HANDBOOK OF FIRE AND EXPLOSION PROTECTION ENGINEERING PRINCIPLES FOR OIL, GAS, CHEMICAL, AND RELATED FACILITIES

by

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About the Author

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Mr. Nolan has received numerous of safety awards and is a member of the American Society of Safety Engineers, National Fire Protection Association, Society of Petroleum Engineers, and Society of Fire Protection Engineers. He is the author of the book "Application of HAZOP and What–If Safety Reviews to the Petroleum, Petrochemical and Chemical Industries," which is widely referred to within the petroleum and chemical industries. Mr. Nolan has also been listed in "Who's Who in California" for the last ten years and has been elected to appear in the 1996 International Edition of "Who's Who of Science and Engineering."
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Notice

Reasonable care has been taken to assure that the book's content is authentic, timely and relevant to the industry today; however, no representation or warranty is made to its accuracy, completeness or reliability. Consequently, the author and publisher shall have no responsibility or liability to any person or organization for loss or damage caused, or believed to be caused, directly or indirectly, by this information. In publishing this book, the publisher is not engaged in rendering legal advice or other professional services. It is up to the reader to investigate and assess his own situation. Should such study disclose a need for legal or other professional assistance the reader should seek and engage the services of qualified professionals.
The security and economic stability of many nations and multinational oil companies are highly dependent on the safe and uninterrupted operation of their oil, gas and chemical facilities. One of the most critical impacts that can occur to these operations are fire and explosions from accidental or political incidents. The recent Gulf War amply demonstrates the impact these events can have on oil installations.

This publication is intended as a general engineering handbook and reference guideline for those personnel involved with fire and explosion protection aspects of these critical hydrocarbon facilities. Several other reference books are available that provide portions of the necessary information required to evaluate hazards, provide fire protection measures, or determine insurance needs. However most are not fully complete in mentioning all technical subjects and some have become somewhat technically outdated. They usually tend to be a collection of technical papers or else provide a broad coverage of subjects without much practical applications or details. The main objective of this handbook is to provide some background understanding of fire and explosion problems at oil and gas facilities and a general source of reference material for engineers, designers and others facing fire protection issues, that can be practically applied. It should also serve as a reminder for the identification of unexpected hazards at a facility.

As stated, much of this book is intended to be a guideline. It should not be construed that the material presented herein is the absolute requirement for any facility. Indeed, many organizations have their own policies, standards and practices for the protection of their facilities. Portions of this book are a synopsis of common practices employed in the industry and can be referred to as such where such information is unavailable or outdated. Numerous design guidelines and specifications of major, small and independent oil companies as well as information from engineering firms and published industry references have been reviewed to assist in its preparation. Some of the latest published practices and research into fire and explosions have also been mentioned.

This book in not intended to provide in-depth guidance on basic risk assessment principles nor on fire and explosion protection engineering foundations or design practices. Several other excellent books are available on these subjects and some references to these are provided at the end of each chapter.

The scope of this book is to provide a practical knowledge and guidance in the understanding of prevention and mitigation principals and methodologies from the effects of hydrocarbon fires and explosions. The Chemical Process Industry (CPI), presents several different concerns that this book does not intend to address. However the basic protection features of the Hydrocarbon Process Industry (HPI) are also applicable to the chemical process industry and other related process industries.

Explosion and fire protection engineering principles for the hydrocarbon industries are still being researched, evolved and expanded, as is the case with most engineering disciplines. This handbook does not profess to contain all the solutions to fire protection problems associated with hydrocarbon facilities. It does however
Preface

try to shed some insight into the current practices and trends being applied in the petroleum industry today. From this insight, professional expertise can be obtained to examine design features in detail to resolve concerns of fires and explosions.

Continually updated technical information is needed so that industrial processes can be designed to achieve the optimum risk levels from the inherent material hazards but still provide acceptable economic returns.

This book is generally written from the point of reference of the United States basis, but does attempt to reference other international codes, standards and practices where they have been referenced or heavily used by the international oil industry. It does use SI units as the normal units of measure, as these are typically used in the international oil industry.
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Chapter 1

Introduction

Fire, explosions and environmental pollution are the most serious "unpredictable" life affecting and business losses having an impact on the hydrocarbon industries today. These issues have essentially existed since the inception of industrial scale petroleum and chemical operations during the middle of the last century. They continue to occur with ever increasing financial impacts. It almost appears that the management of industry is oblivious, or else must be careless, to the potential perils under their command. Although in some circles most accidents can be thought of as non-preventable, all accidents are in fact preventable.

Research and historical analyses have shown that the main cause of accidents or failures can be categorized according to the following basic areas:

Ignorance

a. Incompetent design, construction or inspection occurs.
b. Supervision or maintenance occurs by personnel without the necessary understanding.
c. Assumption of responsibility by management without an adequate understanding of risks.
d. There is a lack of precedent.
e. There is a lack of sufficient preliminary information.
f. Failure to employ competent Loss Prevention professionals.

Economic Considerations

a. Initial engineering and construction costs for safety measures appear uneconomical.
b. Operation and maintenance costs are unwittingly reduced to below what is necessary.

