ENERGY TRANSPORTATION

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Summary

The majority of the world's energy consumption is from coal, oil, and natural gas, but the major production areas are mostly located vast distances away from the regions of the world where the energy is most needed. It is necessary therefore to transport energy resources around the world in very large quantities by means of specialized tankers and railcars, or by pipelines.

The usual practice is to export crude oil and gas and refine it in the receiving country rather than export refined products from the producing country. The transportation process as a whole involves potential dangers during loading and unloading as well as shipping on the open sea and on inland roads and rails. Spills of oil products could have long-lasting environmental and ecological effects in addition to the safety concerns. Partly in response to public opinion and governmental regulations, the oil and transportation industries have raised their standards of safety and environmental care to an extremely high level.

Distribution networks for petroleum and natural gas are of vital importance for everyday life in most nations of the world. Transporting these resources (LPG) could pose severe hazards, and carriers and tankers have been developed to a high level of sophistication in response to such threats. Oil and gas pipelines, which are vulnerable to a range of threats, have also been developed to minimize risks. Environmental and safety considerations demand high standards of materials, comprehensive regulation, efficient measurement and control.

Hydrogen, as a non-fossil energy source, has the potential to supplement existing sources of production of electricity. It has tremendous potential as clean energy, since it burns cleanly with high-energy output. Furthermore, hydrogen can be generated from non-depletable resources. As such, generation, storage, and transportation of hydrogen are of significant importance.

Most coal producing countries also have a well-developed distribution network reaching industrial and domestic consumers. Coal dust can cause significant air pollution as well as potential fire hazards. Again, its handling system needs to be very effectively designed. In some parts of the world, coal is transported over long distances through pipelines as slurry.

All aspects of energy transportation demand high-quality technology, materials and engineering, as well as highly developed health, safety and environmental procedures.

1. Introduction

The majority of the world's energy consumption is from coal, oil, and natural gas, all of which are classified as fossil fuels. Interestingly, these three fossil fuel resources exist in phases of solid, liquid, and gas, respectively. However, the major production areas of these fuels are mostly located far away from the regions of the world where the energy is in highest demand. Resources are not adequately distributed throughout the world, just as the world population and industrialization is concentrated.

The regions that have the highest fossil energy demands are North America, Western Europe, and Japan, whereas the regions with the highest energy output are the Middle East, Eastern Europe, and South America. Therefore, it is necessary to transport these fossil fuels and products around the world in very large quantities by means of rail cars, barges and specialized tankers, as well as by pipelines. The modes of transportation to be chosen depend upon the infrastructure of the distribution network and market demands for specific fuels.

The transportation cost of energy is an important factor in its price. Inadequate supplies to a region for a certain period of time, either long or short, will undoubtedly affect the price of energy in the market. The most common factors that increase the energy price in a region include lack of production, equipment failure in production facilities or in transportation, pipeline problems, labor disputes, wars, regulatory changes, unexpected increase in demands for certain types of fuels, and so on. Factors that affect current and future oil prices, global and local, are, first, population and economic growth, second, end use efficiencies, third, actions by producers such as OPEC and OPEC+, and fourth, price and availability of alternatives.

The consumption of energy for human activities has been constantly increasing even from the pre-historic period. The consumption level and pattern of energy very strongly correlates with the industrialization of society and the quality of life. The growth of energy industries in the world has been in line with the growth of the world economy. Conversely, it may be said that the stability and growth of the world economy has depended heavily upon the availability of needed energy sources.

The usual practice is to export oil and gas in crude form and to refine them in the receiving country. In order to make the necessary fuel available to consumers, there are four important phases involved: production, transportation, refining and upgrading, and distribution and marketing. To make the matter even more complex, there are other factors that also affect the availability of the fuel to consumers, and they are world politics and environmental regulations, global or regional. Furthermore, there are potential dangers during loading, transporting, and unloading as well as on the open sea. Crude oil spills could have serious environmental and ecological effects, and, partly in response to public opinion and governmental regulations, the oil producing and shipping industries have raised their standards of safety and environmental protection to an extremely high level.

Transportation of petroleum and liquefied petroleum gas (LPG) could pose severe environmental dangers and/or significant hazards to human life, if improperly handled. This has led to the development of very large and highly sophisticated LPG carriers. All aspects of technology, operation, and regulation of marine transportation of such fuels have reached a very high level of development and advancement.

