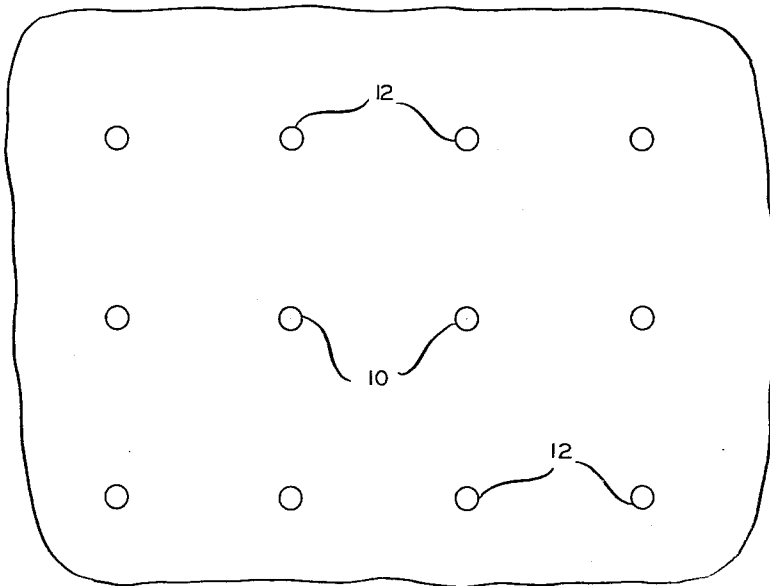


FIG. 3

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This invention relates to an improved process for initiating in situ combustion in a carbonaceous stratum.

In situ combustion in the recovery of hydrocarbons from underground strata containing carbonaceous material is becoming more prevalent in the petroleum industry. In this technique of production, combustion is initiated in the carbonaceous stratum and the resulting combustion zone is caused to move thru the stratum by either inverse or direct air drive whereby the heat of combustion of a substantial proportion of the hydrocarbon in the stratum drives out and usually upgrades a substantial proportion of the unburned hydrocarbon material.

The ignition of carbonaceous material in a stratum around a borehole therein followed by injection of air thru the ignition borehole and recovery of product hydrocarbons and combustion gas thru another borehole in the stratum is a direct air drive process for effecting in situ combustion and recovery of hydrocarbons from the stratum. In this type of operation the stratum usually plugs in front of the combustion zone because a heavy viscous liquid bank of hydrocarbon collects in the stratum in advance of the combustion zone which prevents movement of air to the combustion process. To overcome this difficulty and to permit the continued progress of the combustion zone thru the stratum, inverse air injection has been resorted to. By this technique, a combustion zone is established around an ignition borehole by any suitable means and air is fed thru the stratum to the combustion zone from one or more surrounding boreholes.

In situ combustion techniques are being applied to tar sands, shale, Athabasca sand and other strata in virgin state, to coal veins by fracturing, and to strata partially depleted by primary and even secondary and tertiary recovery methods.

The initiation of counterflow or inverse air injection drive of a combustion front in a carbonaceous stratum utilizing a high intensity heat source, such as open hole gas burners, well bores packed with granular solid fuels (charcoal, coke, coal, etc.), and electric heating elements, has never been successfully accomplished in field tests because of a fundamental difficulty. This difficulty arises from the fact that such high intensity heating against the counterflow air tends to establish a very steep thermal gradient in the rock or stratum near the well. Even though ignition can be established at the well bore sand face, the counterflow combustion front is reflected in the region of the steep thermal gradient, which may be only an inch or less from the sand face. The combustion front is reflected or caused to burn back to the well bore resulting in its extinguishment. The reflection or burn-back is caused by the lowering of temperature of the advancing edge of the combustion front as it reaches the cool stratum only an inch or so from the well bore which is maintained in cool condition because of the heat transfer cooling effect of the counterflowing injected air. The short movement of the counterflow combustion front into the stratum leaves a hot carbonaceous residue which remains hot and, after cooling of the lower edge of the advancing combustion front, the available air passes the cool edge and causes burning of the carbonaceous residue and drives the resulting combustion front back to the wall of the borehole. The result is that a fuel denuded region surrounding the borehole is left, thereby rendering

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further ignition extremely difficult or impossible without depositing in this denuded region a suitable carbonaceous low gravity fuel.