Oversight and Negligence

a. Otherwise competent professional engineers and designers commit errors.
b. Contractual personnel or company supervisors knowingly assume high risks.
c. Lack of proper coordination in the review of engineering designs.
d. Failure to conduct prudent safety reviews or audits.
e. Unethical behavior occurs.
Unusual Occurrences

a. Natural catastrophes - earthquakes, extreme weather, etc.
b. Political upheaval - terrorist activities.
c. Labor unrest, vandalism.

As can be seen, the real cause of most accidents is what might be classified as human errors. Most people have good intentions to perform a function properly, but where shortcuts, easier methods or considerable economic gain opportunities appear or present themselves, human vulnerability usually succumbs to the temptation. Therefore it is prudent in any organization, especially where high risk facilities are operated, to have a system in place to conduct considerable independent checks, inspections, and safety audits of the design and construction of the installation.

This book is about engineering principles and philosophies to identify and prevent accidents associated with hydrocarbon facilities. All engineering activities are human endeavors and thus they are subject to errors. Fully approved facility designs and later minor changes can introduce an aspect from which something can go wrong. Some of these human errors are insignificant and may be never uncovered. However others may lead to catastrophic incidents when combined with other activities. Recent incidents have shown that any "fully engineered" and operational process plants can experience total destruction. Initial conceptual designs and operational philosophies have to address the possibilities of a major incident occurring and provide measures to prevent or mitigate such events.

Historical Background

The first commercially successful oil well was drilled in August 1859 in Titusville (Oil Creek), Pennsylvania by Colonel Edwin Drake. Few people realize that Colonel Drake's famous oil well caught fire and some damage was sustained to the structure shortly after its operation. Later in 1861 another oil well at "Oil Creek", close to Drake's well, caught fire and grew into a local conflagration that burned for three days causing 19 fatalities. One of the earliest oil refineries in the area, Acme Oil Company, suffered a major fire loss in 1880, from which it never recovered. The State of Pennsylvania passed the first anti-pollution laws for the petroleum industry in 1863. These laws were enacted to prevent release of crude oil into waterways next to oil production areas. At another famous early oil field named "Spindletop", an individual smoking set off the first of several catastrophic fires, which raged for a week, only three years after the discovery of the reservoir. Major fires occurred at Spindletop almost every year during its initial production. Considerable evidence is available that hydrocarbon fires were a fairly common sight at early oil fields. These fires manifested themselves either from man-made, natural disasters, or from deliberate and extensive flaring of the then "unmarketable" reservoir gas. Hydrocarbon fires were accepted as part of the early industry and generally little efforts were made to stem the their existence.

Ever since the inception of the petroleum industry the level of fires, explosions and environmental pollution that have precipitated from it, has generally paralleled its growth. As the industry has grown so has the magnitude of its accidental events. Relatively recent events such as the Flixborough incident (1974), Occidental's Piper Alpha disaster (1988), and Exxon's Valdez oil spill (1989) have all amply demonstrated the extreme financial impact these accidents can produce.

After the catastrophic fire that burned ancient Rome in 64 A. D., the emperor Nero rebuilt the city with fire precautions that included wide public avenues, limitations in building heights, provision of fireproof construction and improvements to the city water supplies to aid in fire fighting. Thus it is very evident that
the basic fire protection requirements such as limiting fuel supplies (fireproof construction), removing the available ignition sources (wide avenues and limited building heights to prevent carryover of flying brand embers) and providing fire control and suppression (water supplies), have essentially been known since civilization began.

Amazingly, "Heron of Alexandria", the technical writer of antiquity (circa 100 A.D.), describes a two cylinder pumping mechanism with a dirigible nozzle for fighting fires in his journals. It is very similar to the remains of a Roman water supply pumping mechanism on display in the British Museum in London. Devices akin to these were also used in the eighteenth and nineteenth century in Europe and America to provide fire fighting water. There is therefore considerable evidence society has generally tried to prevent or mitigate the effects of fires, admittedly after a major mishap has occurred.

The Hydrocarbon Processing Industry (HPI), has traditionally been reluctant to invest capital where an immediate direct return on the investment to the company is not obvious, as would any business enterprise. Additionally financial fire losses in the petroleum and related industries were relatively small up to about the 1950's. This was due to the small size of facilities and the relatively low value of oil and gas to the volume of production. Until 1950, a fire or explosion loss of more than 5 million U. S. Dollars had not occurred in the refining industry in the USA. Also in this period, the capital intensive offshore oil exploration and production industry were only just beginning. The use of gas was also limited early in the century. Consequentially its value was also very low. Typically production gas was immediately flared or the well was capped and considered as an uneconomical reservoir. Since gas development was limited, large vapor explosions were relatively rare and catastrophic destruction from petroleum incidents was essentially unheard of. The outlays for petroleum industry safety features were traditionally the absolute minimum required by governmental regulations. The development of loss prevention philosophies and practices were therefore not effectively developed within the industry.

In the beginnings of the petroleum industry, usually very limited safety features for fire or explosion protection were provided, as was evident by the many early blowouts and fires. The industry became known as a "risky" operation, not only for economic returns, but also for safety (loss of life and property destruction) and environmental impacts, although this was not well understood at the time.