The other major means of energy transportation is by oil and gas pipelines, which can run for thousands of kilometers both overland and on the seabed. Since damage, accidents, terrorism, and sabotage to pipelines pose potentially significant threats and hazards, the technology and safety systems have been developed appropriately to minimize such hazards, losses, and environmental dangers. Even a simple breakdown of a major pipeline for an extended period of time can render a sharp increase in the price of fuel at the consumer end, for the region, due to shortages of certain types of fuel.

Petroleum and natural gas are used not only as transportation and heating fuels, but also as raw or starting materials for a wide variety of chemicals, especially petrochemicals (Lee, 1997). Therefore, distribution networks for petroleum and natural gas are of vital importance to everyday life in most nations of the world. Environmental and safety considerations demand high standards of materials, regulation, measurement, and control.

Coal is transported by barge and by rail, particularly to power stations, but most coal producing countries also have a well-developed distribution network to industrial and domestic consumers. Coal dust can cause significant air pollution; as such its handling system needs to be well designed. Fine particles of coal are pyrophoric and render safety problems in handling. In some parts of the world, coal is transported over long distances through pipelines as slurry. In the United States, 56 or 57 percent of electricity has been generated via coal combustion. Due to stricter environmental restrictions by the Clean Air Act Amendments of 1990, high sulfur containing coals from the eastern states have been in far less demand than before. The shift from high to low-sulfur coal has required more coal to be transported for longer distances, and mostly from west to east in the US. Further, a higher percentage of coal prices is due to transportation cost. In Europe and Asia, more dependence on nuclear power generation has been evident for the past several decades, due to the environmental misgivings associated with coal-fired power generation. The major drawbacks of coal combustion for power generation have been the emission of greenhouse gases and the sulfur and nitrogen oxides (SO_x/NO_x) pollution.

All aspects of energy transportation demand high-quality technology, materials, and engineering, as well as very highly developed health, safety, and environmental procedures. In this technology, efficiency, reliability, regulatory compliance, routine monitoring, cost effectiveness, and environmental impact are of primary importance.

2. Energy Distribution System and Network

Energy resources are distributed in uneven concentrations around the entire world. They include all types of resources, identified and unidentified, economically recoverable and unrecoverable. The locations of these resources that are counted as reserves are in most instances remote from the heavy consumption areas, which are typically either industrialized regions or heavily populated metropolitan areas. They are generally far from the plant sites where the final forms of energy for consumers are processed and generated. Therefore, transportation of energy sources is involved in all phases of energy conversion and distribution processes. Figure 1 shows a generalized flowchart for an energy production and distribution system in which transportation is needed.

