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DESIGN OF A FISCHER-TROPSCH SYNTHESIS PILOT PLANT

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ABSTRACT

The design and the construction of a Fischer-Tropsch Synthesis Pilot Plant are given. The plant consists of gas purification units, gas cracking unit (Nickel catalyst reactor) and the synthesis reactor. The synthesis gas is prepared by converting kerosene-cracked gas by reacting it with steam at high temperatures over nickel catalyst. The details of design-calculations are shown. The plant is being tested at present and will shortly go into operation.

INTRODUCTION

The production of synthetic petrol from low grade coal in India is a highly important problem. It is well known that our petrol resources tapped so far are not sufficient for our needs and we have to import a large amount of crude oil to run our refineries. We are also having large reserves of low grade coal which cannot be used for metallurgical coke. The recently discovered lignite deposits of Neivelli are also a significant factor. It is therefore of utmost importance to utilise these low grade coals to produce different types of hydrocarbons. The Government of India was also considering this matter some time back. With this in mind we have decided to set up a pilot plant for hydrocarbon synthesis in our Department.

Another reason for setting up this plant is to enable the research students to design, fabricate, erect and run a pilot plant in order to get true chemical engineering training. We also have some research problems to be solved with the help

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of this plant. We had done some fundamental research regarding the mechanism of Fischer-Tropsch synthesis on bench-scale unit. By adjusting the reaction conditions in such a way as to retard the final reactions below the rate of intermediate reactions, we found that carbonyl formation is the first reaction in synthesis, and direct formation of oxo-compounds is also possible.[1] As these observations were made from inlet and exit gas analysis only, we would like to confirm these results by the analysis of liquid products, that will be obtained in larger quantities from the pilot plant. We have also established a method to predict the distribution of Fischer-Tropsch synthesis products from inlet and exit gas analysis for iron catalyst.[2] For this we have utilised data from a large-scale pilot plant investigation in Germany. We would like to establish this method for cobalt catalyst from our plant data.

PLANT

With these considerations, it was decided to set up a fixed bed Fischer-Tropsch reactor of 5 litres catalyst capacity. The gas throughput for a single pass is to be 500 litres per hour. It can be run upto temperatures of 280° C and gas pressures upto 15 kg/cm.[2] Simultaneously, a pilot plant for 'Total coal-dust gasification' was also designed, fabricated and set up. This plant is now under test runs. As it was thought that it will take some time to set up this plant and establish the operational conditions, we decided to make some other arrangement for the production of synthesis gas. We had at our disposal data from our laboratory[3] for the manufacture of synthesis gas from low-temperature carbonisation gas (which contains mostly saturates and unsaturates) by cracking it with steam over nickel catalyst. Therefore we decided to use kerosene-cracked gas (which also contains predominantly saturates and unsaturates) from our gasworks as the original source of gas.

CATALYST

For our plant we have produced large batches of cobalt, iron and nickel catalysts. For this a catalyst precipitating unit has been fabricated. The composition of cobalt catalyst is 100 Co : 5 ThO_2 : 10 MgO : 200 kieselguhr. It is prepared by precipitating the carbonates over kieselguhr from nitrate solution. The composition of the iron catalyst is 120 Fe : 12 CaO : 40 kieselguhr. The iron nitrate solution was obtained by dissolving scrap-iron in concentrated nitric acid. The composition of nickel catalyst is 30 Ni : 70 kieselguhr. All these catalysts are already tested with regard to their performance in a small unit.

FLOW-SHEET

The flow-sheet of the plant is shown in Figs. 1, 2, and 3. The whole plant can be divided into four sections as follows: (1) Gas purification units (2) Gas cracking unit, Nickel reactor, (3) Fischer-Tropsch reactor (F-T-reactor), (4) Products condensing and collecting units.

PURIFICATION UNITS

The gas from the gas-works is first passed through the purification units by means of a blower. The first unit is a hydrogen-sulfide removal tower, in which wet iron oxide is used as an adsorbent. The second one are two activated-charcoal towers, one of which will be in operation and the other under regeneration by steam. The gas is then passed through a gas heater to the organic sulfur removal tower where organic sulfur is removed by passing the gas over alkalized iron oxide kept at about 300° C.

CRACKING UNIT

The gas is then heated to 400° C in a gas superheater and mixed with steam obtained from a small boiler and also superheated to 400° C. The mixture is then passed over nickel catalyst in the nickel catalyst reactor, where the temperature is maintained at 900° C. The cracked gas is then sent to a water cooler and then to the compressor. A part of the gas from the compressor is sent through a bypass and a gas heater to the activated charcoal tower which is under regeneration.