The expansion of industrial facilities after WW II, construction of large integrated petroleum and petrochemical complexes, increased development and uses of gas deposits, coupled with the rise of oil and gas prices in the 1970s have sky-rocketed the value of petroleum products and facilities. It has also meant the industry was rapidly awakened to the possibility of large financial losses if a major incident occurred. In fact fire losses greater than 50 million U. S. Dollars were first reported during the years 1974 and 1977 (i.e., Flixborough U.K., Qatar, and Saudi Arabia). In 1992, the cost just to replace the Piper Alpha platform and resume production was reportedly over one billion U.S. Dollars. In some instances legal settlements have been financially catastrophic, e.g., the Exxon Valdez oil spill legal fines and penalty was five billion U. S. Dollars. Financial forecasts have predicted that the long term trend in oil prices should increase as oil reserves are eventually reduced and depleted.

It should also be remembered that a major incident may also force a company to literary withdrawn from that portion of the business sector where public indignation, prejudice or stigma towards the company strongly develops because of the loss of life suffered. The availability of 24 hour news transmissions through worldwide satellite networks virtually guarantees a significant incident in the hydrocarbon industry will be known worldwide very shortly after it occurs, resulting in immediate public reaction.

Only in the last several decades has it been well understood and acknowledged by most industries, that fire and explosion protection measures may be also be operational improvement measures, as well as a means of protecting a facility against destruction. An example of how the principle of good safety practice equates to good operating practice is the installation of emergency isolation valves at a facility inlet and outlet pipelines. In an emergency they serve to isolate fuel supplies to an incident and therefore limit damage. In theory they could also serve as an additional isolation means to a facility for maintenance and operational activities when
a major facility isolation requirement occurs. It can be qualitatively shown that it is only limitations in practical knowledge by those involved in facility construction and cost implications that have generally restricted application of adequate fire protection measures throughout history.

Nowadays safety features should hopefully promulgate the design and arrangement of all petroleum facilities. In fact, in highly industrial societies these features must demonstrate to regulatory bodies that the facility has been adequately designed for safety, before permission is given for their construction. It is thus imperative that these measures are well defined early in the design concept in order to avoid costly projects change orders or later incident remedial expenses required by regulatory bodies. Industry experience has demonstrated that reviewing a project design early in the conceptual and preliminary stages for safety and fire protection features is more cost effective than performing reviews after the designs have been completed. The "Cost Influence Curve" for any project acknowledges that 75% of a project cost is defined in the first 25% of the design. On average the first 15% of the overall project cost is usually spent on 90% of the engineering design. Retrofit or modification costs are estimated at ten times the cost after the plant is built and 100 times after an incident occurs. It should also be realized that fire protection safety principles and practices are also prudent business measures that contribute to the operational efficiencies of a facility. Most of these measures are currently identified and evaluated through a thorough and systematic risk analysis.

Legal Influences

Before 1900, the U.S. industry and the Federal Government generally paid little notice to the safety of industrial workers. Only with the passage of the Workmen's Compensation Laws in the U.S. between 1908 and 1948 did businesses start to improve the standards for industrial safety. Making the work environmentally safer was found to be less costly than paying compensation for injuries, fatalities and governmental fines. Labor shortages during World War II focused renewed attention on industrial safety and on the losses incurred by industrial accidents, in order to keep production output available for the war effort. In the 1960s, a number of industry specific safety laws were enacted in the U.S. They included the Metal and Nonmetallic Mine Safety Act, the Coal Mine Health and Safety Act, and the Construction Safety Act, all of which mandated safety and fire protection measures for workers by the companies employing them. A major U.S. policy towards industrial safety measures was established in 1970, when for the first time all industrial workers in businesses affected by interstate commerce were covered by the Occupational Safety and Health Act. Under this act, the National Institute for Occupational Safety and Health (NIOSH) was given responsibility for conducting research on occupational health and safety standards, and the Occupational Safety and Health Administration (OSHA) was charged with setting, promulgating, and enforcing appropriate safety standards in industry.

Hazards and Their Prevention

Petroleum and chemical related hazards can arise from the presence of combustible or toxic liquids, gases, mist, or dust in the work environment. Common physical hazards include ambient heat, burns, noise, vibration, sudden pressure changes, radiation, and electric shock. Various external sources, such as chemical, biological, or physical hazards, can cause work related injuries or fatalities. Although all of these hazards are of concern this book primarily concentrates on fire and explosions hazards that can cause catastrophic events.

Hazards may also result from the interaction between company employees and the work environment; these are called "ergonomic" hazards. If the physical, psychological, or environmental demands on workers exceed their capabilities, an ergonomic hazard exists. These hazards, in themselves may lead to further major incidents when the individual cannot perform properly under stress during critical periods of plant
Ergonomic hazards can cause either physiological or psychological stress in individuals.

Industrial fire protection and safety engineers attempt to eliminate hazards at their source or to reduce their intensity with protective systems. Hazard elimination may typically require the use of alternative and less toxic materials, changes in the process, spacing or guarding, improved ventilation or, spill control or inventory reduction measures, fire and explosion protective measures - both active and passive mechanisms, protective clothing, etc. The level or protection is dependent on the risk prevalent at the facility versus the cost to implement safety measures.

