Section 12.

At 400°F., hydrogen sulphide becomes increasingly more corrosive. This corrosion is particularly severe in cracking coils where complex sulphur compounds are broken down to release hydrogen sulphide. Lime may be mixed with cracking coil charge to combine with the hydrogen sulphide formed during the cracking. Lime is not used at Sarnia since the inside of towers and drums on the cracking coils are gunited for protection against hydrogen sulphide corrosion.

Naphthenic acids present in Colombian, Peruvian and Venezuelan crudes are extremely corrosive at temperatures encountered in cracking. Guniting is also used as a protection against naphthenic acid corrosion. Where severe corrosion from hydrogen sulphide is encountered at high temperatures, some refineries use corrosion-resistant alloy tubes in the cracking furnaces and bubble towers. For the protection of soaking drums under these severe conditions gunite is often applied to the inside surface, or corrosion-resistant liners are used. The use of special alloy tubes and towers at Sarnia has not been necessary up to the present as a protection against hydrogen sulphide corrosion, since guniting gives sufficient protection and at a much lower cost. Cracking coil furnaces where the oil is heated to temperatures over 1000°F. require the use of alloy tubes to give high temperature strength and resistance to oxidation.

Periodic inspection of refinery equipment is carried out to determine the extent of corrosion. This is indicated by the metal loss of test plates and test plugs which are located where corrosive conditions are known to exist. The extent of the corrosion as indicated by the periodic inspections determines the methods that should be used to combat the corrosion.
PRODUCTION CONTROL

The preceding sections have given an outline of the routing of petroleum through the refinery, indicated the refining processes and have stressed the importance of testing. To manufacture a complete series of petroleum products requires many individual processing steps due to the many stringent specifications imposed by those who use the products. Each processing step increases the possibility of loss of some of the product. An ideal refinery would consist of one unit, which would convert crude petroleum into marketable products without loss. This ideal has not been realized to date and in a large and complex refinery losses become an important item.

Where so many individual processing steps are carried out, as at Sarnia, it is essential that each one be carefully controlled so that the cost of the finished product is definitely known and can be kept at a minimum. To ensure efficient processing throughout the refinery, standardization of all units and utilities is the means of keeping these costs at a minimum. Control of production through standardization is necessary, particularly due to the high cost of transportation of crude and products in Canada, and to the narrow margin of profit on which all petroleum refineries operate.

Production control is concerned not only with the control of chemicals and utilities, but covers all technical phases of refinery operations. Thus, it is not the concern of one department, but requires full cooperation from all of the technical groups in order to assist the operating group to maintain standardized operations and keep costs at a minimum. Production control assists the executive office to forecast profits, operating costs and the evaluation of crudes. Some of the items coming under the heading of production control are—

Anticipation of Crude Runnings
Standardization of Refinery Operations
Control of Losses
Chemical Control
Control of Utilities

Anticipation of Crude Runnings

From a knowledge of market requirements, the amounts of the various products that must be obtained from a crude petroleum are known. The composition of the crudes available are determined with this in view. The first step is to obtain an analysis of the crude petroleum by what is known as a true boiling point workup. From this true boiling point workup a yield statement can be set up, indicating the products obtainable by plant operation. The true boiling point workup is carried out by the Technical and Research Department. The laboratory workup indicates what could be expected in the refinery if the fractionating equipment was as efficient as the laboratory apparatus. Most commercial distillation towers do not give this high degree of separation due to overlapping of the distillation ranges on each cut.

Since shipping demands on Sarnia refinery are seasonal due to weather conditions and crude petroleum receipts, crude runnings must be balanced with these periods of seasonal demands to give smooth refinery operations and maintain inventories of all stocks through the year. The production control group,
with a knowledge of the Sales Department's requirements and crude petroleum receipts, draws up running schedules for the various units. In this connection the availability of different types of crude petroleum must be taken into consideration, as well as changes in product quality requested by the Sales Department, which materially affect production schedules. These changes may require extra refining steps or adjustments in yields.

Each crude presents a special processing problem. In some cases a premium may be paid for certain types of crude. This premium may apply to a crude petroleum that contains a high yield of aviation type gasoline, or to one containing large quantities of lubricating oil distillates. These premium crudes must be processed in order to obtain maximum yields of these products, otherwise the premium is lost to the company.

Wartime conditions place an abnormal demand on the refineries for certain products, such as Aviation Gasoline, Motor Gasoline, Motor and Aviation Lubricating Oils and Dunker Fuel Oils. In addition, Sarnia refinery must provide the raw materials for the synthetic rubber program. Consequently crude petroleum runs must be based on providing the maximum yield of aviation base, the maximum recovery of heavy lubricating oil distillates for the manufacture of aviation oils, and the conversion of as large a proportion as possible of the remainder of the crude petroleum charge into stocks suitable for cracking, to give the maximum yield of the gaseous and light liquid hydrocarbons that will be used in the preparation of synthetic rubber polymers. A few years ago our cracking operations were carried out for the maximum yield of gasoline. Today we are concerned with the maximum yield of gaseous and light liquid hydrocarbons for the rubber program. Since the delivery of feed stocks to the synthetic rubber units must be uniform, the cracking operations, in turn, must be levelled out for the whole year. Crude runnings at Sarnia are seasonal and as a consequence it will be necessary to store cracking coil feed stocks during the Summer months for running during the Winter. All these items involve planning in advance. This is one of the functions of production control.

Standardization of Refinery Operations

Knowing the types of crude petroleum available and the demands of the market, the production control group is able to set up operating standards for the various refining units, in order to give maximum yields of the products desired. These standard operating conditions are usually determined by a series of test runs, this work being the correlated effort of all the technical groups. Temperatures and other conditions are adjusted on the various towers and furnaces to give maximum yields of desired product, as indicated from the true boiling point workup of crude petroleum. When these standard conditions are obtained, it is then necessary to determine the maximum crude petroleum charging rate for each individual unit while maintaining standard conditions and product quality. Standard operating conditions are obtained on all treating plants and subsequent finishing plants, such as phenol treating, dewaxing, clay contact and lye washing plants. Periodic testing of all products on different units is carried out by the inspection laboratory to ensure uniformity and adherence to specifications. It is apparent that if all units were operated according to standards the number of tests required would be considerably reduced.

With the establishment of standard operating conditions, standard yields are obtained for each individual operation; thus, there are standard
operating conditions and yields for the Kellogg Unit processing Louden crude for the maximum production of aviation base stock and furnace fuel oil. There will be another set of standard operating conditions and yields for the same unit processing the same crude but running for maximum production of water white distillate. In setting up the standards which are necessary to the management to ensure maximum operating efficiency, it is necessary to have a department whose responsibility it is to see that these standards are maintained.

As stated above, this control starts with the establishment of standard operating conditions and yields, which represent optimum operating yields correlated with true boiling point yields, the most up-to-date cracking information and the market requirements.

After the establishment of these standard conditions and capacity, the minimum consumption of labour, utilities, chemicals and maintenance is established for every piece of equipment. To assist the operating group in maintaining these standards, instrumentation has been adopted as widely as possible. It should be emphasized that automatic controls supplement rather than supplant the operating group. When standards are not maintained it indicates that either the mechanical equipment is at fault, or there has been a change in charging stock, or that the operating group are not on their toes. Each refinery has invested large sums of money in automatic controls to assist in maintaining these operating standards, but a great deal depends on the vigilance and skill of the operating personnel. It is one of the functions of the production control group to assist the operating personnel in seeking out any operating difficulties when standards are not being maintained.

Failure to maintain these standards on one unit may upset the operation of many other units in a refinery and reflect on the efficiency of the operating groups on these units. As an example, failure to maintain standards on the Vacuum Flash Coils may result in the paraffin distillates containing small quantities of asphaltic material. When these stocks are phenol treated emulsion difficulties will occur, reducing the charging capacity of the Phenol Plant and the yield of treated oil. Temperatures of the treating towers will have to be increased and treating rates reduced to overcome these emulsion difficulties. When this stock is delivered to the Dewaxing Plant low filter rates will be encountered due to the asphaltic material plugging the filter screens. This will decrease the capacity of this plant due to the higher dilution ratio necessary, which results in higher solvent losses. On clay treating the dewaxed oil, higher quantities of clay than standard will be required to bring the oil to colour specifications, resulting in a further loss, lower throughput and the higher consumption of clay at this plant. Many other examples of the effect of failure to meet standards on one unit and subsequent effect on others could be given.