FISCHER-TROPSCH REACTOR

The gas from the compressor is then fed to the F-T- reactor at the top. The temperature of the reaction is controlled by controlling the cooling jacket water temperature of the reactor. The temperature of the cooling water is regulated by adjusting the steam pressure in the boiler by condensing the steam in it by circulating known amount of water through the cooling coils in the boiler. The gas comes out through the bottom of the reactor. The wax is kept in the molten condition by heating the exit pipe electrically. The products are then condensed and collected and the tail gas is recirculated if required. The bottom portion of the reactor can be electrically heated to start the reaction.

DESIGN DETAILS

(1) *Gas Purification Units*

(*a*) *H_2S Removal Unit.*—The adsorbent used is wet iron oxide. The maximum H_2S content of the gas is assumed to be 500 g/100 m.^{3} 180 tons of the adsorbent is required for a gas throughput of 40,000 m^3/hr (from industrial data). Therefore, for a gas throughput of 500 litres/hr 2·25 kg of iron oxide will be required. As the bulk-density of this adsorbent is 0·5, 4·5 litres of it will be required.

Dimensions: Height = 711·0 mm.
Diameter = 152·4 mm.

(*b*) *Activated Charcoal Towers.*—The activated charcoal is used to remove aromatics and the remaining traces of H_2S. Two units are used. The charcoal is in the form of pellets of 4 mm diameter. The gas is assumed to contain 2 g/m^3 of disagreeable material, and if we take 500 litres/hr gas throughput, 1·2 g/hr impurities are to be removed. 1% of the charcoal is assumed to be saturated per hour, and so 120 g of charcoal are required per hour. The bulk-density of the charcoal is 0·35 and so 350 cm^3 charcoal per hour is needed. For 48 hours run approximately 20 litres of charcoal will be required.

Dimensions: Height = 660·4 mm.
Diameter = 190·5 mm.

(*c*) *Gas Heater.*—Amount of gas to be heated

= 1500 liters/hr from 30° C–280° C.

Average molecular weight of gas = 23·764.
Weight of gas to be heated = 1·438 kg/hr.
Average specific heat of gas = 0·305 kg cal/kg × ° C.
Heat to be supplied = Q = 1·438 × 0·305 × (280–30).
= 109·6 kg cal/hr.

Assuming 700° C as the temperature of the heating element,

log mean temp. difference = 515° C.
Reynolds No. in ¼ in. dia. pipe = 8590.
Over-all heat transfer coefficient = 9·76–29·28 kg cal/hr m^2 ° C.
For safety, Q is assumed to be 201·6 kg cal/hr.
Therefore, heating area A = 201·6/9·76 × 515 = 0·04 m^2.
Hence length of ¼ in. pipe = 2133 mm.

Heating wire requirement

Wire used: Kanthal A ribbon 1/16 in × 0·0063 in.
Amperes for 700° C = 5·0.
Resistance of the wire = 1·84 ohms/ft.
Voltage supplied = 220.
Length of wire required = 7314 mm.

The heater is thermally insulated by placing it in a galvanised iron box filled with asbestos magnesia powder.

(*d*) *Organic Sulfur Removal Tower.*—Pellets of alkalized Fe_2O_3 (6–7 mm size) are used. The composition is 66% Fe_2O_3 and 33% NaOH on dry basis. 50 tons of this material are required for 20,000 m^3/hr gas throughput, and so for 500 litres per hour gas rate, 1·25 kg are required, *i.e.*, 1·80 litres (0·7 bulk-density).

Dimensions: Height = 1016·0 mm.
Diameter = 101·6 mm.

Heating arrangement.—The tower is heated electrically to maintain the temperature at 300° C.

(2) *Nickel Catalyst Reactor*

Calculation of steam requirement:

(*a*) *For uncracked gas.*—Steam is taken in the ratio of C-No.: steam = 1 : 2 with respect to all the hydrocarbons in the gas. Following is the composition of the uncracked gas.

TABLE I

Composition of kerosene-oil-cracked gas and steam requirement

Component	Vol. %	Steam required (litres)	
CO_2	4·54	..	
C_4H_8	2·16	17·28	
C_3H_6	4·14	24·84	
C_2H_4	16·32	65·28	
O_2	1·97	..	
CO	5·1	..	
H_2	12·2	..	
C_nH_{2n+2}	14·0	29·96	C-No. = 1·07
N_2	39·4	..	
Sum ..	100·0	137·36	

Therefore, 500 litres of gas will require 137·36 × 5 = 686·80 litres of steam.