**Systems Approach**

In recent years, engineers have developed a systems approach (termed system safety engineering) to industrial accident prevention. Because accidents arise from the interaction of workers and their work environments, both must be carefully examined to reduce the risk of injury. Injury can result from poor facility designs, working conditions, the use of improperly designed equipment and tools, fatigue, distraction, lack of skill, and risk taking. The systems approach examines all areas in a systematic fashion to ensure all avenues of accident development have been identified and analyzed. Typically the following major areas are examined: all work locations to eliminate or control hazards, operating methods and practices, and the training of employees and supervisors. The systems approach, moreover, demands a thorough examination of all accidents and near misses. Key facts about accidents and injuries are recorded, along with the history of the worker involved, to check for and eliminate any patterns that might lead to hazards.

The systems approach also pays special attention to the capabilities and limitations of the working population. It recognizes large individual differences among people in their physical and physiological capabilities. The job and the worker, therefore, should be appropriately matched whenever possible.

The safety and risk of a hydrocarbon facility cannot be assessed solely on the basis of fire fighting systems or past loss histories. The overall risk can only be assessed by defining loss scenarios and an understanding of the risk philosophy adopted by senior management.

Due to the destructive nature of hydrocarbon forces when handled incorrectly, fire and explosion protection principles should be the prime feature in the risk philosophy of any hydrocarbon facility. Vapor cloud explosions in particular are considered the highest risk at a hydrocarbon facility. Disregarding the importance of protection features or systems will eventually prove to be costly both in economic and human terms should a catastrophic incident occur without adequate safeguards.

**Fire Protection Engineering Role**

Fire protection engineering is not a stand alone discipline that is brought in at an indiscriminate state of a project design or even as an after the fact design review of a project. Fire protection principles should be an integrated aspect of an oil or gas project that reaches into all aspects of how a facility is designed arranged and constructed. They are usually the prime starting and focal points in the layout and process arrangements of hydrocarbon facility.

Fire protection engineering should be integral with all members of the design team, be it structural, civil, electrical, process, HVAC, etc. Although a fire protection or risk engineer can be employed as part of a project team or engineering staff, he should mainly be in an advisory role. He can advise on the most prudent and practical methods to employ for fire protection objectives. The fire protection or risk engineer must therefore be knowledgeable in each of the various disciplines. In addition he must have expertise in hazard, safety, risk and fire protection principles and practices applied to the petroleum or other related industries.
Risk Management and Insurance

It should also be realized that science of risk management also provides other avenues of protection besides technical solutions to a risk. There are four elements of risk management available to resolve a concern.

The four methods, in order of preference are:

1. Risk Avoidance
2. Risk Reduction
3. Risk Insurance
4. Risk Acceptance

This handbook concentrates primarily on risk avoidance techniques and risk reduction. Risk acceptance and risk insurance techniques are general monetary measures that are dependent on the financial options available to the Facility Manager. These are based on a company's policy and preferences in the insurance market. If used, they rely on financial measures within an organization to provide for financial security in case of an incident. Although these measures can accommodate financial losses, they are ineffective in reputation and prestige affects from an incident (i.e., negative effects). This is why risk avoidance and risk reduction measures are the preferred method of solution for a high risk problem with the petroleum and industrial community at large.

Risk avoidance involves eliminating the cause of the hazard. This is accomplished by changes in the inherent risk features of the process or facility. Risk reduction concerns the provision of prevention or protective measures that will lessen the consequences of a particular accidental event.

Risk insurance is the method chosen when the possible losses are financially too great to retain internally by risk acceptance and in some cases too expensive to prevent or avoid. However even the risk insurers will want to satisfy themselves that adequate precautions are being taken at facilities they are underwriting. Thus, they will look very carefully at risks they feel are above the industry norm or have high loss histories.

Most offshore installations, international onshore production sharing contracts and large petro-chemical plants are owned by several companies or participating national governments. The majority owner or most experience company is usually the onsite operator. The objective is to share the funding and financial risk of finding oil, developing and operating the facility. Should the exploration hole prove "dry", i.e., commercially uneconomical, it prevents an undue economic impact to the exploration budget for a particular area. Investments in other exploration wells with other companies may prove fruitful thereby spreading the risk over a wider range of prospects. It also lessens the financial impact to the companies if a catastrophic incident occurs that destroys the facility, since each company must also share in the damage cost proportionately to their investment stake. If a company historically has a poor record in relation to safe operations, other companies may be hesitant to invest funds with it, since they may consider that company too high a risk. Alternatively they may demand to be the operator since they would feel better qualified and the risk of losing the facility would be lower.

Property damages and legal liabilities are not the only sources of financial impacts a company may suffer at the time of an incident. Business interruption losses will also occur since the facility will not longer be able to function as intended. Analysis of insurance industry claims data shows that business interruption losses are generally three times the amount of physical property damage. Often the justification for a safety feature may not be the loss of the component itself but of the impact to operations and loss revenue it produces.
Senior Management Responsibility and Accountability

Most of the major oil companies were originally started as a drilling organization for the exploration of oil. Drilling personnel have traditionally been idolized by company management as the individuals who have supplied the real resources or profit to the company by successfully drilling and "finding" the oil or gas. Since the early days of oil, exploration activities were considered somewhat reckless and hazardous, especially due to wildcard drilling operations. This impression or the "inheritance" of drilling personnel has always been one of wild, aloof or above safety features or requirements. Due to the dramatic effects of occasional drilling blowout incidents, this impression is still difficult to eradicate. This conception also exists within the general public. In some organizations where these drilling personnel are idolized, they will usually or may eventually be promoted to senior management positions. Their independent attitude may still prevail or impressions by subordinate employees will be preconceived to a lack of safety concern due to their background. This is not to say other departments or individual job classifications within an organization may not be just as ill perceived (e.g., construction or project management).