When equipment has been operated at a high rate of efficiency, as determined by the setting of standards, its limitations are known. If at any time any radical change in crude processing is contemplated, the management will have full information as to whether it is economical to carry out these changes in existing equipment or install additional equipment. The production control group are constantly revising standards of all equipment and thus maintaining all operations in as high a state of efficiency as possible.
Control Losses

Control of the refinery losses is one of the important functions of production control. Losses resulting from line and tank leakage and evaporation losses are mechanical in their nature and can be controlled by frequent inspection and maintenance, and the installation of vapor recovery devices. While some of the products lost in leakage can be recovered in the form of "trap slops" this means a direct loss to the management since this oil must be reprocessed. Production of off-specification products is one form of loss and can be minimized by strict adherence to operating standards. Losses from spills and frequent line washings indicate that the operating personnel are not carrying out their duties efficiently. A refinery with a low percentage of loss and a minimum production of slop indicates a well-managed organization.

Chemical Control

Chemicals are controlled by the production control group in conjunction with the laboratory. Standards for chemical consumption are set up for each unit. Whenever it is possible these standards are based on theoretical requirements with suitable allowance for mechanical losses. In cases where it is not possible to base the chemical consumption on the theoretical requirement, the standard is established on the basis of controlled plant results correlated with laboratory data. Thus, in setting up standards for clay treating lubricating oils for colour improvement, these are based on preliminary laboratory determinations, giving the quantity of clay required for colour improvement to meet specifications. This laboratory-determined quantity is then correlated with carefully controlled plant tests. Standards for the consumption of phenol are based on plant tests over a period of time under carefully controlled conditions. The importance of these standards is emphasized in view of the fact that many of the chemicals used at the Sarnia Refinery are quite expensive and under present conditions difficult to obtain.

Strict adherence to standards in treating plants is necessary and the quantities of chemicals used should not be exceeded, in which case quality is given away, nor should the quantity be underestimated, in which product quality is degraded, necessitating retreatment. As an example, there is no point in using more than the standard amount of clay to treat a lubricating oil for colour, obtaining a lighter coloured oil than specifications require, since additional value is not received for a more highly treated product. At the same time, a certain quantity of clay and oil has been lost.

Standards for chemicals used in combatting corrosion are estimated by laboratory determinations of the amount of neutralizing agent required, correlated with regular metal inspection to determine the effects of the chemical. The production control group are constantly reviewing and revising standards for chemicals to maintain all treating operations at maximum efficiency and assisting in the establishment of new standards when there is any change in product specification or crude supply.

Control of Utilities

Fuel costs are a major item in a petroleum refinery. Distillation is the main process for refining the different fractions and in this process heat is required to vaporize the oil. This heat may be supplied directly by
the combustion of fuels or indirectly by the use of steam, which requires fuel to generate it. From test run data, standards are set up on each distilling unit for the amount of fuel (gas or oil) required. This standard is based on the most economical utilization of the fuel, bearing in mind the limitations of the equipment. When these standards are exceeded it indicates that fuel is being wasted up the stack through improper firing methods. To assist in maintaining these fuel standards, instruments are provided to measure the draft in the furnace and the carbon dioxide content of the flue gases. An experienced fireman can tell from the conditions of his furnace if proper combustion is taking place. Fuel standards are also maintained for all steam generating equipment.

Steam is used in distillation processes to assist in vaporizing oil and also for pumping purposes. These quantities are measured on each unit and standards set up, which should not be exceeded. Likewise quantity standards are set up for water and air. These standards have been determined as the result of plant test runs and represent the most economical quantities to be used to maintain operating conditions. Standards for utilities may change frequently due to changes in product quality and type of fuel available. The production control group constantly revises all standards for utilities.

The production control group is responsible to the management for the maintenance of standard operating conditions and control of all utilities and chemicals entering into the production of finished products from crude petroleum. These standards are set up and maintained to take much of the guesswork out of refinery operations and the maintenance of standards depends on the co-operation of all technical and operating groups. The position of the operating personnel has not deteriorated; rather it is the duty of the production control group to assist them in all operating problems to ensure that the refinery is being operated in the most economical manner.
INTRODUCTION

During the last decade, vast strides have been made in developing continuous processes, as compared with batch or semi-continuous methods. This is especially true in the modern oil refinery. Processes developed in laboratories and pilot plants have been expanded into commercial units with throughputs much higher than ever before possible. Furthermore, the expansion program now under way to increase the output of high-octane fuel, and other special products, involves processes requiring fractionation of mixtures to purity standards never before attempted.

In order to maintain high standards of efficiency and uniform quality of products comparable to the experimental units, it has been found necessary to equip the commercial units with instruments and control equipment in a much greater degree than in the laboratory work. This equipment is required to be as accurate as possible and as dependable as the highly corrected instruments used in the original development work. The instruments manufacturers have provided new equipment when required, and adapted standard designs to new services in order to meet the requirements of designers of new units.

All these modern units have comparatively very little storage capacity and their operation is impossible without automatic control of all vital factors. However, before control can be applied, it is necessary to provide instruments which will quickly and accurately respond to changes in the various factors and these instruments, in turn, may be equipped to actuate control devices. Before discussing control equipment or its application, we will consider briefly various types of instruments available for the more important services, such as pressure, temperature, flow and liquid level.

PRESSURE MEASUREMENT

The average oil refinery uses more instruments to indicate, record or control pressure than any other classification. Every distillation apparatus must have its pressure accurately measured and controlled before temperature regulation can be of any value in obtaining desired product specifications. The choice of the best equipment available for each individual case is most important and this can only be done by those well acquainted with available equipment as well as the service involved. It is also necessary to have accurate pressure indication of steam, fuel gas, all flow lines, etc.

In the measurement of pressures, there are three main classifications:

(1) Static:

Pressure measured above atmospheric - therefore base pressure changes with the barometer.

(2) Absolute:

Pressure measured above absolute vacuum - not affected by changes in barometric pressure.

(3) Differential:

Measures the difference between two pressures either one or both of which may be above or below atmospheric pressure - as in flow meters or liquid level gauges.
Since there is no fundamental difference between the measurement of pressure and vacuum, the instruments used for both services will be considered as one group. These may be classified under two main headings as other types are not important commercially:

1. Pressure measurement by balancing an unknown pressure against a known force.
   (a) Liquid Column gauges - range limited by length of column and density of liquid - limit about 20 lbs.
   (b) Limp Diaphragm gauges - used only for very low pressures - as in draft gauges.
   (c) Bell Type gauges - range limited to about 1 lb.
   (d) Piston Gauges - suitable for high pressures where accuracy is essential - especially for suppressed ranges.

2. Pressure measurements by means of the deformation of an elastic membrane.
   (a) Bourdon tube - used for indicators from 15 lbs. to 10,000 lbs. - also simple controllers.
   (b) Helix - used for recorders and controllers up to about 2,000 lbs.
   (c) Spiral - as for helix - can be used in more shallow case but larger diam. requires more space.
   (d) Metallic diaphragm - used on solutions that would congeal and plug tubes in (a) (b) or (c) - mostly used for indicating gauges.
   (e) Bellows (metallic) - used for low range pressure and vacuum recorders.
TEMPERATURE MEASUREMENT

In oil refining practice, temperature measurement is unquestionably the most important of all instrument functions. Furthermore, the degree of accuracy and speed of response required are much more exacting than in most industries. It is therefore essential that indicating or recording thermometers purchased should be of highest quality and that the most accurate equipment available be provided for testing and checking purposes.

Glass Thermometers

Mercurial glass test thermometers are often used for test purposes for temperatures from -30 to 1000°F. Their accuracy is usually guaranteed within one scale division. Calibration certificates will be supplied by the manufacturer or the Bureau of Standards.

A great many industrial type mercurial thermometers are used, and while not so accurate as the test thermometers, their construction is very similar except for the design of the protecting case. They provide an inexpensive means of obtaining temperature indication at the point where the temperature exists, which limits their usefulness.

Tube Type Thermometers

In industries as a whole, pressure actuated recording or indicating thermometers are the largest class of major industrial instruments in use today. There are four main reasons for this fact.

1. A record of temperature is most important in the control of industrial processes.
2. They are available for ranges from -50 to 1000°F which is sufficient for most industrial or chemical processes.
3. The first cost, as well as the cost of maintenance, is lower than all other types of temperature recorders.
4. The instrument can be located up to 200' from the point of measurement and still provide sufficient speed of response for most processes. Their wide acceptance is indicative of their sensitivity and accuracy.

There are three main classes of these instruments. All consist of a sensitive bulb connected by flexible armoured capillary tubing to a pressure-sensitive recording element with required linkage and pen or indicating pointer. This may incorporate a helix, spiral or metal bellows. The entire tube system is permanently sealed on completion of calibration. Any leakage from the closed system destroys the calibration. The classes available are as follows.

1. Gas filled
   Operation is based on the volumetric expansion of an inert gas, usually pure nitrogen, in accordance with the gas laws, with pressure increasing in direct proportion to temperature. This is advantageous since it permits the use of a uniformly graduated chart. Temperature limit 800-1000°F maximum.