(*b*) *For cracked and recycled gas.*— Steam is taken in the ratio of C-No.: Steam = 1 : 2. Following is the composition of the cracked gas. All the saturates are assumed to be completely converted in one pass.

TABLE II

Composition and steam requirement of the cracked and recycled gas

Component	Vol. %	Steam required (litres)
CO_2	2·14	..
CO	25·00	..
H_2	57·00	..
CH_4	2·14	4·28
N_2	13·72	..
Sum ..	100·00	4·28

Therefore, 1000 litres of gas will require 42·8 litres of steam.

Hence total amount of steam required is 729·6 litres. Weight of the total mixture of gas and steam per hour:

500 litres of uncracked gas	= 0·5498 kg (Av. Mol. Wt. 23·64)
1000 litres of cracked gas	= 0·5852 kg (Av. Mol. Wt. 13·41)
730 litres of steam	= 0·5729 kg
	1·7079 kg

Heat requirement

(*a*) *Heat of reaction.*—Let us assume for simplification that saturates in the gas occur as methane and unsaturates as ethylene. That means we will have 14% methane and 22% ethylene in the gas. The following reactions will give the heats of reactions:

$$C_2H_4 + 2\,H_2O = 2\,CO + 4\,H_2 - 56{,}030 \text{ cal} \quad (1)$$

$$CH_4 + H_2O = CO + 3\,H_2 - 54{,}245 \text{ cal} \quad (2)$$

Moles of CH_4 in 500 litres of uncracked gas $= 500 \times 14/22{\cdot}4 \times 100$
$= 3{\cdot}349$

Moles of CH_4 in 1000 litres of cracked gas $= 1000 \times 2{\cdot}14/22{\cdot}4 \times 100$
$= 0{\cdot}955$

Moles of C_2H_4 in 500 litres of uncracked gas $= 500 \times 22/22{\cdot}4 \times 100$
$= 4{\cdot}911$

Therefore heat of reaction $= 4{\cdot}304 \times 54{,}245 + 4{\cdot}911 \times 56{,}030$
$= 507{,}704$ kg cal/hr

(*b*) *Heat required for heating uncracked gas from* 400°–900° *C.*

Sp. Heat of gas = 0·5 kg cal/kg × °C.

Therefore, $Q = 0{\cdot}5498 \times 0{\cdot}5 \times 500$
$= 137{\cdot}5$ kg cal/hr.

(*c*) *Heat required for heating cracked gas from* 400°–900° *C.*

Sp. Heat of gas = 0·6 kg cal/kg × °C.

Therefore, $Q = 0{\cdot}5852 \times 0{\cdot}6 \times 500$
$= 175{\cdot}6$ kg cal/hr

(*d*) *Heat required for heating steam from* 400°–900° *C.*

Sp. Heat of steam = 0·5 kg cal/kg × °C.

Therefore $Q = 0{\cdot}5729 \times 0{\cdot}5 \times 500$
$= 143{\cdot}2$ kg cal/hr.

(*e*) *Radiation losses.*—The nickel reactor is thermally insulated by covering it by a galvanized iron sheet box of dimensions 406·4 mm × 406·4 mm × 1346 mm which is packed with asbestos magnesia powder.

Outside temperature of the box = 80° C.

Room temperature = 25° C.

$h_c + h_r = 8 \cdot 294$ kg cal/hr × m² × ° C.

Area of the exposed sides of the box = 2·537m².

Heat losses = 8·294 × 2·527 × 55

= 1153 kg cal/hr

(*f*) Therefore, total quantity of heat to be supplied = 2117·0/kg cal/hr

= 2·47 kw.

Heating arrangement

A radiation type of heater is used. It consists of an asbestos cylinder round the reactor, on the inside of which Kanthal wire is wound. Two heaters are used to keep the temperature uniform over the entire length of the reactor. The first one is supplied with 9·5 amperes at 220 volts and the other at the bottom is supplied with 5·0 amperes at 220 volts. The spacing between the windings is arranged in such a way as to keep the temperature uniform.

Volume of catalyst required

Total volume of gas to be passed is 2230 litres per hour (500 litres of uncracked gas + 1000 litres of cracked gas + 730 litres of steam). The optimum space velocity to be used is 700 vol. of gas per unit vol. of catalyst per hour. The volume of catalyst required is 3185 cm.[3] All these calculations are based on the data available from our laboratory work.[3]

Reactor dimensions

Height = 1219·0 mm.

Diameter = 101·6 mm.

Material of construction : Steel pipe.