There are and probably will always be requirements to achieve oil and gas production or refining for any given project as soon as possible. Therefore the demands on drilling, construction and project management to achieve a producing or refining facility as soon as possible may be in some cases be in direct conflict with prudent safety measures, especially if they have not been adequately planned or provided before the start of the project. Operations management should not be mistakenly led into believing a facility is ready to operate just because it is "felt" by those performing its construction that it is complete.

However unfortunate, drilling personnel have been historically directly connected with major incidents within the petroleum industry on numerous occasions and the impression, consciously or unconsciously still remains. On the other hand, it is very rare or non-existent that a loss prevention professional is promoted to the ranks of senior management, even though they may have been keenly conscientious in maintaining a high economic return to the company by the prevention of catastrophic accidents.

Safety achievement is a team approach. All parties to the operation must participate and contribute. Without team cohesiveness, commitment and accountability objectives will not be met. Specifically important is the leadership of a team, which in business operations is the senior management.

Senior management responsibility and accountability are the keys to providing effective fire and explosion safety measures at any facility or operation. The real attitude of management towards safety will be demonstrated in the amount of importance placed on achieving qualitative or quantifiable safety results. Providing a permissive attitude of leaving safety requirements to subordinates or to the Loss Prevention personnel will not be conductive or lead to good results. The effect of indifference or lack of concern to safety measures is always reflected top down in any organizational structure. Executive management must express and contribute to an effective safety program in order for satisfactory results to be achieved. All accidents should be thought of as preventable. Accident prevention and elimination should be considered as an ultimate goal of any organization. Where a safety culture is "nurtured", continual economic benefits are usually derived. On the other hand, it has been stated that the 150 largest petroleum and chemical industry incidents during the past 30 years have involved breakdowns in the management of process safety.
Bibliography


Chapter 2

Overview of Oil and Gas Facilities

Petroleum and gas deposits occur naturally throughout the world in every continent and ocean. Most of the deposits are several thousand meters deep. The petroleum industry’s mission is to find, develop, refine, and market these resources in a fashion that achieves the highest economic return to the owners or investors while adequately protecting the fixed investment in the operation.

Oil and gas operations today are almost universally constitute a continuous run operation versus a batch process. Once fluids and gases are found and developed they are transported from one process to another without delay or interruption. This provides improved economics, but also increases the fuel inventories and thereby inherent risk in the operation.

The main facets of the oil and gas industry are exploration, production, refining, transportation and marketing. A brief description of each of these sectors is provided in this chapter. Although some petroleum companies are fully integrated with each of these operations others are segmented and only operate in their particular area of expertise or highest financial return.

Exploration

Exploring for oil and gas reservoirs consist mainly of geophysical testing and drilling "wildcat" wells. To find crude oil or gas reserves underground, geologists search for a sedimentary basin in which shales rich in organic material have been buried for a sufficiently long time for petroleum to have formed. The petroleum must also have had an opportunity to migrate into porous traps that are capable of holding a large amount of fluid or gas. The occurrence of crude oil or gas is limited both by these conditions, which must be met simultaneously, and by the time span of tens of millions to a hundred million years. Surface mapping of outcrops of sedimentary beds makes possible the interpretation of subsurface features, which can then be supplemented with information obtained by drilling into the crust and retrieving cores or samples of the rock layers encountered.

Seismic techniques, the reflection and refraction of sound or shock waves propagated through the earth, are also used to reveal details of the structure and interrelationship of various layers in the subsurface. The shock or sound waves record densities in the earth’s surface that may indicate an oil or gas reservoir. Explosive charges or vibration devices are used to impart the required shock wave.

Ultimately the only way to prove that oil is present underground is to drill an exploratory well. Most of the
oil provinces in the world have initially been identified by the presence of surface seeps, and most of the actual reservoirs have been discovered by so-called wildcatters who relied perhaps as much on intuition as on science. The term wildcatter comes from West Texas, USA, where in the early 1920s, drilling crews came across many wildcats as they cleared locations for exploratory wells. The hunted wildcats were hung on the oil derricks, and the wells became known as wildcat wells. A wildcat well is considered essentially a test boring to verify the existence and "commercial" quantities of quality oil or gas deposits. Since the absolute characteristics of a wildcat well are unknown, a high pressure volatile hydrocarbon reservoir may be easily encountered. As drilling occurs deeper into the earth the effects of overburden pressure of any fluid in the wellbore increases. If these reservoirs are not adequately control during exploratory drilling, they can lead to an uncontrolled release of hydrocarbons through the drilling system. This is commonly termed a "blowout", whether it is ignited or not. Blowout preventers, BOPs (i.e., hydraulic shear rams) are provided to control and prevent a blowout event. Uncontrolled drilling hydrostatic pressure is considered the primary cause of drilling blowouts (while evidently the underlying cause is human error).

An oil field may comprise more than one reservoir, i.e., more than one single, continuous, bounded accumulation of oil. Indeed, several reservoirs may exist at various increasing depths, stacked one above the other, isolated by intervening shales and impervious rock strata. Such reservoirs may vary in size from a few tens of hectares to tens of square kilometers. Their layers may be from a few meters in thickness to several hundred or more. Most of the oil that has been discovered and exploited in the world has been found in a relatively few large reservoirs. In the USA, for example, 60 of the approximately 10,000 oil fields have accounted for half of the productive capacity and reserves in the country.