This invention is concerned with a novel method of initiating in situ combustion in a carbonaceous stratum utilizing the counterflow injection method.

Accordingly, it is an object of the invention to provide a process for initiating counterflow in situ combustion in a carbonaceous stratum. Another object is to simultaneously ignite a carbonaceous stratum around a borehole therein and move the resulting combustion front through the stratum by counterflow air injection without reversing the direction of air flow. A further object is to provide an improved method or process of initiating counter-flow in situ combustion which is fast, simple, and certain. It is also an object of the invention to provide a process for initiating combustion in a carbonaceous stratum which utilizes a minimum of equipment and reduces the cost of the process. Other objects will become apparent upon consideration of the accompanying disclosure.

A broad aspect of the invention comprises heating the wall of a borehole within a carbonaceous stratum to ignition temperature of the carbonaceous material therein; while at said temperature, passing a combustible mixture of O_2 and fuel gas containing excess oxygen thru the stratum toward the borehole and into the hot section adjacent the borehole so as to burn the mixture therein and ignite the carbonaceous material; and venting produced gases from the borehole. A mixture of air and fuel gas is suitable for the process and the concentration of fuel gas is preferably in the range of about 1 to 5 percent by volume and more desirably in the range of 2 to 4 percent. The propane is the preferred fuel gas but other fuel gases may be used in the process. The B.t.u. content of the fuel gas should be high; hence, propane is generally more desirable than other available fuel gases.

The wall of the borehole is preferably heated by burning a bed of charcoal therein which is at least as deep as the thickness of the carbonaceous stratum so as to ignite the entire exposed section of stratum within the borehole. The charcoal bed, preferably in the form of briquettes, is ignited in any suitable manner, the preferred manner being to drop a lighted fusee (railroad signal flare) on top of the bed of charcoal and flowing the premix of air and fuel gas thru the stratum from one or more injection boreholes therein into the ignition borehole where the excess O_2 burns the charcoal ignited by the fusee along with the fuel gas entering the ignition borehole in the premix. In this manner the entire stratum adjacent the borehole is heated to the ignition temperature of the in-place carbonaceous material and the excess of O_2 in the premix establishes in situ combustion in the heated zone around the borehole, thereby establishing inverse in situ combustion wherein the combustion front moves radially outwardly from the borehole counterconcurrently to the flow of air or premix. It is believed that the advancing edge of the combustion front is kept at combustion supporting temperatures during the initial phase of this process because of the presence of fuel gas in the air stream which burns in the leading edge of the combustion front and thereby maintains suitable temperature therein.

While any combustible gas such as butane, natural gas, methane, producer gas, synthetic gas, etc., may be utilized in premix in lieu of propane it is preferred that the gas have a low ignition temperature. It is desirable to use a premix containing fuel gas approximately 2 percent below or about 2 percent (by volume) above the stoichiometric mixture with air or oxygen to effect the process of the invention; however, the invention is not limited thereto and the use of propane in the range of 1 to 7 percent (by volume) of the air in the premix is operable. To illustrate, although the stoichiometric quantity of pro-

pane in air is about 4 percent by volume, the amount may range from about 1 to about 7 percent and, preferably, in the range of 2 to 6 percent.

More complete understanding of the invention may be had by reference to the accompanying schematic drawings in which FIG. 1 is an elevation in partial section of an arrangement of apparatus and boreholes in a carbonaceous stratum for effecting the invention.

FIGURE 2 is a plan view of an arrangement of boreholes showing a central ignition and production well radially surrounded by input wells. FIGURE 3 is a plan view showing an arrangement of in-line injection boreholes having on each side an in-line parallel arrangement of input wells.

Referring to the drawings, an ignition borehole 10 and injection borehole 12 penetrate a carbonaceous stratum 14 and are provided with casings 16 extending from well heads 18 down approximately to the top of the stratum. The ignition borehole 10 contains a bed of charcoal 19 and is provided with tubing 20 which is connected by production line 21 with conventional product separation means 22, which in turn connects with a delivery line 24 leading to a storage facility 26.