Steam boiler

It is a small boiler with 4 kw immersion heater. The amount of steam produced per hour is regulated by controlling the wattage supplied to the heater.

Steam and gas super-heaters

The kilowatts to be supplied are calculated in the same way as already shown. Both the heaters are supplied with 1 kw.

Dimensions of the super-heaters:

Pipe length = 3962·0 mm.

Diameter = 7/16 in.

Material of construction: Steel

Wire requirements:

Kanthal A ribbon, 3/32 in × 0·0080 in.

Amperes = 6·0

Voltage = 220

Cooler

The gas is cooled in a cooler, directly by a water shower.

Dimensions:

Height = 711·2 mm.

Diameter = 152·4 mm.

Fischer-Tropsch Reactor

The catalyst capacity of the reactor is 5 litres. As the reaction is exothermic, an outer cooling jacket is provided. This outer pipe is connected to a boiler containing a cooling coil. The temperature of the reaction is controlled by adjusting the steam pressure in the boiler by means of cooling water circulated in the cooling coils. A provision for a thermo-couple to measure the catalyst temperature is also made. The amount of steam that will be produced is calculated from actual plant data. 700 kg of steam per hour is produced when the gas throughput is 1000 m^3/hr. And therefore, with 500 litres gas per hour, approximately 350 g of steam per hour will be produced. The water required for condensing the steam and the length of the cooling coil in the boiler are then calculated.

Cooling water required = 0·014 m^3 per hour.

Cooling surface required = 0·046 m^2

Cooling water rate = 1 m/sec.

Dimensions of the reactor:

Height = 5792·0 mm.

Inside pipe diam. = 1 29/32 in. O.D. × 6 SWG thick seamless steel tube.

Outside pipe diam. = $4\frac{1}{2}$ in. O.D. × 5/16 in. thick seamless steel tube

Dimensions of the boiler:

Height = 647·6 mm.

Diameter = $10\frac{3}{4}$ in. O.D. × $\frac{1}{2}$ in thick seamless steel tube.

Cooling coil: $\frac{1}{8}$ in. N.B. cooling coil of 3 turns (coil diam. = $4\frac{7}{8}$ in.).

The drawings of the boiler and the reactor are given in Figs. 4 and 5. The reactor along with the boiler is fabricated to run under working pressure of 600 lb/sq. in. It has been fabricated by Stewards and Lloyds of India Ltd. according to our drawings.

The whole plant is under testing and will be put into operation soon.