Production

Underground oil or gas deposits are produced through wells that are drilled to penetrate the oil bearing rock formations. Most oil wells in the world are drilled by the rotary method. In rotary drilling, the drill "string", which is a series of connected pipes, is supported by a derrick (a structural support tower). The string is rotated by being coupled to a rotating "table" on the derrick floor. The drilling device or "bit" at the end of the string, is generally designed with three cone-shaped wheels tipped with hardened teeth. Additional lengths of drill pipe are added to the drill string as the bit penetrates deeper into the earth's crust. The force required for cutting into the earth comes from the weight of the drill pipe itself. Drill cuttings or the formation rock is continually lifted to the surface by a circulating fluid ("mud") system driven by a pump. The drilling mud is constantly circulated down through the drill pipe, out through nozzles in the drill bit, and then up to the surface through the space between the drill pipe and the bore through the earth (the diameter of the bit is somewhat greater than that of the pipes). By varying the force and momentum on the drill bit, the bore can be angled into or penetrate horizontally into a reservoir.

Once the well is drilled, the oil is either released under natural pressure or pumped out. Normally crude oil is under pressure; (were it not trapped by impermeable rock it would have continued to migrate upward), because of the pressure differential caused by its buoyancy. When a well bore is drilled into a pressured accumulation of oil, the oil expands into the low-pressure sink created by the well bore in communication with the earth's surface. As the well fills up with fluid, a back pressure is exerted on the reservoir, and the flow of additional fluid into the well bore would soon stop, were no other conditions involved. Most crude oils, however, contain a significant amount of natural gas in solution, and this gas is kept in solution by the high pressure in the reservoir. The gas comes out of solution when the low pressure in the well bore is encountered and the gas, once liberated, immediately begins to expand. This expansion, together with the dilution of the column of oil by the less dense gas, results in the propulsion of oil up to the earth's surface. As fluid withdrawal continues from the reservoir, the pressure within the reservoir gradually decreases, and the amount of gas in solution decreases. As a result, the flow rate of fluid into the well bore decreases, and less gas is liberated. The fluid may not reach the surface, so that a pump (artificial lift) must
be installed in the well bore to continue producing the crude oil. Gas reservoirs by their nature are high in pressure and can be essentially tapped into to obtain the deposit.

The produced oil or gas is connected to surface flowlines from the wellhead pumping unit or surface regulating valve assembly typically referred to as a Christmas tree but to its arrangement. The flowlines collect the oil or gas to local tank batteries or central production facilities for primary oil, water, and gas separation. The reliability of electrical submersible pumps (ESPs) has increased to the point where the submersible electrical pump is commonly used for the production of liquid hydrocarbons where artificial lift is required for production.

Primary separation facilities process the produced fluids and gases into individual streams of gas, oil and water. These facilities are commonly referred to as Gas Oil Separation Plants (GOSP's), Central Processing Facilities (CPF) or if located offshore on drilling, production and quarters platforms (PDQ's). The offshore platform may either float on the sea or be supported on steel or concrete supports secured to the ocean floor, where it is capable of resisting waves, wind, and in Arctic regions ice flows. In some instances surplus oil tankers have been converted into offshore production and storage facilities.

The produced fluids and gases are typically directed into separation vessels. Under the influence of gravity, pressure, heat, retention times, and sometimes electrical fields, separation of the various phases of gas, oil, and water occurs so that they can be drawn off in separate streams. Suspended solids such as sediment and salt will also be removed. Deadly hydrogen sulfide ($H_2S$), is sometimes also encountered, which is extracted simultaneously with the petroleum production. Crude oil containing $H_2S$ can be shipped by pipeline and used as a refinery feed but it is undesirable for tanker or long pipeline transport. The normal commercial concentration of impurities in crude oil sales is usually less than 0.5% BS & W (Basic Sediment and Water) and 10 Ptb (Pounds of salt per 1,000 barrels of oil). The produced liquids and gases are then transported to a gas plant or refinery by truck, railroad tank car, ship, or pipeline. Large oil field areas normally have direct outlets to major, common-carrier pipelines.

**Enhanced Oil Recovery (EOR)**

Most petroleum reservoirs are developed by numerous production wells. As the primary production approaches its economic limit, perhaps approximately 25 percent of the crude oil in place from a particular reservoir has been withdrawn. The petroleum industry has developed unique schemes for supplementing the production of gaseous and liquid hydrocarbons that can be obtained, by taking advantage of the natural reservoir energy and geometry of the underground structures. These supplementary schemes, collectively known as enhanced oil recovery (EOR) technology, can increase the recovery of crude oil, but only at the additional cost of supplying extraneous energy to the reservoir. In this way, the recovery of crude oil has been increased to an overall approximate average of 33 percent of the original "in the ground" oil. As the industry matures and reservoirs are considered depleted, EOR techniques will become the prevalent method of production for most of the petroleum reservoirs and the overall recovery rates will increases.