2. Vapor Tension
   A rise in temperature produces an increase in vapor pressures of the special filling liquid used - such as alcohol, toluene, hexane, ether, etc. The relationship between vapor pressure and temperature is not a straight-line function, therefore the chart or scale is unequally divided, the divisions increasing in width as the temperature rises - Maximum Temperature limit approximately 600°F.
3. Liquid-Filled

This system is based on the volumetric expansion of a liquid, caused by a change in temperature. The pressure varies directly as the temperature and is almost irresistible in its force. It will operate over wide temperature ranges.

(a) Mercury-filled has a temperature limit of 1200°F - most expensive of tube types.

(b) Other liquids used have temperature limit about 600°F - and are not all suitable for uniformly graduated charts.
RESISTANCE THERMOMETERS

This type is used largely for the measurement of temperatures from -150° to 300°F, due to the high degree of accuracy obtainable within this range; actually better than any other type. However, this type can be built for temperature up to 1800°F.

The basic principle of the resistance thermometer is the fact that the electrical resistance of a metallic conductor will increase as its temperature rises and the temperature-resistance relationship will be sufficiently constant to permit the measurement of temperature by means of the known relation between temperature and resistance. The thermometer consists of a specially wound resistance bulb subjected to the temperature being measured, connected by three copper wires of equal resistance, to a suitable instrument for measuring and recording the resulting variations in resistance in terms of temperature. The recording instrument used in most cases is a self-balancing Wheatstone bridge similar in appearance and operation to the Potentiometer Type recorder. The electrical circuit differs as well as the resistance values of the coils used in the instrument. The mechanical mechanism is almost identical.

---

To source of direct current

---

G

H

T

Galvanometer

Slider

J

Slide wire

S

C

B

Bulb

A

---

Schematic diagram of balanced type of Wheatstone-bridge circuit for resistance thermometers.

Potentiometer Pyrometers

In the year 1821, Seebeck discovered that if, in a closed circuit of two metals, the two junctions of the metals are at different temperatures, an electric current will flow in the circuit. From this it was determined that with the temperature of one junction fixed at that of the room temperature or of melting ice, etc., the temperature of the other junction can be determined by measuring the e.m.f. developed in the circuit. This is the basic principle of thermoelectric pyrometry.

The fused junction of two different metals is called a thermocouple. The e.m.f. developed by a thermocouple is very small, usually a few thousandths of a volt (millivolts).
Section 14

To measure such small e.m.f.'s, special types of sensitive instruments are required. These may be (1) indicating or recording millivoltmeters, (2) Potentiometers or (3) a special type of instrument embodying both of these principles. Any of these may be graduated to read either millivolts or temperature — for a given type of thermocouple. For various reasons, the recording or indicating potentiometer, number (3) above, has proven to be most satisfactory for application to oil refining and is therefore generally used.

Inasmuch as highly accurate instruments are available from several manufacturers, the weakest point has been found to be the detecting elements, i.e. the thermocouple. This is due to the difficulty of obtaining metals which —

(1) are resistant to corrosion and oxidation
(2) develop relatively large e.m.f.'s and
(3) have a temperature - e.m.f. relationship such that the e.m.f. increases continuously with the increasing temperature over the range required.

The usual combinations of metals used are as follows:

<table>
<thead>
<tr>
<th>Metals</th>
<th>Approx. Max. Temp. °F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper - Constantan</td>
<td>600</td>
</tr>
<tr>
<td>Iron - Constantan</td>
<td>1,500</td>
</tr>
<tr>
<td>Chromel - Alumel</td>
<td>2,200</td>
</tr>
<tr>
<td>Platinum - Plat. - Rhodium</td>
<td>2,700</td>
</tr>
</tbody>
</table>

![Graph showing emfs of various materials versus platinum.](image)
Other alloys are available for special services. When installed, the Thermocouple (hot junction) is placed where the temperature is measured; the free ends are connected with suitable leads to the instrument (the cold junction). In the potentiometer system, the e.m.f. generated is balanced against a known e.m.f. across a potentiometer circuit. Any unbalance is detected by a sensitive galvanometer. A motor-driven balancing mechanism detects the motion of the galvanometer pointer and moves a sliding contact along a variable resistance until the galvanometer returns to zero. The position of the contact is a true indication of the temperature at the thermocouple. Hence, by having a recording pen move with the sliding contact, a record of temperature may be produced. This system is known as the zero-balance or null method.

![Simplified Electric Circuit Diagram]

An important feature of this instrument is that the length of lead wire to the recorder does not affect the accuracy of the reading. Also, the amount of galvanometer motion is not important so long as it moves an amount that can be detected by the balancing mechanism. An automatic cold-junction compensating coil is incorporated to correct for changes in temperature within the recorder case.
Optical and radiation pyrometers are available for high temperatures but are unimportant in refinery processes. Other types of potentiometers more recently developed include:

The Galvanometer - contact potentiometer
The Photo-electrically balanced slide-wire potentiometer
The Electronic-relay slide-wire potentiometer
The Photoelectric potentiometer

![Diagram of Slide Wire Potentiometer]

**ELECTRONIC RELAY Slide Wire Potentiometer**
(A) FLOW MEASUREMENT

The use of positive displacement meters in oil refineries is limited to special applications, hence will not be covered in this short course.

Orifice Meters

Rate of flow meters is one of the most important groups of instruments used in refinery service. Practically all flow measurement is done by these differential type meters.

The differential flow meter operates on the principle that there is a definite differential pressure created across a primary element, usually an orifice plate, in the flow line for each rate of flow. This differential is measured by a specially-designed manometer or bellows to which the recorder is attached. The recorder may be calibrated to read either in terms of differential pressure or directly in rate of flow.

Illustrating the differential pressure created by fluid flow through an orifice.

Remote recording is becoming more popular and in such cases the meter transmitter is located adjacent to the orifice plate and the flow reading is recorded, either electrically or pneumatically, at a distant centrally located point.

(1) Primary Elements:

Several types of differential-producing devices are available as follows:

(a) Orifice Plates -
  Concentric
  Eccentric
  Segmental - fixed or adjustable
(b) Flow Nozzles.

Bailey Flow Nozzle.

![Diagram of Bailey Flow Nozzle]

(c) Venturi Tubes

Illustrating the effect of orifice shape upon the location of the low pressure connection.

Pressure distribution in the neighborhood of an orifice. (Courtesy of The Foxboro Company.)
All primary elements must have an accurately calculated hole or throat diameter and be manufactured within limits of $\pm 0.001''$ per inch of hole diameter.

Orifice Design

While it is not within the scope of this discussion to cover orifice design in detail, it is considered that a general idea of the factors involved should be had by all those using flow meters.

The orifice is possibly one of the oldest devices for measuring or regulating the flow of fluids. Records show that the Romans of Caesar's time used it to measure water to householders. In spite of this, it is only within the last 35 years that its behaviour as a device for the measurement of the flow of fluids in pipe lines has been systematically studied. The early investigations were carried out by independent organizations and the results were closely guarded secrets for the benefit of their own commercial use. However, in recent years the A.S.M.E. and A.G.A. have sponsored a joint committee, in whose report the reliable data have been correlated and published for the benefit of all manufacturers and users of flow meters.

An orifice plate is simply a thin metal disc, with a specially designed opening, which is installed between a pair of flanges in the flow line. Its function is the creation of an artificial, though temporary, pressure drop in the pipe in the region immediately following the orifice. The design is always on the basis of a certain definite set of operating conditions, as follows:

1. The maximum rate of flow to be measured.
2. The density of the fluid, or its equivalent, expressed in terms of pressure, temperature, quality or specific gravity.
3. The viscosity at flowing conditions.
4. The pipe size where the orifice is to be installed.

When these conditions are known they serve as a basis for the selection of the proper meter differential, which largely determines the size of the orifice hole.

(2) Secondary Elements

(a) Indicators

Glass tube manometers are widely used as an inexpensive flow indicator. They consist essentially of a glass tube, U-shaped, and half full of mercury or other liquid, and the ends connected to the two sources of pressure. A scale is mounted behind the tube on which to read the difference in height of the liquid columns. In some instruments only one leg has a glass tube, the other forming a well at the base of the column. A specially-calibrated scale is mounted beside the tube. Another similar method is to have the glass tube slanting at about 30° with the horizontal. This in effect magnifies the readings giving greater sensitivity.

(b) Recorders

Most recording flow meters use a modification of the simple U-Tube manometer. The simplest type is a mercury manometer with a large float chamber for one leg of the instrument, containing a metal float connected by a lever arm to one end of a shaft extending through the wall of the chamber. The other end of the shaft carries the pen arm which moves across a circular chart of conventional design. A pressure seal is provided on the shaft to prevent leakage from the manometer.
As far as practicable, the float chamber is designed so that:

1. The float is as large and flat as possible.
2. The lever arm is as long as possible.
3. The float travel is a minimum.

The low pressure leg is made of such height and diameter to permit calibration of the instrument to the differential range desired. The maximum differential may be anywhere from 20" to 200" of water or in special cases, even higher.