Injection borehole 12 is provided with injection tubing 28 which connects with a fuel gas supply 30 by means of lines 31 and 32 and with air supply source 34 (usually one or more compressors) through line 36. A gas supply line 38 connects injection tubing 28 thru line 31 with a gas line 40 leading from separator 22 for use where produced gas is to be utilized in the premix. This produced gas may come from any well in the vicinity which is functioning as a producing well during the in situ combustion process. The well heads 18 are also provided with auxiliary vent or injection lines 42.

An instrument borehole 44 also penetrates stratum 14 and is closed in by means of a short casing string 46, closed by head 48. Thermocouple lines in conduit 50 extend into the stratum and carry thermocouples 52. Numeral 54 designates a fire or combustion front moving radially outwardly from ignition borehole 10 counter-currently to air or premix moving toward the ignition borehole.

The drawing illustrates either a central ignition borehole 10 surrounded by a ring of injection boreholes 12, as in a 5, 7 or 9-spot well pattern or ignition well 10 may be one of a series of in-line ignition boreholes flanked on each side by a parallel row of in-line injection boreholes 12 (only one line of injection boreholes being illustrated). In the ring type pattern, ignition is effected around the central well 10 by heating the wall of the borehole to ignition temperature and, while hot, injecting premix thru the stratum from the surrounding injection boreholes 12 so that premix is entering the hot borehole wall radially from all directions. In this manner, as ignition of the in-place hydrocarbons adjacent the ignition borehole takes place, the resulting combustion front is moved outwardly in all directions from the ignition borehole. When a series of in-line ignition boreholes are utilized, the premix injected thru the stratum to the several ignition boreholes from the two lines of injection boreholes (one on each side of the line of ignition boreholes and generally parallel thereto) also enters the hot boreholes from virtually every direction and after effecting ignition of the stratum around the ignition boreholes moves the combustion front outwardly toward the two lines of the injection boreholes.

Another method of establishing a suitable combustion front along a line of ignition boreholes comprises initiating combustion around alternate boreholes of the in-line ignition boreholes by heating the walls of these alternate boreholes to ignition temperature and injecting premix through the remaining ignition boreholes in the line so as to establish in situ combustion around the heated boreholes and advance the combustion fronts to the ignition boreholes being temporarily utilized as injection boreholes. When this has been accomplished a complete

combustion zone extending along each side of the line of ignition boreholes is established and these zones can then be advanced to the adjacent lines of injection boreholes by injecting air, alone, or premix thru the injection boreholes. During the in situ combustion process the ignition boreholes become production boreholes from which the produced hydrocarbons are recovered preponderantly in gaseous form by conventional methods, principally by venting the produced hydrocarbons thru a well tubing, such as tubing 20 in borehole 10.

Borehole 44 is of small diameter such as 2 to 4 inches and is drilled at any location intermediate of boreholes 10 and 12, usually in the range of about 18 inches to 15 feet from the ignition borehole. Borehole 12 is usually in the range of 10 to 50 feet or more from borehole 10. Thermocouples 52 and instrument borehole 44 are utilized to sense the temperature in the stratum at the location of the borehole and, of course, indicate when the combustion front reaches and passes the instrument borehole.

Successful ignition of counterflow underground combustion requires that adequate fuel and oxygen be available while the formation is at or above the necessary ignition temperature. In the case of tar sand reservoirs, these standard combustion requirements are complicated by several factors.

To achieve a successful ignition, it is necessary both to initiate combustion and to propagate the resulting fire front beyond the immediate ignition zone. If the front fails to propagate because of premature thermal reflection (burn-back), formation plugging, or any one of several possible reasons, the ignition would be classed as unsuccessful even though combustion has been established temporarily in the ignition zone itself. Several field ignition failures were also labelled because the fire front failed to propagate successfully—not because of a failure in establishing combustion at the well bore sand face.