**Secondary Recovery**

**Water Injection**

In a completely developed oil or gas field, the wells may be drilled anywhere from 60 to 600 m (200 to 2,000 ft) horizontally from one another, depending on the nature of the reservoir. If water is pumped into alternate wells in such a field, the pressure in the reservoir as a whole can be maintained or even increased. In this way the daily production rate of the crude oil also can be increased. In addition, the water physically displaces the oil, thus increasing the recovery efficiency. In some reservoirs with a high degree of uniformity and little clay content, water flooding may increase the recovery efficiency to as much as 60 percent or more of the original oil in place. Water flooding was first introduced in the Pennsylvania oil fields, somewhat accidentally, in the late 19th century, and has since been used throughout the world.
Steam Injection

Steam injection is used in reservoirs that contain very viscous oils, i.e., those that are thick and flow slowly. The steam not only provides a source of energy to displace the oil, it also causes a marked reduction in viscosity (by raising the temperature of the reservoir), so that the crude oil flows faster under any given pressure differential.

Gas Injection

Some oil and gas reservoirs contain large volumes of produced natural gas or carbon dioxide (CO₂). This gas is produced simultaneously with the liquid hydrocarbons. The natural gas or CO₂ is recovered, recompressed, and reinjected into the gaseous portion of the reservoir. The reinjected natural gas or CO₂ maintains reservoir pressure and helps push additional liquid oil hydrocarbons out of liquid portion of the reservoir.

Tertiary Recovery

As the production lives of secondary methods lose their efficiency, further techniques have been tested and found to continue to release additional amounts of oil. These methods are considered tertiary methods and are generally associated with chemical or gaseous recirculation methods of recovery. Some instances of in-situ thermal recovery have been used but not on a large extent.

Chemical Injection

Proprietary methods are developed which inject chemical detergent solutions into the oil reservoirs to increase the viscosity of the remaining oil reservoirs. After the chemical detergent solutions are injected, polymer thickened water is provided behind the chemical detergent to drive the oil towards producing wells.

Thermal Recovery

Underground hydrocarbons are ignited, which creates a flame front or heat barrier that pushes the oil towards the producing well.

Recirculated Gas Drive

Natural gas or CO₂ is reinjected to mix with the underground oil, to free it from the reservoir rock. The gas is continually recirculated until it is economically nonproductive (i.e., the recovery rate is marginal).

Other experimental methods have been proven technologically feasible but are still commercially unviable. These include in-situ combustion, electromagnetic charging, and similar methods.

Transportation

Transportation is the means by which onshore and offshore oil and gas production is carried to the manufacturing centers and from which refined products are carried to wholesale and retail distribution centers.

Petroleum commodities (gas and oil), are normally transported in pipelines from source points to collection and processing facilities. Pipelines route unprocessed or refined products to centers of manufacturing and sales from areas of extraction, separation and refining. Where a pipeline system is unavailable, trucking is
usually employed.

Shipment from continent to continent is accomplished large tanker vessels, carriers or ships, which is the most economical method of shipment. These economies have produced the largest ships in the world, appropriately named Very Large Crude Carrier (VLCC), and Ultra Large Crude Carrier (ULCC) of size range between 160,000 to 550,000 dwt. Refined products are typically shipped in vessels of up to 40,000 dwt. Class rating. LNG or LPG vessels are typically in the range of up to 100,000 cubic meter (838,700 bbls.) capacity.

In order to achieve a complete transportation system a host of other subsystems support the transportation system operations. Loading facilities, pumping and compressor stations, tank farms and metering and control devices are necessary for a complete transportation system of liquid or gases hydrocarbon commodities.

Refining

In its natural state, crude oil has no practical uses except for burning as fuel after removal of the more volatile gases that flow with it from the production well. It therefore is "taken apart" and sorted into its principal components for greater economical return. This is accomplished in a refinery that separate the various fractions into fuel gases, liquefied petroleum gases, aviation and motor gasolines, jet fuels, kerosene, diesel oil, fuel oil and asphalt. Refinery operations can be generally divided into three basic chemical processes: (1) Distillation, (2) Molecular structure alteration (Thermal Cracking, Reforming, Catalytic Cracking, Catalytic Reforming, Polymerization, Alkylation, etc.), and (3) Purification.

There are numerous refining methods employed to extract the fractions of petroleum liquids and gases. A particular refinery process design is normally dependent on the raw feedstock characteristics (e.g., crude oil and produced gas natural specifications) and the market demands (e.g., aviation or automotive gasolines), which it intends to meet.

Refining is superficially akin to cooking. Raw materials are prepared and processed according to a prescribed set of parameters such as time, temperature, pressure and ingredients. The following is summary of the some of the basic processes that are used in refinery processes.

Basic Distillation

The basic refining tool is the common distillation unit. It is usually the first process in refining crude oils. Crude oil normally begins to vaporize at a temperature somewhat less than what is required to boil water. Hydrocarbons with the lowest molecular weight vaporize at the lowest temperatures, whereas successively higher temperatures are applied to separate or distill the larger molecules.

The first material to be distilled from crude oil is the gasoline fraction, followed in turn by naphtha and then by kerosene. The residue in the batch vessel or "kettle", in the old still refineries, was then treated with caustic and sulfuric acid, and finally steam distilled. Lubricants and distillate fuel oils were obtained from the upper regions and waxes and asphalt from the lower regions of the distillation apparatus. In the later 19th century, gasoline and naphtha fractions were actually considered a nuisance because little need for them existed. The demand for kerosene also began to decline because of the growing production of electricity and the wide spread use of electric lights. With the
introduction of the automobile, however, the demand for gasoline suddenly burgeoned, and the need for greater supplies of crude oil increased accordingly.