A chain and segment arrangement is used by the Foxboro Company instead of the conventional float lever, in order to eliminate the error due to angularity of the linkage.
The flow through an orifice or other primary device varies as the square root of the differential pressure produced. Hence, since the above-described indicators and recorders read in terms of differential pressure, the actual flow is shown on a square, root scale, the disadvantages of which are:

(1) The spacing on the scale or chart is cramped and difficult to read up to 30% of the chart.

(2) The actual distribution of flow is not evident from the chart, since there is no direct relation between flow and pen movement.

(3) The testing and calibration are somewhat confused by the square-root relation.

(4) If an integrator is used to totalize the flow, the mechanism is very complicated and critical in adjustment.

(5) With automatic control requiring a wide throttling range, the square root relation between flow and pen movement may disturb the balance of the system.

These two charts measured the same flow. Note the distorted, misleading result by the Square Root Chart and the accurate visualization of load conditions afforded by the Uniform Chart.

These difficulties may be overcome by the use of a square-root compensated flow meter.
In the Foxboro compensated meter, the range tube is bellshaped increasing in size toward the base of the tube. If the shape of the curve is parabolic, perfect compensation will result. The actual compensation begins at 10% flow.

Sectional View: Universal Meter

In the Bailey flow meter, a compensating Ledoux bell is used to extract the square-root function. The inner wall of the mercury-sealed bell follows a parabolic curve to effect the compensation all the way from zero to full scale.

Type C Flow Mechanism (left) and Type CH Flow Mechanism (right). Rear view cross sections.
Other systems have been developed for this purpose, but are less widely used. The Taylor Instrument Company have recently developed a mercuryless, bellows, operated, differential recording flow meter employing a torque-tube pen operating shaft. This eliminates the usual pressure-tight bearing necessary with most float or bell-type meters.

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*Principal parts and operating details of the Taylor Aneroid Flow Meter*

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*Single-Pen Recording Thermometer, showing methods for compensating ambient temperature errors. (a) Simple case compensation. (b) Double-tube capillary compensation.*
(3) Electric Remote Transmission

The Brown Electric flow meter uses the Inductance Bridge System. Although this eliminates friction or leakage due to the usual pressure-tight bearing, its accuracy below 70% of flow is not as good as the mechanical float-type meters. From 70% to 100% they are of equal accuracy.

![Diagram of Electric Remote Transmission](image)

There are other electrical transmission systems available having greater accuracy. They are more elaborate and expensive and are not used to any great extent by Imperial Oil Limited.

(4) Pneumatic Remote Transmission

This system consists essentially of a mechanical flow indicator, equipped with an air control mechanism. The air pressure set up varies uniformly from 2 to approximately 15 lbs. as the flow increases from 0 to 100%. This pressure is transmitted through a small tube to the recording receiver in which a pressure element is used to operate the pen, calibrated to read in the original flow units.

![Diagram of Pneumatic Remote Transmission](image)
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This system consists essentially of a mechanical flow indicator, equipped with an air control mechanism. The air pressure set up varies uniformly from 2 to approximately 15 lbs., as the flow increases from 0 to 100%. This pressure is transmitted through a small tube to the recording receiver in which a pressure element is used to operate the pen, calibrated to read in the original flow units.
(b) LIQUID LEVEL MEASUREMENT

In continuous processes, such as modern petroleum refining units, the measurement of liquid level has become more important from an operational standpoint, then it was previously when processes required a large inherent storage capacity for their operation. The control of level was largely done by hand-operated valves and a gauge glass served as the indicator. This was quite satisfactory since it was impossible for the level to change rapidly. In the newer designs of continuous units, throughputs have been stepped up and, at the same time, initial costs have been reduced by cutting out all excess liquid storage capacity. This makes it necessary to use an efficient level controller to compensate for rapid fluctuations in level due to changes in inflow and outflow without the stabilizing effect of large liquid volume.

Before satisfactory control can be obtained, a sensitive and reliable level-responsive instrument must be available from which to operate the control mechanism. Most equipment of this type can be supplied as a recorder, the chart giving a permanent record of operation as well as serving as a valuable operating guide, especially when the unit is designed with a central control room.

We will consider only those types suitable for use on closed vessels under pressure.

(i) Float-Operated Instruments

Most float-operated recorders suitable for application to closed vessels are of the float and lever type. This consists of a float rigidly attached to the end of a lever arm pivoted at a point on the side of the vessel. The recorder pen arm is moved by linkage connected to the float lever arm.

In some types the float is located external to the vessel in a suitable chamber installed on the side of the vessel, with pipe connections above and below the liquid level. The float mechanism may be provided with a compressed-air pilot valve, similar to that used for control purposes, which varies the pressure in an air line leading to the recording instrument in direct proportion to changes in level. The recorder is then essentially a pressure gauge calibrated to read in terms of level.
Except in special cases, float-operated instruments are suitable only for narrow ranges, often being satisfactory for control purposes but of little value as a recorder. The range is limited by the length of float arm and the permissible angular travel. An appreciable error due to angularity is introduced beyond certain narrow limits. Some manufacturers such as Mason-Neilan apply suitably designed cams in the linkage to eliminate this source of error.

The Fisher Governor Company has developed a float type level indicator in which a slim cylindrical float is supported vertically by a cantilever spring. As the liquid level rises or falls, the buoyancy of the float is changed, permitting the spring to move an amount much less than the change in level, but proportional to it. In so doing, a small secondary lever is moved which controls an air pilot valve connected by a small tube to the indicator or recorder. These are available for ranges up to about 36”.

(2) Differential Pressure Type Instruments

Any differential type manometer having straight-walled chambers, such as used for flow measurement, is applicable to liquid level service. This has several advantages over the float-operated type -

1. Standard instruments are available for ranges up to about 300 inches of water differential.

2. Being a standard design flow meter it is produced in large quantities, hence the cost is relatively low.

3. Standard instruments are available for any working pressure eliminating the element of danger involved in the use of a glass manometer when high pressures and temperatures are encountered.

4. Direct-connected mechanically-operated instruments may be located at a considerable distance from the vessel without the expense of remote transmission.

5. When applied to service on corrosive liquids, seals may be provided to protect the instrument without the use of special alloy parts in the instrument.

When installed, the high pressure side (float chamber) is piped up to the point of maximum liquid level where a volume chamber is inserted. This is necessary in order to maintain a practically constant level in the high pressure leg regardless of the movement of the mercury or other mechanism in the manometer. The low pressure side (range tube) is connected to the tank bottom or minimum recorded level. Thus a constant pressure is maintained on the high pressure side and all the pressure differential is produced by variations in liquid level in the vessel.
In comparing this operation with that of flow meter service, there are some important differences:

The maximum differential reading is produced when the pen is at zero level, whereas in flow measurement the pen is at the outer edge of the chart for maximum differential. It is therefore necessary to provide a reversing linkage or use charts with zero level at the outer edge. The former procedure creates less confusion and is better practice from an operational standpoint.

When instruments of this type are installed on vessels where the density of the liquid in the vessel, as caused by high temperatures, is different from the density in the external high pressure leg, the required compensation may be made in the calibration of the instrument. Liquid seals between the liquid in the vessel and the manometer should only be used when absolutely necessary, since any leak of the sealing liquid creates unbalanced liquid columns in the system with a corresponding error in readings. Conditions requiring liquid seals are:

1. When the liquid is chemically corrosive.
2. When the liquid tends to solidify at the ambient temperature.
3. When the liquid is highly volatile.

The reasons for (1) and (2) are obvious. With volatile liquids there is the tendency to form gas in the connecting piping, thus disturbing the balance of the liquid columns.
Differential-type level instruments are not affected by the pressure in the vessel since it acts on both sides of the manometer. However, in some cases at high operating pressures the vapor density above the liquid is sufficiently great to create a readable error and compensation must be provided in calibration.

Either electric or pneumatic remote transmission systems, as used for flow meters, are available for operation from both float-operated and differential types of level instruments.

References

AUTOMATIC CONTROL OF PETROLEUM REFINING PROCESSES

Automatic Control could be defined as the mechanical technique of integrating responses obtained from primary measuring instruments and producing counter-responses calculated to maintain a state of internal balance in a process under control. It is obvious to all concerned with the operation of refining processes, that some mechanical means of maintaining a steady state of internal balance in a continuous process is essential. In fact, a modern refining unit is so dependent on the instruments that control it, that it would be necessary if these instruments were not available, to confine the operations to simple units incapable of producing the quality or quantity of inexpensive products available today. In view of this, to list the advantages of automatic process control would require the inclusion of the advantages of the continuous refining process itself. Some of the advantages of automatic process control are:

1. Lower labor cost
2. Elimination of the human error
3. Closer control of the process
4. Reduction in space and material required for process equipment of a given capacity.

The scientific application of control is comparatively new in its more complex forms. Simple controls have been available almost as long as the primary instruments upon which they depend for their operation. The more complex controllers have been developed within the last ten or fifteen years. In every case the instrument was developed to solve a control problem already in existence.