In general, the ignition temperature will not be a rigorous physical constant for any given formation. By varying the heating rates, packing density, and the gas flow during the warm-up period, ignition temperatures ranging from 450 to 700° F. were observed during laboratory experiments on the same tar sand. In part, these variations are believed to result from the multi-component nature of the reservoir fuel. A temperature of 550° F. was taken to be the most representative ignition temperature for the Bellamy tar sand pay zone used in our field tests.

In addition to heating a given rock segment above the ignition temperature, it is also desirable to establish an appropriate temperature profile in the formation just beyond the ignition zone, particularly when the injection gas is air alone. Premature thermal reflection, or burn-back, has been shown to occur when the temperature gradient at the edge of the ignition zone is too steep. Addition of fuel gas to the injected air prevents such "thermal echo" and permits the counterflow fire front both to penetrate regions of steep thermal gradient and to jump formation fractures.

Field tests in the Bellamy tar sand, about 12 feet thick lying between 50 and 75 feet below the surface, have been conducted utilizing various ignition techniques with different well patterns, including the ring type and the in-line drive type. The technique of the invention utilizing counterflow pre-mix with heating of the ignition borehole by burning charcoal therein and by heating the borehole wall with an enclosed gas fired U-type heater constructed as disclosed in the U.S. application of Allen S. Rogers et al., Serial No. 719,890, filed March 7, 1958, has been successful in every instance. Up to this time, ignition of the tar sand utilizing both ring type and in-line well patterns with the premix-counterflow-preheated borehole technique and a hot charcoal bed as the heating means has been successful in establishing and continuing counterflow in situ combustion in the tar sand on six different occasions without failure in any attempt to ignite the tar sand and move

a combustion front thru the sand counterconcurrently to the flow of air. Tests utilizing preheating of the borehole and without including fuel gas in the injected air, were unsuccessful in every instance. Ignition was also attempted by omitting the preheating of the ignition borehole wall and burning the premix in the ignition borehole as the premix entered this borehole from the surrounding injection boreholes, but under various flow rates and injection conditions it was found impossible to effect a self-sustaining combustion around the borehole which could be advanced thru the stratum by continued injection of the premix. Attempts were also made to establish self-sustaining ignition around an ignition borehole in the tar sand by heating the wall of the borehole to ignition temperature and passing counterflow air devoid of fuel gas to the hot stratum around the borehole but a self-sustaining combustion could not be established even when the temperature of the borehole was well above the minimum combustion requirements and different air rates were utilized.

In the tests utilizing burning charcoal and premix, as well as in the other tests, excess mobile water was removed from the formation adjacent the ignition well or wells by injecting air into the ignition wells until the off-set injection wells ceased producing water at a significant rate. The ignition boreholes were packed with charcoal briquettes which had been soaked in diesel fuel. Each linear foot of the 6 $\frac{3}{4}$ inch diameter hole held about 8 pounds of charcoal containing 20 percent diesel fuel by weight. The 2 inch production tubing was bottomed about 1 foot above the charcoal bed.

Combustion of the charcoal was started by dropping a lighted fusee down the producing tubing. After the charcoal fire was well established on a reduced air supply, the well was allowed to blow wide open and propane was added to the injection air. Under these conditions, the charcoal fire persisted for about five hours. Within 26 hours, temperature measurements taken in nearby instrument wells indicated that the combustion zone had moved into the formation and that ignition had been general over the exposed sand face. Propane concentration in the injected air varied from 1.0 to 3.8 percent by volume during this time. Subsequent successful operation was maintained with variations in the propane content of the injected air from zero to 3.0 percent. Post mortem coring confirmed that this ignition technique had been successful in all five ignition wells.

In one of the tests of propane content of the injected air was maintained below 1 percent during the time the charcoal was burning in the ignition borehole and then was raised to the range of 1 to 3.8 percent during the succeeding phase of the process. In each of the tests utilizing premix and heating of the well bore with burning charcoal, the instrument wells positioned at different distances from the ignition boreholes indicated successful transfer of the combustion zone into the formation over the entire exposed sand face. When utilizing a closed U-tube heater for heating the well bore and passing premix to the heated area from injection boreholes in the stratum 88 percent of the stratum was ignited. In utilizing charcoal as the heat source and premix as the combustion supporting gas ignition was effected in 100 percent of the stratum around the ignition borehole in each instance.