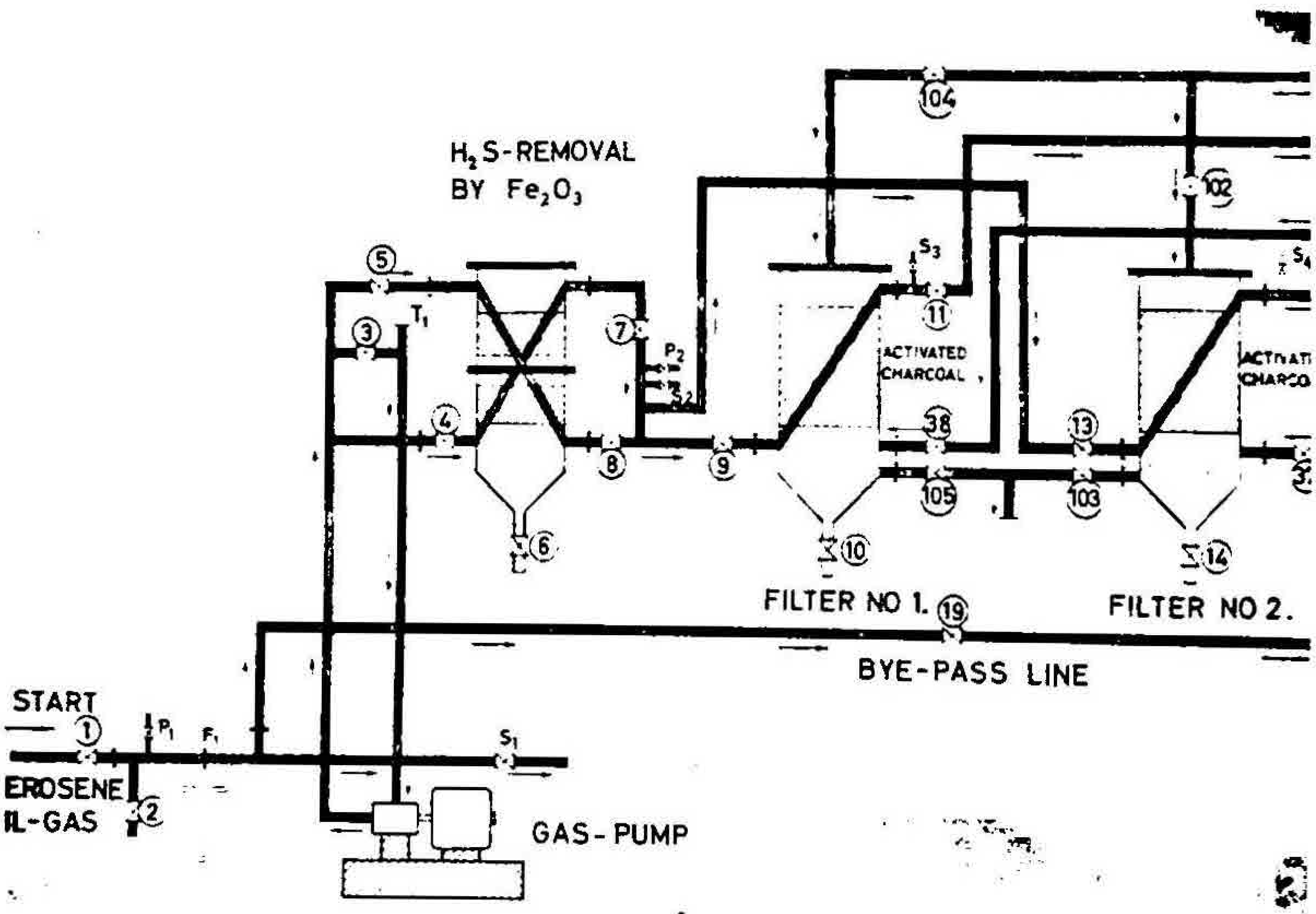

FIG. 1. Flow Sheet of Gas Purification Units

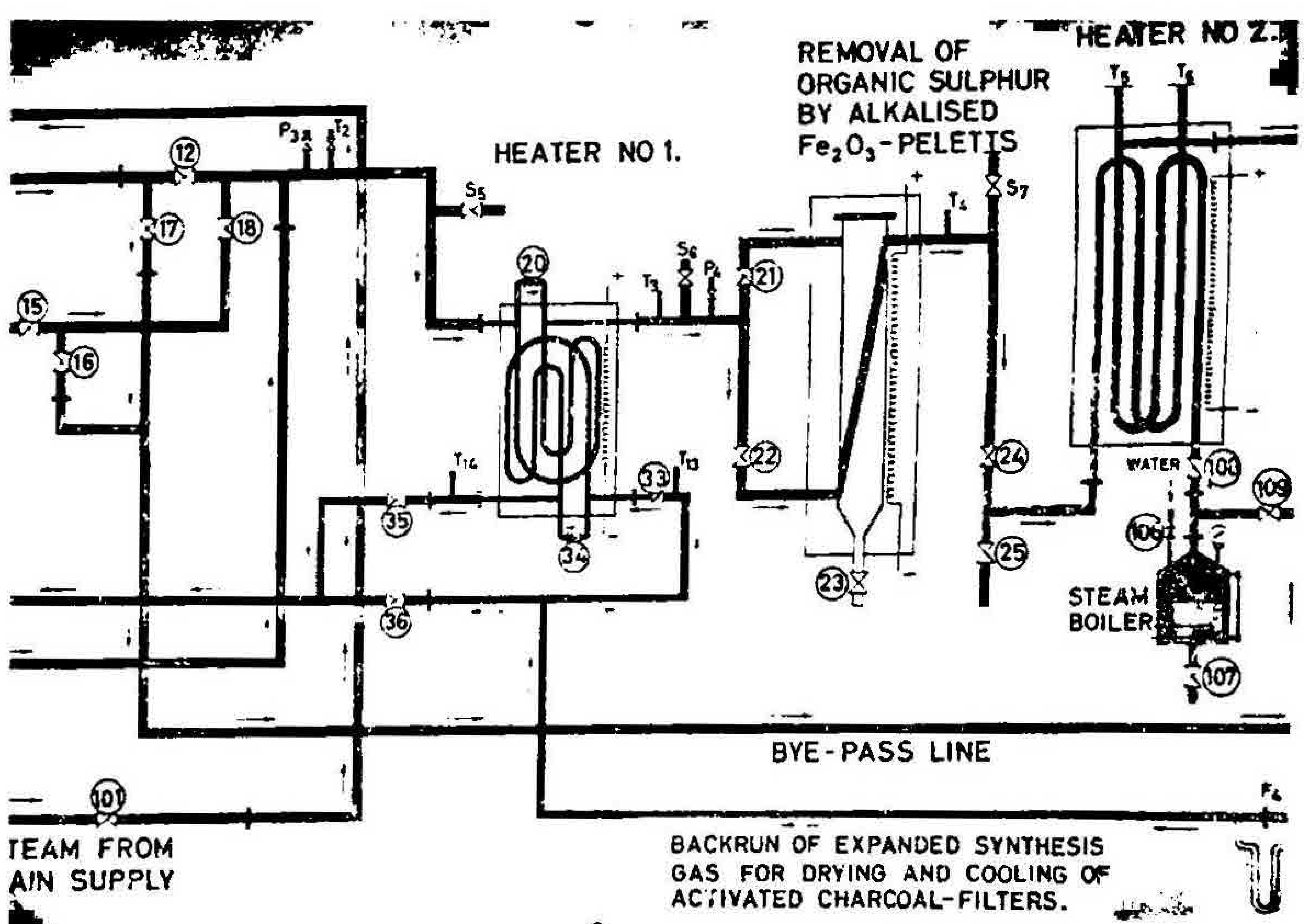

FIG. 2. Flow Sheet of Gas Heaters and Organic Sulphur Removal Tower

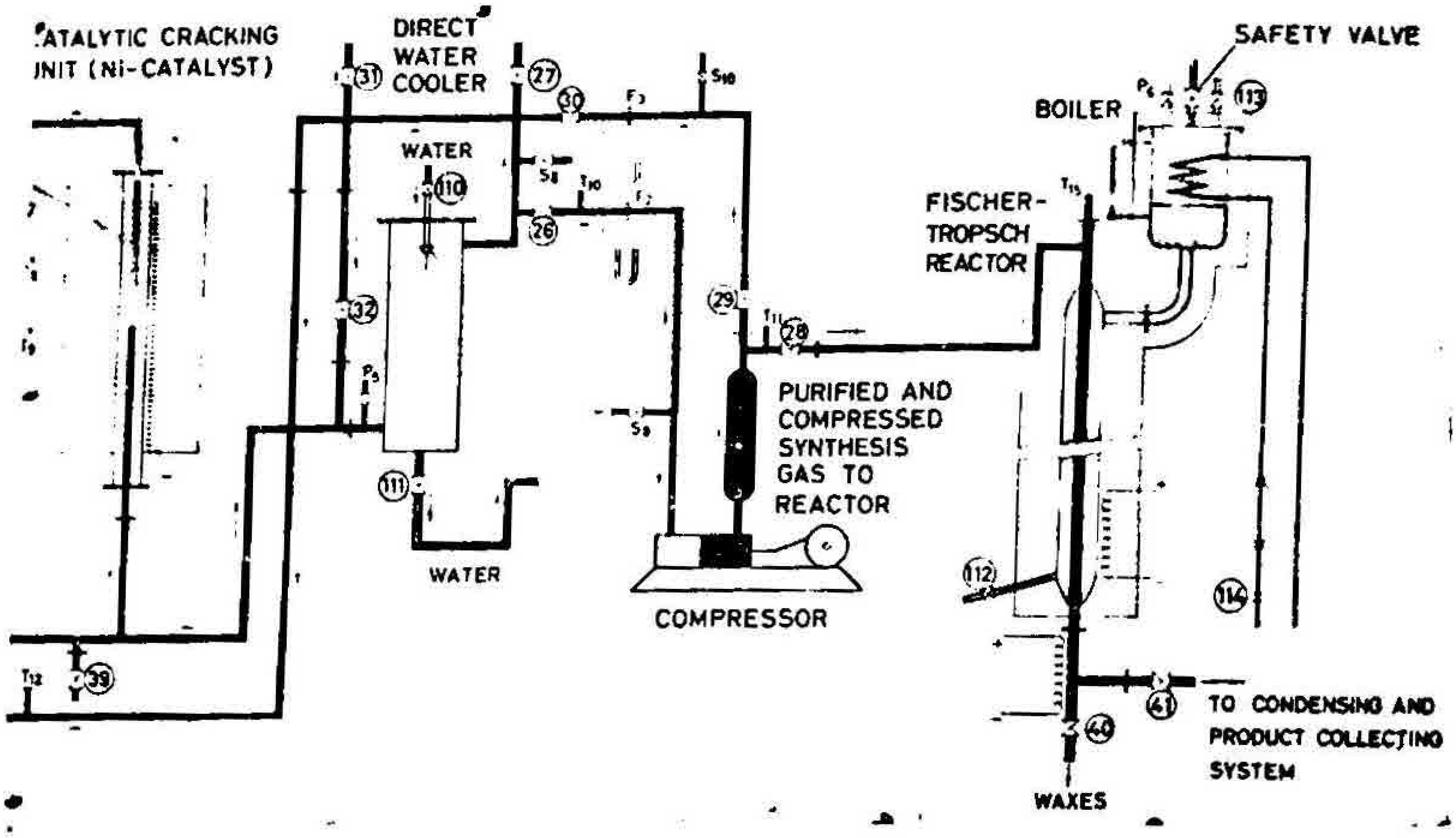