In the petroleum refining industry wide-spread use of controllers has taken place only during the last ten years or so. Many people feel that too much emphasis has been placed on the subject because they recall the time when little or no control equipment was used and, in their opinion, equally as good results were obtained. A study of the situation reveals, however, that the acceptance of control in refining processes is due to fundamental changes in design of distillation equipment, for example, rather than desire to go modern.

CONTrollable FACTORS IN REFINING PROCESSES

Due to the limited amount of time available, we will be unable to discuss all controllable factors in detail. However, the more important applications will be discussed more or less briefly.

1. Temperature

Temperature is by far the most important factor requiring control in Oil refining. Maximum yield and quality of each product withdrawn from a fractionating column is largely dependent on the maintenance of a constant specified temperature in the tray from which the product is obtained. Temperature is equally important in all distillation, cracking and oil treating processes. In consideration of the above and the large number of factors affecting the control of temperature, a more detailed discussion of this subject will follow.
Furnace Outlet Temperature Control using gas as fuel.

Automatic Fireman Installed on Gas-Fired Tubular Furnace
2. Flow

In order to maintain any sort of balance in a continuous process, the control of the flow of materials to and from the process is essential. This may be simple volumetric metering regulated by delivery pump speed, or it may be a complicated flow measuring and controlling instrument capable of maintaining a constant rate of flow against variable delivery pressures, viscosities, etc.; the latter based on flow measurements obtained by means of the flow meters discussed in a previous lecture.

The flow of liquids and gases may be controlled usually by the use of orifice type meters. The control of materials in solid or powdered form is more difficult since they are most readily injected at atmospheric pressure by feeder valves, automatic feeding scales, etc., all of which are more difficult to keep in satisfactory operating condition than the valves used for liquids and gases. They can, however, be incorporated, when necessary, into a complex continuous process.

3. Pressure

The control of pressure or vacuum is also very important in all distillation and many other refining processes. Pressure control is used not only as a means of obtaining the desired condition for the required inter-dependent combination of pressure and temperature in distillation but also to obtain constant flow through control valves, etc.

4. Liquid Level

Fractionating towers, reboilers, etc., are dependent as a rule on a correct liquid level for the successful operation of the process of which they are a part. Level control is closely associated with flow control, since one is often affected by the other. Devices for measuring level were discussed in a previous lecture. Their adaption to control will be considered briefly later.
The following factors are also controllable but being of less importance will not be discussed.

5. Speed of Pumps and Turbines
6. Viscosity
7. Specific Gravity
8. pH
9. Calorific Value of Gaseous Mixtures
10. Flow Ratio

FACTORS AFFECTING THE CONTROLLABILITY OF A PROCESS

As mentioned previously, the control of temperature is highly important in any Petroleum Refining Process. For this reason, and since it is affected by more factors than most other control applications, it has been chosen for further discussion. Fortunately, certain basic principles apply to all control problems. It is not within the scope of this lecture to cover this phase in detail but some knowledge of the various factors affecting the controllability of a process should be had by the operating staff.

A detailed study must be made by the designers of any new unit in determining the most desirable types of equipment and their proper application. It should be borne in mind that all control of temperature involves the control of heat transfer. This may be by direct mixing, by tubular exchangers, by furnaces, by a bubble tower involving vaporization and condensation, etc.
STORAGE CAPACITY

In a continuous process, storage capacity, either as fluid volume or as heat content, constitutes the equivalent of a fly wheel to keep the system in equilibrium. Large storage capacities sometimes introduce lags which may be unfavorable to control but the predominant effect of all storage capacity is favorable. Its absence generally indicates that careful consideration must be given to the type of control equipment used. Its favorable effect increases as the rate of heat input approaches the rate of heat absorption. It can become an unfavorable factor if the rate of heat input exceeds, to any great degree, the rate of heat absorption.

In the case of continuous shell stills run in series, the amount of stored liquid in the stills is high compared to the rate of throughput. The stored heat capacity is large enough to permit wide variations in rate of throughput or rate of firing, without seriously affecting oil temperatures.

The modern tube still, which has replaced the shell still, is quite different. It has tubes in the floor, walls and roof of the combustion chamber to absorb radiant heat; and a bank of tubes, in a convection section for absorbing convection heat. The stored heat in the liquid is small compared with the rate of heat input, although it is possible in some furnaces, to have a fairly large ratio of stored heat in the brickwork as compared to the rate of heat absorption by the oil. With this radical change in furnace construction, it has become essential to provide constant heat input and constant rate of flow through the heating coil in order to maintain a steady outlet temperature. In most cases, heat is absorbed so rapidly, as compared to old methods, that the small amount of heat stored in the brickwork has lost its steadying effect due to the rapidity with which it is absorbed.

The effect of storage capacity on the control of level will be included in our discussion of level control.

TRANSFER LAGS

Of equal importance in the effect on the controllability of a system are transfer lags. Although the use of the word "transfer" as a proper descriptive adjective for the lags referred to may be the subject for some discussion, it is sufficiently broad to cover the various subdivisions of lag which go to make up the composite group always present in all process work. The word "lag" implies a time factor and for purposes of this discussion, we will define lag as the time interval which elapses between a load change and the time that its effect is felt by the sensitive element. As a rule, the shorter the lag, the simpler the control problem. It is not, however, intended to infer that a problem with no lag whatsoever can be solved with the simplest type of control mechanism, as lags must be considered with capacity effects, etc. We will consider some typical cases of lag.

Assume we have a tube still with a long run of heating tubes in which oil is heated to 1000°F outlet temperature. Regardless of the velocity of oil through the tubes, some definite time is required for a molecule of oil to pass through the heater – it may be seconds or minutes. At a given instant, with every ordinary variable constant except inlet temperature, it is obvious there will be a lag in recording this temperature change if the thermocouple is located at the coil outlet. A controller on outlet temperature must wait for the indication of this change in demand before it can begin to adjust the control system to the new load conditions. This type of lag is known as "velocity-distance" lag or "transportation lag" and is one of the most difficult for which to compensate. Its effect is also increased due to the fact that heat is not applied to all parts of the coil.
evenly and the temperature change has been decreased somewhat by the time the oil reaches the coil outlet. A partial solution might to be locate the thermocouple at a point in the coil where the highest temperature differential exists and where larger temperature changes are felt.

A very obvious type of transfer lag is that involved in transferring heat through a conventional type counter-current heat exchanger. The time factor involved in this type of lag is a function of (a) the coefficient of heat transfer of the heat-transferring surfaces (b) the temperature potential and (c) the velocity of flow of the transfer medium. If the conductivity factor is low and the temperature potential is small, the lag will likely be large even with high velocities. Regardless of the ability of the designer of an exchanger, even the best commercial types involve a lag of some definite quantity.

The capacity of a heat exchanger is affected by the specific gravity and specific heat of the transfer mediums as well as their velocities through the system. Any change in these factors may affect the control of the process, and this often explains why a process may be in good control at one time and suddenly become very erratic for no apparent reason.

**THERMAL POTENTIAL**

While advances have been made in the design of heat transfer equipment, most of the improved efficiency of exchangers has been effected by increasing transfer rates and velocities of flow, without any great change in thermal potentials. From the process angle, the problem is nearly the same as ten years ago since we are heating and cooling through practically the same differentials. In cooling tower bottoms, the inlet oil temperature and initial cooling water temperature are the same as years ago. Although most such cooling is by tubular exchangers rather than "worms" in open boxes, the temperature potentials remain unchanged.

In the case of the tube-still furnace, the situation is somewhat different. The older designs had small radiant sections and large convection sections. Modern design makes use of radiant heat for the major portion of the heat input without danger of localized overheating. This had stepped up furnace capacity materially due to increased thermal potentials.

This increase in thermal potential has made control more difficult. All other factors being equal, the greater the thermal potential between supply and demand, the more difficult the control problem. A similar effect can be produced by an over-sized control valve. In either case, extremely accurate positioning of the control valve is necessary to compensate for a specific load change.

In summing up the foregoing discussion, it can be stated that the most difficult control problem would be one which had a minimum storage capacity, a maximum transfer lag, a high thermal potential in the heat transfer system, and an oversized control valve. It is obvious there are a wide variety of combinations of the above factors with varying degrees of intensity and therefore no simple formula can be laid down for their analysis. Until such an analysis is attempted, it is poor policy to pass judgment on the type of control equipment best suited for the service.

**AIR-OPERATED CONTROLLERS**

Since pneumatic control is most widely used in refineries, electric and hydraulic types will not be considered.
Assuming a process has been designed properly, it is necessary to choose a control mechanism that will function in such a way as to minimize the effects of the lags present. The controller mechanism is of great importance since it is the only means available for counteracting the inherent instability of a continuous process. Those available are:

1. On-and-off or two position control
2. Proportional or throttling control
3. Proportional combined with automatic reset or droop correction

**ON-AND-OFF CONTROL**

This classification is almost self-explanatory. It refers to all types of controls in which high and low contacts around a given control point are made to open or close a valve, or to move a valve to two positions, not necessarily fully open or fully closed. Although the number of such controls sold is greater than all other types combined, they are rarely, if ever, used in oil refineries.