Certain modifications of the invention will become apparent to those skilled in the art and the illustrative details disclosed are not to be construed as imposing unnecessary limitations on the invention.

We claim:

1. A process for initiating in situ combustion in a carbonaceous stratum around an ignition borehole therein which comprises heating said stratum adjacent said ignition borehole to at least the ignition temperature of the carbonaceous material therein; passing into said thus heated stratum and toward said ignition borehole a combustible mixture containing a fuel gas and oxygen in excess over the amount needed to burn said fuel gas by

way of at least one other borehole only, burning said combustible mixture in said stratum surrounding said ignition borehole, continuing to pass said combustible mixture into said stratum as described so as to establish an in situ combustion zone in said stratum around said ignition borehole, and recovering gases and vapors thus produced from said ignition borehole.

2. The process of claim 1 wherein said mixture consists essentially of air and fuel gas.

3. The process of claim 2 wherein the fuel gas concentration is in the range of about 1 to about 4 volume percent.

4. The process of claim 1 wherein said mixture consists essentially of air containing propane in the range of 2 to 4 volume percent of the mixture.

5. The process of claim 1 wherein said stratum is ignited around each of a series of in-line ignition boreholes and a mixture of air and fuel gas is passed thru said stratum to the combustion zone from boreholes in two series of in-line injection boreholes, one on each side of and parallel to the line of ignition boreholes.

6. The process of claim 5 wherein the injection of air thru said two series of in-line injection boreholes is continued after ignition so as to move the resulting combustion zone toward each line of injection boreholes.

7. A process for initiating in situ combustion in a carbonaceous stratum around an ignition borehole therein which comprises heating said stratum adjacent said ignition borehole to the ignition temperature of the carbonaceous material therein by burning a mass of charcoal in said ignition borehole; while burning said charcoal in said ignition borehole, passing into said thus heated stratum and toward said ignition borehole a combustible mixture containing a fuel gas and oxygen in excess over the amount needed to burn said fuel gas by way of at least one other borehole only, burning said combustible mixture in said stratum surrounding said ignition borehole, continuing to pass said combustible mixture into said stratum as described so as to establish an in situ combustion zone in said stratum around said ignition borehole, and recovering gases and vapors thus produced from said ignition borehole.

8. The process of claim 7 wherein said mixture is passed through said stratum to said ignition borehole from surrounding injection boreholes and wherein the concentration of fuel gas during the burning of said charcoal is maintained below about 1 percent by volume and the concentration is advanced to the range of 2-4 percent by volume when said charcoal is burned.

9. The process of claim 7 wherein said mixture is passed thru said stratum to said ignition borehole from a ring of surrounding injection boreholes; and the concentration of fuel gas during the burning of said charcoal is maintained below about 1% by volume and said concentration is advanced to the range of 2 to 4% by volume when said charcoal is burned.

10. The process of claim 9 wherein injection of air thru said injection boreholes is continued after ignition is effected, so as to move the resulting combustion zone outwardly toward said ring of boreholes.

11. The process of claim 7 wherein said mass of charcoal is ignited by burning a fusee in contact with same and injecting said mixture thru said stratum into said borehole to sustain combustion of said charcoal until ignition of said stratum around said borehole is effected.

12. A process for initiating in situ combustion in a carbonaceous stratum around an ignition borehole therein which comprises simultaneously igniting a mass of charcoal in said borehole within said stratum and passing a combustible mixture of fuel gas and air containing excess O₂ into and thru said stratum by way of at least one other borehole only into said ignition borehole so as to burn said charcoal and said fuel gas within said mass thereby heating said stratum adjacent said ignition bore-

hole to ignition temperature; continuing the passing of said mixture thru said stratum so as to ignite the wall of said borehole and establish in situ combustion in said stratum.

13. The process of claim 12 wherein said fuel gas is maintained in the range of 2 to 4 volume percent of said mixture after said charcoal is burned.

14. The process of claim 13 wherein said charcoal is soaked with a heavy fuel oil prior to ignition thereof.

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