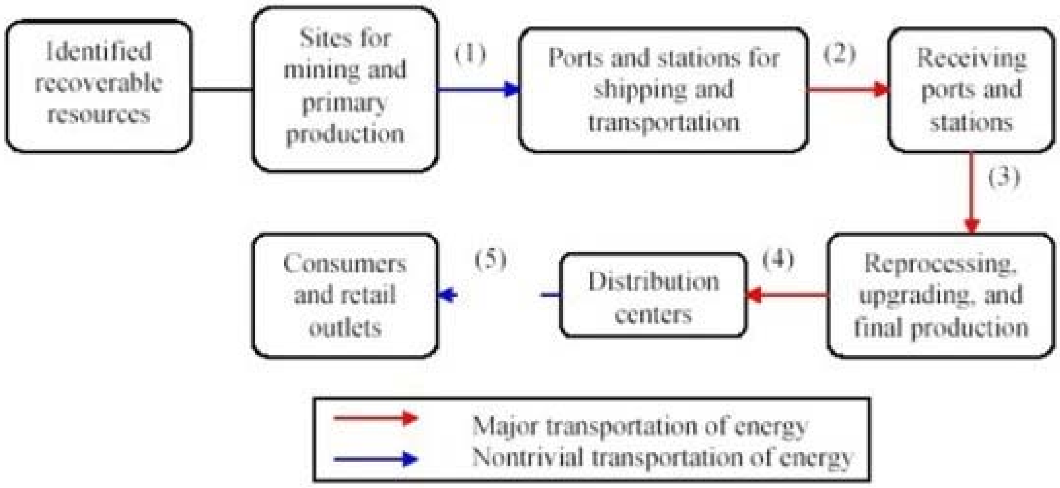

Figure 1. A generalized flowchart for energy production and distribution system

Any irregularity or breakdown of any network system described in Figure 1 for a specific type of energy would cause problems in the balance and stability of energy supply and demand. For the network systems in the world, there is a material balance relation, which is valid after considering systematic wastes, rejects, spills, and other forms of conversion. Therefore, energy, in its raw or refined form, is a limited resource in the market place. The slowest step in the transportation of energy can be considered a rate-limiting step, since the slowest step controls the overall rate of transportation. This step may be called a bottlenecking step. For example, any transportation step designated as (1) through (5) in Figure 1 may be called a rate-limiting step if it is the slowest of all and is bottlenecking the entire process.

The crude oil price change in 1999 provides an excellent example of the effect of the production rate on the final price of crude oil in the international market. In January 1999, the world oil price fell to US$9.93/bbl and, as a countermeasure, OPEC cut its production by 1.7 million bbl/day. Mexico, Norway, Russia, and Oman collectively cut an additional 0.4 million bbl/day, making a total reduction of 2.1 million bbl/day, or about 3 percent of the world oil output. As a result, the oil price rebounded to US$23.69 by November 15 1999, proving that the mere 3 percent reduction in production was indeed quite significant.

There have been great efforts to refine the distribution network in modern energy industries. The refinement efforts include investment in pipelines and superports, design of efficient tankers and docks, the application of operation research principles, mergers and spin-offs of industries, computerized monitoring systems, safety precautions and loss prevention efforts, and advances in supportive technology.

3. Modes of Energy Transportation

Technologies have been developed, utilized, and refined over a long period of time for energy transportation. Various means and modes have been utilized, depending upon geographical necessity, the fuel type, the volume to be transported, and the transportation cost. Each mode of transportation has advantages and disadvantages for a variety of fuels. To transport even a single type of fuel from its production point to another destination for consumption, a number of different transportation modes may be used as a hybrid system.

3.1. Rail Transportation

Ever since the railroads were built, coal has been an important commodity for the energy industry. Considering that 56–57 percent of the electricity generated in the United States currently comes from coal combustion, a very large amount of coal needs to be transported from mining sites to power plants. It is safe to say that about nine out of every ten tons produced in the US are consumed in coal-fired power generating plants, with one tenth used industrial consumption (excluding power generation) and for foreign export.

Since the acquisition of Conrail by CSXT and NSC in the middle of 1999, four mega-sized railroads have dominated the US market: CSXT, NSC, BNSF, and UP. These four networks account for approximately 96 percent of the annual US coal transportation based on freight tonnage. Most US railroads have offered four distinct types of railroad freight services for coal transportation: single carload, multiple carloads, trainload volume, and unit train (unitrain). These four basic types of railroad service to transport bulk commodities have evolved over the last 100 years. As can be imagined, coal was first transported by rail in single-car shipments in conventional trains. In due course, coal production and mining capacity increased to over 100 carloads per day originating from one location, and the railroads responded with trainload volume movements for greater efficiency and economy. Railroad operating efficiency has been constantly improved in unit-train operations, thanks to developments of modern technologies in engine design, efficient design of trains, computerized monitoring, and carload management. As a result, many of the original distinctions between the basic four service types have been lost. For example, the number of carloads required to form a trainload depends upon many factors that may vary from one railroad to another, depending on local operating conditions, and the availability of railcars often assigned from a railcar pool. The rail service has further improved to offer unit-train movements on regularly scheduled trains, thus avoiding all terminals and switching operations. A unit-train movement is an integral movement of (usually) one commodity moving from a single origin to a single destination on a regularly scheduled train, thus maximizing efficiency. This transition has been beneficial to both coal producing companies and railroad industries, as long-term contracts for coal transportation have become popular.

The rail transportation system in Europe is highly developed. The Channel Tunnel, popularly called the "Chunnel," is a three-tunnel railroad connection running under the English Channel, connecting Folkestone in England to Calais, France. The tunnel is 50 km long and passenger service began in 1994. The technological advances and experience derived from the project will undoubtedly provide valuable information for future rail transportation design and development.