**PROPORTIONAL CONTROL**

The first refinement of the simple basic 2-position control was the construction of a control mechanism that would cause the control valve to assume a position proportional to the deviation of the temperature from the point of control. In this type, there is one position of the control valve for each temperature within the temperature range encompassed by the open and shut positions of the valve. This temperature range is known as the "control band" or "throttling range". The width of the band with respect to the total range of the temperature measuring device is usually expressed as a percentage or ratio. The narrow-band controllers have a range of about 10% of the full scale. The wide-band type may have a throttling range of 100% or in some cases as high as several hundred percent. In the latter case, the valve cannot be moved through its full travel without manual readjustment, and for a normal temperature deviation, the valve moves only a very small amount. Most proportional controllers have an adjustment permitting variation of the control band width. The set point about which the control operates is also variable throughout the instrument range. There is no functional difference between narrow band and wide band controllers, although a more complicated and expensive mechanism is required to achieve the wide band characteristics.

Due to the fact that a departure from the control point is required to move the control valve, there is only one point on the scale where the temperature will be on the control point. This characteristic is sometimes termed "droop", the degree of which is a function of both the load change and the width of throttling range adjustment. A manual resetting adjustment is usually provided which is satisfactory if load changes are infrequent.

![Diagram](image-url)

(Proportional-position control characteristics.)
PROPORTIONAL WITH DROOP CORRECTION

If the characteristics of the system under control require a wide throttling range adjustment in order to avoid cycling control, best results will be obtained by using an instrument with automatic droop correction. This incorporates a "floating" feature which automatically corrects for the departure from the control point or "droop". It is added or superimposed characteristic and does not ordinarily affect or change the throttling range adjustment. It begins to operate the instant there is the slightest departure of the pen from the control point. It changes the air pressure to the control valve just enough to make up the difference between that required to hold the pen at the control point and that which would be supplied by a throttling controller to hold it at a point other than the controlled temperature.

![Graphs showing the operation of droop correction](image)

- Graphic analysis of floating and proportional control.

PRACTICAL POINTS

1. Failure of Air Supply

All pneumatic controls should be designed so that in case of air failure, the control valve will assume the position whereby the least trouble will result. For instance, in the case of reflux control, the valve should go wide open since, less trouble results from an excess of reflux flow and resultant temperature below normal, than would be the case if the reflux were to be suddenly cut off, causing a rise in tower top temperature. On the contrary, in firing a furnace, it is obvious that the fuel valve should close on air failure in order to prevent excessive temperatures which may cause failure of furnace tubes.
2. Control Valve Position

Although there has been a lack of standardization among manufacturers of control equipment, control valves are generally designed to operate over a range of approximately 2 to 15 lbs. Each controller is provided with a gauge showing "air to valve" or "Diaphragm" pressure, from which the operator may tell at a glance, the approximate position of the control valve. Whenever the pressure is less than 3 lbs. or more than 13 lbs., the valve is approaching or has reached the open or closed position, as the case may be. At such times, the limit of the ability of the equipment to control is being approached or has been attained, and the operator should immediately attempt to find the cause. Once the control valve has moved to either limit of its travel, the process is no longer under control. If the control equipment is properly designed, this condition can only exist when something abnormal is occurring within the process and it is the duty of the operator to get the unit back on control as soon as possible.

3. Pump Control

Pumps may be controlled from instruments measuring flow, pressure, temperature or liquid level. In practically all cases, if the pump should lose suction, the controller will continue to move the control valve, in an attempt to restore the controlled medium to the control point. This aggravates the condition which can only be corrected by the operator. If there is no liquid available, the solution to the problem is obvious. However, if the pump has lost suction due to some other cause, it can very often be corrected by slowing the pump by hand control for a short period, following which the system may be gradually put back on automatic control.

4. Swinging from hand to automatic control

It is most important that this be done slowly. That is, the block valve ahead of the regulator must be opened slowly and at the same time the by-pass valve, used for hand control, must be slowly closed so that no sudden change in flow will occur. Otherwise, the system will be upset until such time as the controller can adjust its regulating valve to the position required for the existing demand.

There are other points equally important in the satisfactory operation of control equipment, but they can generally be learned only by experience.

References:

T. J. Rhodes - "Industrial Instruments for Measurement and Control" - McGraw Hill

COMBUSTION

Introduction

The purpose of this lecture is to explain briefly the fundamental principles of combustion. A knowledge of these principles by the foreman and operators of refining units is essential for two main reasons:

1. As an aid in good operation - Modern refining units, particularly cracking furnaces, must have close temperature control on the heater coil outlet. An understanding of the combustion principles involved is of great help in obtaining good furnace operation, whether the furnace is fired automatically or by hand.

2. As an aid in decreasing costs - Since fuel is one of the largest controllable items of expense, it is possible, by its efficient use, to help keep costs at a minimum.

In the new plant, there will be several units that do not have furnaces, but all units will use steam and it should always be remembered that every piece of equipment that uses steam, uses fuel indirectly. Approximately 85% of the cost of steam is for fuel. Therefore, although fuel may not be used directly in some units, steam is used by all, and any saving made in the use of steam is indirectly a saving in fuel.

Fuels

The fuels which are most commonly used in refinery furnaces are refinery fuel gas and fuel oil. Of late, due to the great demand on bunker fuel for war purposes, coal has also become a refinery fuel to a limited extent. In the new units being built here - other than the boilerhouse - it is expected that fuel gas will be used entirely.

Each different fuel has its own Heating Value or Heat of Combustion. This is the amount of heat released when a unit quantity of that fuel is completely burned. There are usually two values given, called the Higher and Lower heating values. The Higher Heating value is the total heat given up by the fuel, assuming that the products of combustion including steam formed are condensed and cooled to 60°F. The Lower Heating value is the heat released, assuming that the water vapor formed is allowed to go up the stack as steam. Since water vapor or steam is formed when hydrogen is burned, it follows that, for a fuel containing no available hydrogen, the higher and lower heating values would be equal. The higher heating value is used in all calculations of fuel consumption for accounting purposes in this organization. It would seem that the logical basis for any calculation would be to use the Lower Heating value, because that is all that is available from the fuel under ordinary furnace conditions. But a laboratory determination of the heat content of a fuel by means of the calorimeter, gives the higher heating value, and this is one of the reasons why it is used. The Higher Heating value of fuel oil may be computed by using Dulong's formula,
B.T.U./pound = 14,600C + 62,000 (H - \frac{O}{3}) + 4050S

where C, H and S are the percentages of carbon, hydrogen, oxygen and sulphur respectively in the fuel.

For determining the higher heating values of pure hydrocarbon gases, Nelson gives a method using the structural formula of the compound. The following values for the various parts of the structural formula are given:

<table>
<thead>
<tr>
<th>Bond</th>
<th>Gross Heat Liberated B.T.U. per pound mol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>C - C</td>
<td>95,220</td>
</tr>
<tr>
<td>C - H</td>
<td>94,860</td>
</tr>
<tr>
<td>C = C</td>
<td>219,240</td>
</tr>
<tr>
<td>C = C</td>
<td>365,760</td>
</tr>
</tbody>
</table>

It is recommended that the Esso Blue Book be used for determination of Heating Values of fuels for accurate calculations.

Refinery fuel gas is composed of light hydrocarbon gases, principally methane, ethane and propane, and its main source is from cracking operations. Its B.T.U. or higher heating value varies between 1400 and 1700 B.T.U. per cubic foot, depending on the percentage of each component. It is slightly lighter than air, its specific gravity ranging between .9 and 1. Fuel gas is an exceptionally clean fuel and is ideal for use where close control of combustion is required. Because of the small amount of fuel in the furnace, at any one time and the fact that it requires no special preparation, fuel gas lends itself very readily to automatic control. It is, of course, necessary that the gas be supplied at sufficient pressure in order for its delivery to the furnace to be under control. For the customary type of automatic fireman, the gas is supplied at a minimum pressure of 15 pounds gauge. The B.T.U. value should also be reasonably constant.

The fuel oil burned in the refinery is generally a cracked tar of fairly low A.P.I. gravity. The heating value of fuel oil varies with the gravity a 10° A.P.I. fuel oil having a higher heating value of approximately 18,300 B.T.U. per pound. It might be well to point out that a pound of heavy fuel oil contains less B.T.U.'s than a pound of lighter fuel, but that a gallon or barrel of heavy fuel contains more B.T.U.'s than a similar volume of light fuel. Therefore, if fuel oil is being bought by the barrel, it is advantageous to buy fuel with a low A.P.I. gravity, or a high specific gravity.