FIG. 3. Flow Sheet of Nickel Reactor and Fischer-Tropsch Reactor

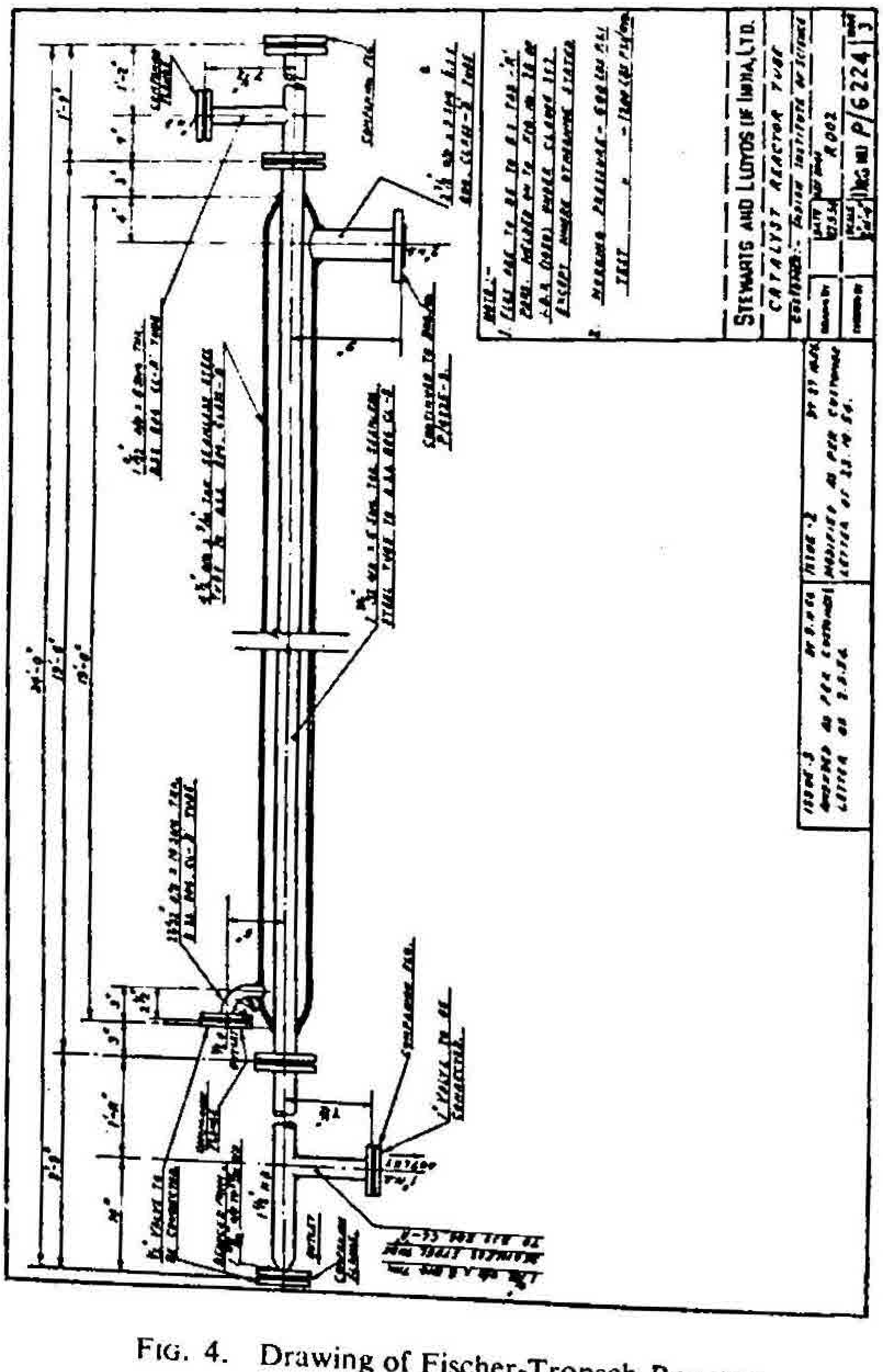

FIG. 4. Drawing of Fischer-Tropsch Reactor

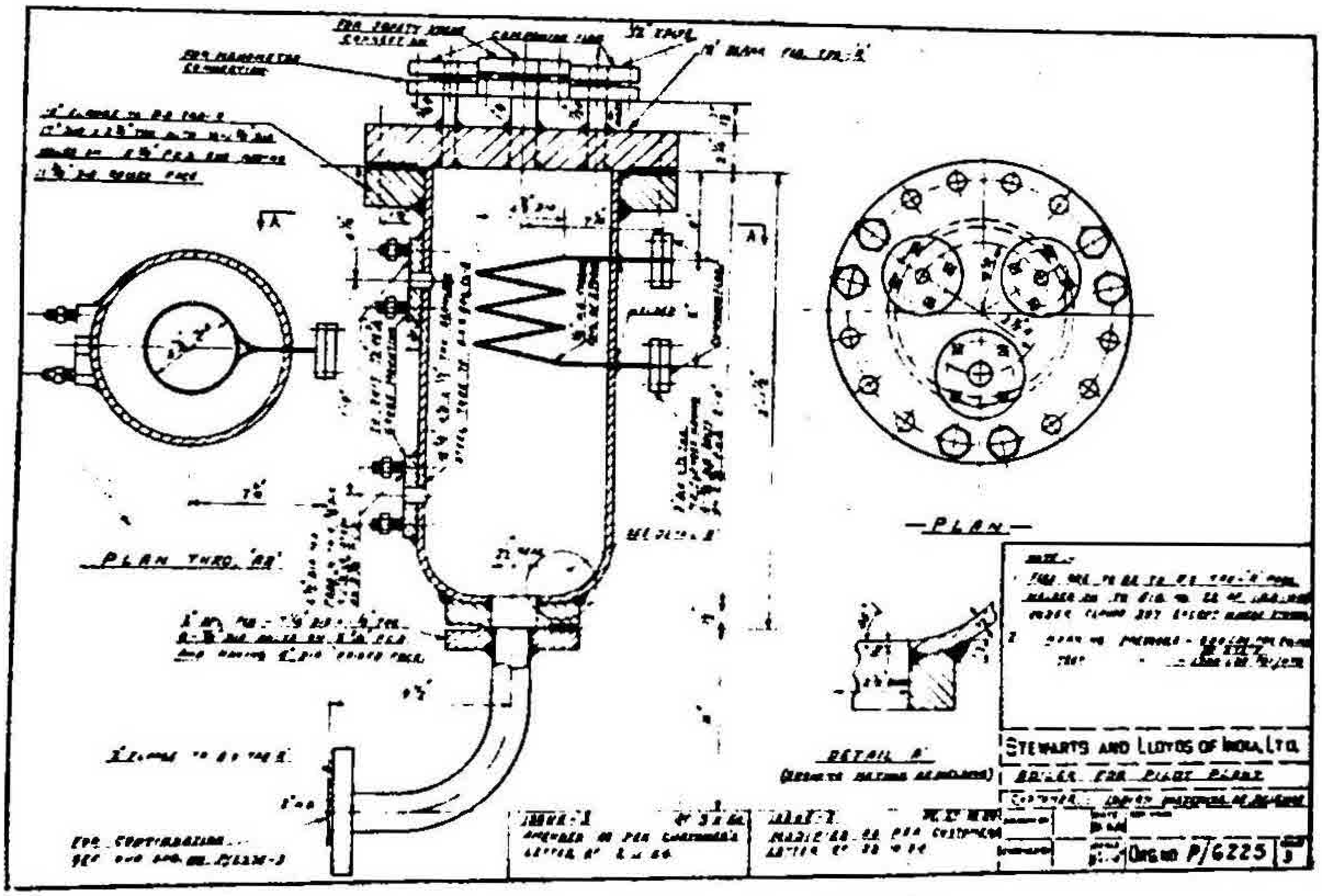

FIG. 5. Drawing of Fischer-Tropsch Boiler

ACKNOWLEDGEMENT

The construction and building up of the plant has resulted out of a teamwork in which Mr. B. S. Venkatakrishnappa, Dr. M. Ramacharyulu, Mr. B. Ramananda Rao and personnel of our workshop have mainly contributed. The construction of the plant was for more than a year under the direct supervision of Mr. B. S. Venkatakrishnappa, former Lecturer of this Department. The authors want to express their thanks to the active co-operation of these colleagues.

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