**Thermal Cracking**

In an effort to increase the yield from distillation a thermal cracking process was developed. In thermal cracking, the heavier portions of the crude oil are heated under pressure and at higher temperatures. This results in the large hydrocarbon molecules being split into smaller ones, so that the yield of gasoline from a barrel of crude oil is increased. The efficiency of the process is limited because at the high temperatures and pressures that are use. Typically a large amount of coke is deposited in the reactors. This in turn requires the use of still higher temperatures and pressures to crack the crude oil. A coking process was then invented in which fluids were re-circulated, the process ran for a much longer time, with far less buildup of coke.

**Alkylation and Catalytic Cracking**

Two additional basic processes, alkylation and catalytic cracking, were introduced in the 1930s and further increased the gasoline yield from a barrel of crude oil. In the alkylation process, small molecules produced by thermal cracking are recombined in the presence of a catalyst. This produces branched molecules in the gasoline boiling range that have superior properties (e.g., higher antiknock ratings as a fuel for high-powered internal combustion engines as those used in today automotive engines).

In the catalytic-cracking process, crude oil is cracked in the presence of a finely divided catalyst, typically platinum. This permits the refiner to produce many diverse hydrocarbons that can then be recombined by alkylation, isomerization, and catalytic reforming to produce high antiknock engine fuels and specialty chemicals. The production of these chemicals has given birth to the Chemical Process Industry (CPI). This CPI industry manufactures alcohols, detergents, synthetic rubber, glycerin, fertilizers, sulfur, solvents, and the feedstocks for the manufacture of drugs, nylon, plastics, paints, polyesters, food additives and supplements, explosives, dyes, and insulating materials. The petrochemical industry uses about five percent of the total supply of oil and gas in the U.S.

**Purification**

Purification processes are used to remove impurities such as sulfurs, mercury, gums and waxes. The processes include absorption and stripping, solvent extraction and thermal diffusion.

**Typical Refinery Process Flow**

At a refinery all crude oil normally first goes to crude distillation. The crude is run though piping inside a furnace where high temperatures cause it to partially vaporize before it flows into a fractionating tower. The vapors rise up through the tower, cooling and liquefying in a number of "bubble trays". The cooling and liquefying action is assisted by a relatively cold stream of liquid naptha being pumped into the top of the tower to flow downward from one bubble tray to another. The liquid on the different bubble trays condenses the heavier part of the vapors and evaporates its own lighter components.

Liberated gasses are drawn off at the top of the tower with the naptha. The gas is recovered to manufacture refrigerated liquefied petroleum gas (LPG). The naptha is condensed at a temperature of about 52 °C (125 °F). Part of the condensed naptha is normally returned to the top of the tower. The naptha product stream is split into light naptha for gasoline blending and heavy naptha for further reforming. Inside the tower, kerosene is withdrawn at a temperature of about 149 °C (300 °F). Diesel is withdrawn at a temperature of 260 °C (500 °F). These middle distillates are usually brought up to specification with respect to sulfur content with hydrodesulfurization. The heavy oil
from the bottom of the crude unit can be used in fuel oil blending or can be processed further in vacuum distillation towers to recover a light distillate used in blending white and black diesel oils. The low pressure in the vacuum tower enables the recovery of additional distillate with the danger of affecting fuel oil quality by subjecting it to excessive temperatures.

After products are produced by refining they are further enhanced in a blending unit. In this unit the finished products are made by mixing the components in blending tanks. To gasoline for example, coloring dyes or special additives maybe added. The completed blends are tested and then routed to tank farm storage or shipment.

Production Percentages

The demand for lighter distillation products for gasoline and jet engines has also increased the relative hazard levels of refinery facility processes over the years. A comparison of product yields from 1920 to today shows the dramatic increases in light product production percentages.

<table>
<thead>
<tr>
<th>Product</th>
<th>1920s</th>
<th>Today</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>11</td>
<td>21</td>
<td>+90 %</td>
</tr>
<tr>
<td>Kerosene</td>
<td>5.3</td>
<td>5</td>
<td>-6 %</td>
</tr>
<tr>
<td>Gas Oils</td>
<td>20.4</td>
<td>13</td>
<td>-36 %</td>
</tr>
<tr>
<td>Heavy Oils</td>
<td>5.3</td>
<td>3</td>
<td>-6 %</td>
</tr>
</tbody>
</table>

By producing higher quantities of "lighter" fuels, the plants themselves have become higher risks just by the nature of the produced percentages than in previous years. The corresponding expansion of these facilities through the decades has also combined with more explosive products to heighten risks levels unless adequate protective measures are provided.

Marketing

Bulk Plants, Distribution and Marketing Terminals store and distribute the finished products from the refineries and gas plants. Typically these facilities handle gasoline, diesel, jet fuels, asphalts, and compressed propane or butane.

The facilities consist of storage tanks or vessels, loading racks (or unloading) by ship, rail or truck, metering devices, and pumping or compression systems. Their capacities are relatively smaller compared to refinery storage and are normally dictated by local commercial demands in the bulk storage location.
Bibliography