In addition to the Heating Value there are several physical qualities of fuel oil which are important.

The Viscosity of an oil is a measure of its resistance to flow, that is, its internal friction. Since this is decreased by heating, the viscosity determines to what temperature oil must be heated in order to pump easily or to be atomized thoroughly. A special quality of cracked fuels is that it is possible for them to have a low gravity, and yet at the same time have a low viscosity.
The Pour Point of a fuel is the lowest temperature at which it will flow, or can be pumped. This quality must be known if a fuel is to be stored, as it determines the temperature at which it will become a semi-solid. Some fuels may have a low viscosity and yet have a high pour point. This characteristic is found in waxy oils.

The Flash Point is that temperature at which the oil begins to give off inflammable vapors, and is important from the safety standpoint. Fuels which are marketed have a minimum flash point of 150°F, but occasionally the refinery may be called upon to burn a slop fuel of low flash point, which requires careful handling.

Combustion

Combustion may be defined as the rapid oxidation or combining with oxygen, of a substance, accompanied by the evolution of heat and light. This oxidation takes place by means of a series of chemical reactions of progressive oxidation, with heat being released in proportion to the degree of oxidation carried out. The actual chemical reactions are complex, and different authorities on the subject differ as to the exact nature of the intermediate reactions which occur. For practical purposes, these intermediate reactions are not essential, since it is the final products of combustion which are important, and which tell whether or not combustion is complete and efficient.

The combustible elements in any fuel are carbon, hydrogen and sometimes small amounts of sulphur. The carbon combines with the oxygen in the air to form carbon dioxide, if the combustion is complete, with the liberation of 14,600 B.T.U. per pound of carbon burned. If combustion is incomplete, carbon monoxide is formed with the liberation of 4,440 B.T.U. per pound of carbon. If the carbon monoxide is burned to carbon dioxide by the further addition of air, then an additional 10,160 B.T.U.'s are released. Hydrogen in fuel burns to form water vapor with the release of 62,000 B.T.U. per pound.

These reactions are shown in the following equations:-

\[
\begin{align*}
C + O_2 &= CO_2 + 14600 \text{ B.T.U./lb. Combustible} \\
2C + O_2 &= 2CO + 4440 \quad " " \\
2CO + O_2 &= 2CO_2 + 10160 \quad " " \\
2H_2 + O_2 &= 2H_2O + 62000 \quad " " \\
S + O_2 &= SO_2 + 4050 \quad " "
\end{align*}
\]

The proportion of carbon and hydrogen in different fuels varies. Since hydrogen burns to form water vapor and does not show up in an Orsat analysis, different theoretical maximum CO₂ percentages are obtained from combustion of fuels containing different amounts of hydrogen. Thus we find that for refinery fuel gas, the maximum CO₂ possible is about 13%. Fuel oil will give about 16%, soft coal 18% and pure carbon could theoretically produce 21% CO₂ when burned, or the same as the percentage of oxygen in the air. (See Graph No. 1).

Excess Air

For any fuel there is a definite theoretical amount of air required for complete combustion, which amount can be computed provided the chemical analysis of the fuel is known.
The theoretical air required per pound of fuel is given by the formula:

\[ \text{Theoretical Air lbs/lb. fuel} = 11.52 + 34.56 \left( H - \frac{0.5}{8} \right) + 4.32S, \]

where C, H, O and S are the percentages of carbon, hydrogen, oxygen and sulphur respectively in the fuel. The constants in this formula are derived from the combustion reaction. This theoretical amount is all that would be required for complete combustion, provided every particle of combustible in the fuel could be contacted by the necessary amount of oxygen, so that when combustion was complete there would be no oxygen left over. Since this is impossible, due to imperfect mixing of the fuel and air and also the fact that only 21% of the air is used for combustion, it is always necessary to supply an extra amount of air over that required theoretically, in order to give every particle of combustible a greater chance of contacting its required amount of oxygen. This extra amount of air which is supplied is called "Excess Air." The use of more excess air than that actually required means a loss of heat up the stack, hence the minimum quantity which will give complete combustion should be used.

The quantity of excess air which must be used depends on the type of fuel, and the efficiency of the fuel – air mixing devices used. When burning gas in refinery furnaces, from 18% to 22% excess air or 10 to 11% CO₂ is good operation. Slightly more excess air is used for oil fuel, since the atomization must be almost perfect to get as good air-fuel mixture as with gas. 25% excess with oil gives about 13% CO₂ and is very good operation for process units. Decreasing the excess air increases the furnace temperature, and it is sometimes necessary in steam boiler furnaces without waterwalls to increase the excess air so as to keep the furnace temperature down, since at very high furnace temperatures the increased maintenance of refractory more than offsets the saving in fuel. (See Graph’s Nos. 2 and 3).

Flue Gas Analysis

In a furnace burning gas or oil of known analysis, the temperature and analysis of the flue gases give almost complete information on the thermal efficiency of the unit. This shows the importance of complete and accurate analysis in obtaining good furnace operation.

A complete analysis will give the percentages of CO₂, O₂ and CO in the gas, and they are obtained in that order by the use of the Orsat apparatus. It is the practice in recent years to install continuous CO₂ recorders on all furnaces, as this gives a much more complete record than that from spot samples. These instruments can give excellent returns on their investment cost, provided the information obtained from them is used intelligently.

For any given firing rate, the volume of CO₂ obtained from complete combustion is constant. Hence any air supplied over that which is used, passes through the furnace unchanged, except in temperature, and acts only to increase the volume of flue gas. This reduces the concentration or percentage of CO₂ and of course raises the percentage of oxygen in the gas. The amount of excess air can be determined by measuring the CO₂ in the flue gas, and in fact this is the purpose of CO₂ measurement. The point should be emphasized that "CO₂" and
"excess air" are not synonymous terms, one is measured in order to determine the other.

As stated previously, it is the practice to use CO₂ recorders on refinery furnaces. Care should be taken not to put too much confidence in CO₂ readings alone, and it is well to take a complete analysis on the flue gases occasionally, especially if gas is the fuel and the furnace is firing near capacity.

As shown on Graph No. 4 it is possible to have the same CO₂ reading with both an excess and a deficiency of air. A deficiency of air, which results in CO in the flue gas, is shown up by smoke when burning oil, but not when burning gas. Consequently a complete flue gas analysis is advisable when there is any doubt as to the completeness of combustion.

The presence of oxygen in the flue gas means that more air is being supplied the furnace than is being used. As shown previously some excess air is necessary, but large amounts of oxygen in the flue gas with corresponding low CO₂ may mean air leakage into the furnace through the setting. The setting must be tight with no cracks in the brickwork, so that all the air will enter the furnace at the proper place. The air leakage can be checked by obtaining an analysis of the gases at the point in the furnace where combustion is complete, and also at the entrance to the stack. The difference will show the air leakage.

The presence of CO in the flue gas indicates incomplete combustion with a consequent high heat loss. The most common cause is a deficiency of air, but it can also be caused by poor design of burner or furnace. If the furnace gases should strike relatively cool heating surfaces before combustion is complete, the reaction may be stopped or slowed up by the sudden decrease in temperature so that it will not be complete on leaving the combustion section of the furnace. Most furnaces today are of good design so that if they are properly operated CO rarely appears in the flue gas.

Heat Losses

Practically all the heat lost in a furnace burning gas or oil fuel is that which is lost up the stack, the remaining loss is radiation from the furnace roof and walls. There is not much that the foreman or operator can do about the radiation loss, but the loss up the stack is controllable. Graphs Nos. 2 and 3 give the stack heat loss for gas and oil fuels for different excess air and stack temperature. These charts are to be used only as an approximation. For more accurate determinations the Blue Book charts should be used.

As shown on the Graph No. 4 the total heat loss decreases as the excess air decreases. This is because as less excess air is used, there is a smaller volume of gases carrying heat up the stack. Also, as the excess air decreases, the temperature of the exit gases decrease thus helping to decrease the total stack heat loss. This loss continues to decrease as the excess air is decreased until at a certain point, the excess air becomes too low for complete combustion and CO begins to appear with flue gas. Since carbon only releases 30% of its total heat when burned to CO as compared to CO₂, the heat loss begins to increase suddenly, and the loss due to incomplete combustion soon becomes greater than that saved by decreasing excess air. This
point of minimum heat loss is the point of maximum furnace efficiency, and it is at this point that the excess air should be controlled if possible. The amount of excess air used at the point of maximum efficiency will vary for different installations depending on the design of the furnace, burners, type of fuel, etc.

The ideal firing condition of a furnace is when it operates at this point of maximum efficiency. But in furnaces with automatic temperature control - such as cracking coil or pipe still furnaces, but without automatic draft control - this point cannot be maintained. If the excess air is kept too low in these furnaces, "smothering" of the furnace may result. For instance, assume that the excess air is at a minimum and for some reason the load on the furnace increased. The automatic control would increase the fuel to the furnace and, as there is no increased draft to carry away the increased products of combustion, the furnace will build up a positive pressure, the air supply decrease, the outlet temperature falls and the automatic control will feed even more fuel to the furnace. Thus the situation would become progressively worse until the automatic control was wide open. The furnace would become "smothered". Hence the stack damper or draft should be set so as to take care of any variations in furnace load, which means that the excess air must be somewhat greater than the optimum and the CO₂ consequently lower. The load on processing furnaces in a refinery is fairly constant, so that one setting of the damper is sufficient, but on a furnace with widely fluctuating loads as are possible in a steam plant, automatic draft control must be tied in with automatic firing.

Burners & Furnaces

The function of the burner is the final preparation of the fuel for combustion. For gas fuel, this preparation consists only of thoroughly mixing the gas and air in the proper quantities, using a minimum amount of excess air. Air for combustion is sometimes supplied by the burner in two stages called primary and secondary air, which support, in turn, primary and secondary combustion. In gas burners it is generally the practice to provide sufficient air for complete combustion as primary air, which is mixed with the gas in the burner. This results in complete combustion taking place almost at the burner tip, or as soon as the ignition temperature is reached. This makes the flame non-luminous and very short, so that flame impingement on heating surfaces is avoided. By having the combustion all take place as primary combustion with a very short flame, the B.T.U. released per cu.ft. of furnace volume can be much greater than if combustion were slower with a long, lazy flame.

When burning fuel oil, the oil must be heated to the necessary temperature, depending on its viscosity, and then pumped to the burners through strainers to take out any solid particles. The burner must vaporize or atomize the oil thoroughly and pass it through a stream of air with as much turbulence as possible, so as to get proper mixing. The atomization is accomplished by either breaking the oil up with steam, that is, steam atomization, or by forcing it through a small orifice under high pressure, known as mechanical atomization. For steam atomization, the oil pressure at the burner is 50 to 70 lbs., but for mechanical atomization it must be considerably higher. Steam consumption for atomization is approximately 0.4 lbs. steam/lb. oil. It is very easy to waste steam in atomization, and care must be taken to prevent more being used than necessary.
The furnace serves as a chamber where heat may be released by the combustion of the fuel, and heat absorbed by the heating surfaces. The heating surfaces in pipe stills and cracking furnaces are tubes in which is carried the fluid to be heated. Heat is transferred to this fluid by all three ways of heat transfer, namely radiation, conduction and convection.

Although that section of a furnace where combustion takes place is called the radiant section, and the tubes in that section are called radiant tubes, actually these tubes receive heat by all three methods mentioned. They receive the largest amount by radiation from the hot furnace gases and indirectly by reflection or re-radiation from the walls and floor. They receive it by conduction through the film of cooler gases surrounding the heating surface, and by convection by the mixing of the hotter with the cooler gases in the area around the heating surfaces.

The balance of the heat liberated by combustion, except that lost through the furnace walls, passes on to what is called the convection section of the furnace and which contains the convection tubes. The lower the temperature of the gases leaving the convection section for any given firing rate, the higher will be the thermal efficiency of the furnace. The exit temperature of the gases cannot be lower than the inlet temperature of the oil, but should be as near to it as possible to attain. In order for the exit or stack temperature to be a minimum, the amount of heat leaving the radiant section must be a minimum, which is the same as saying that the excess air used must be a minimum, consistent with complete combustion.

The heat liberated per cubic foot of combustion space in cracking furnaces is much lower than in steam boiler furnaces. An average figure is from 5,000 to 10,000 B.T.U. per cu. ft. per hour. It is most important that burners and furnaces be designed so that there is no impingement of the flame on heating surfaces which might cause local overheating. Of the total heat absorbed by the heating surfaces, approximately 60% is absorbed in the radiant section, and 40% in the convection section.

Firing Practices — Although the firing in nearly all refinery furnaces is done by automatic controllers, still it is necessary for the fireman and operator to know what to do when starting up a furnace and in case it becomes necessary to fire by hand.

(a) Gas Firing — When a unit is ready to be fired, the first thing the fireman does is to check the gas burners to make sure the gas cocks are all turned off, as they should have been when the furnace was shut down. He then opens the valve on the main gas supply line, which also should have been turned off when the furnace was shut down. Before lighting any burners, he must clear the furnace of any gas accumulation by opening the stack damper wide, and turning steam into the furnace. This procedure must be followed as otherwise a serious explosion may result. With the stack damper still open, he proceeds to light up a burner. This is done by first placing a lighted torch in front of the burner and opening the burner gas cock. If the burner does not light immediately, the gas cock should be shut off and investigation made to see if there is gas pressure at the burner. The burner should never be left turned on unless it is burning. After the first burner is fired, the torch should be used to light each burner separately, especially when starting up a cold furnace. After the required number of burners are lighted, the stack damper is closed until there is only a slight negative pressure on the
furnace. Care should be taken not to fire a cold furnace too hard until it has had a chance to warm up. This is to allow uniform expansion of the refractory and supports so as to avoid cracks in the furnace walls, etc.

If the gas burners are equipped with primary and secondary air dampers, the primary air shutter should be closed until the gas flame turns white and luminous, then opened up until the flame turns a bluish color and becomes non-luminous. In general, the secondary air shutters are almost closed, provided sufficient air for combustion can be obtained through the primary air shutters. A good time to test the burners for flame impingement is when they are first turned on and while the furnace is relatively cold. If there is no flame impingement with full gas pressure and a cold furnace, there will be none later, since a hot furnace accelerates combustion and shortens the flame considerably.

After the heater coil outlet temperature is up in place and the firing changed over to automatic control, the final adjustment of the stack damper and air shutters is made. The stack damper should be closed to bring the carbon dioxide (CO₂) in the flue gas up to 10-11%, but still maintaining slight negative pressure in the furnace. The burner air shutters are adjusted to give a short blue flame as outlined previously.

When shutting down a gas fired furnace, all the gas cocks are shut and also a block valve in the main supply line. If an inspection is to be made in the furnace, the gas line must be blanked.

(b) Oil Firing - The proper firing of oil is considerably more difficult than firing gas, as there are more variables with which to contend.

It is first necessary to see that the oil is heated sufficiently to bring the viscosity down so that it can be atomized. For steam atomization of Bunker C fuel, this temperature is in the range of 160-180°F. The oil must also be at a pressure of 50-70 lbs. gauge at the burner. In most installations the oil is continuously circulated past the furnace and the lines to the burners come directly off the circulating line.

Before attempting to light an oil burner, the steam line supplying the steam for atomizing should be thoroughly blown out to clear any water from the line. Slugs of water in the atomizing steam will always put the burner out when starting up. This steam is blown into the furnace so that it also serves to clear the furnace of any gas accumulation. The stack damper should be opened wide when starting up. When lighting the burner, the torch is placed in front of and just below the burner. The steam is turned on first, then the oil valve is slowly opened until the spray lights. The torch is kept under the spray while both the oil and steam are alternately increased until a proper flame is obtained.

The fireman should take care to keep out of the way of "flarebacks" or "puffbacks", which often occur when lighting an oil burner. Also, if the flame goes out, the torch should always be used to light up again, instead of trying to light the burner off hot brickwork, a practice which can cause a serious explosion. If the burner does not light readily, shut off the oil and allow time for the vaporized oil in the furnace to be carried up the stack before trying again. Unburned oil must not be allowed to accumulate on the furnace floor.
As the furnace is heated up, the burners must be continually adjusted. The proper amount of atomization steam can be obtained by cutting it down until dark streaks begin to show in the flame, then increase the steam until they disappear and there are no sparks in the ends of the flame. If the burner flame is a dazzling white colour and the furnace walls are clearly visible, then considerable excess air is being used. The excess air is reduced by closing down on the stack damper, and as the air is reduced, the colour of the flame at the rear of the furnace becomes pale yellow, then yellowish orange, or light red. Under good conditions, the products of combustion are practically colorless and the flame tip is yellowish orange in colour.

When burning oil, the appearance of the gases leaving the stack are an indication of combustion conditions. A perfectly clear stack is deceiving, as it may mean a small amount of excess air or a very large amount. Under good furnace conditions, a slight gray haze leaving the stack generally means a minimum of excess air. It should also be remembered that smoke does not necessarily mean a deficiency of air, or high carbon monoxide (CO.) An inefficient installation, poor atomization, poor mixing, or unburned oil striking the cooling surfaces frequently cause smoke even when the excess air supplied is far in excess of that required. Defects of this type must be eliminated before a proper study of efficient fuel and air regulation can be attempted. An analysis of the flue gases is essential before it can be said that any furnace is operating at its maximum efficiency.

When shutting down an oil fired furnace, the burners are shut off and steam is blown through the burners to clear out any remaining oil. The oil and steam lines are then shut off against the main supply line and the burner removed for cleaning.