US coal producers and shippers recognize that railroad regulatory reform, in the form of the Staggers Rail Act of 1980, has produced benefits to both railroads and railroad shippers. According to the US General Accounting Office (GAO), railroad finances improved in the 1990s, compared to the prior decades. Their improved financial health was clearly evidenced by higher railroad returns on investment and on equity. On the other hand, the GAO also found that the average annual change for real rail rates for coal traffic fell substantially more in the 1990s than in the 1980s. One of the most significant regulatory changes was that the Staggers Act both authorized and encouraged carriers and shippers to negotiate private agreements (contracts) for specific railroad contracts. Such contracting, which had previously not been legal, enables the railroads to manage their locomotive power, railcar equipment, crew assignment, and planning operations much more efficiently. This is often referred to as deregulation.

Railroad transportation of petroleum and petroleum products also has a long history. The history of the tankcar in the United States began with the very first successful oil well in Titusville, Pennsylvania, on August 27 1859. Immediately after the oil well was drilled, a railroad was built in the region and used for transporting oil in small wooden barrels on ordinary flatcars. The small wooden barrels used in this type of operation have become collectors' items in the current antique market. If we were to witness this type of transportation of oil in modern situations, we would immediately report it to local and/or federal authorities as a safety threat and a potential environmental hazard.

Tankcar design has been improved for capacity, safety, and leakage protection. The credit for inventing and developing the railroad tankcar is generally given to Charles P. Hatch (an employee of the Empire Transportation Company) and Amos Densmore (an oil well owner), for their independent accomplishments in 1865. Their tankcar designs were based on large wooden tubs on railroad flatcars, but the wooden tubs were soon replaced with heavy iron tanks in order to overcome the leakage problems. Iron tanks were subsequently changed to higher quality steel equipment. Railroad companies, faced with unending investment in new tanker equipment, argued that it is not only impractical, but also economically unwise to maintain a fleet of tankcars to satisfy all shippers, petroleum and petrochemical industries, along their rail routes. In 1888 the Interstate Commerce Commission agreed with the railroads, and procurement and securing of tankcar equipment became the shippers' responsibility. This was the start of a tradition that has become one of the industry's standards.

Railroad tankcar design has been constantly improved in all aspects involving capacity, materials of construction, and specifications for specialized products. Such enhancements were accelerated during the First World War to handle the increased volume of transportation of petroleum products. Welding was first authorized in 1920. The very first railcar for liquid propane was built in 1928 for Phillips Petroleum Company, and consisted of thirty large ICC-27 cylinders mounted vertically on a flatcar with a total capacity of 8,000 gallons. Fusion-welded tankcars were first used experimentally after authorization by the Association of American Railroads (AAR) Committee on Tank Cars in 1938, and this test led to a new series of tankcar specifications being established in 1941. Further technological advancements were made during the Second World War, in order to meet the drastically increased demand for petroleum and its products. Most of the advances were in the area of increased capacity, which resulted in production of jumbo tankcars (10,000 gallons or higher, as compared to 3,500 gallons in the earlier years). In 1970, the US Department of Transportation (US DOT) limited the size of tankcars to 34,500 gallons and to 263,000 pounds over-the-rail weight, which includes the weights of the car and its load. Most conventional jumbo-sized tankcars moving flammable liquids and corrosive fluids were generally in the range of 20,000 gallons. The US Department of Transportation also defined hazardous materials, on the basis of principal four criteria: reactivity, flammability, corrosivity, and EP-toxicity. In recent years, improvements have been made in tankcar design, with emphasis placed on environmental and occupational safety, and stricter regulations have been imposed on the transportation of petroleum and petrochemical products (see "Occupational safety," EOLSS on-line, 2002). In the United States, regulatory supervision, enforcement, and guidance for railroad transportation is provided by Surface Transportation Board (STB) and Federal Railroad Administration (FRA). Governmental agencies of similar nature are also responsible for regulatory control in developed countries.

Special tankcars have been developed for shipping bulk quantities of liquefied petroleum gas (LPG) and other compressed gas fuels, such as liquefied natural gas (LNG), by rail. These tankcars were constructed from sturdier materials following the specifications by the US Department of Transportation. Safety, and great emphasis is placed on environmental issues, due to the potential severity of the impacts that could be caused by mishaps and accidents involved with transportation of compressed gas or liquid fuels. Concerns for risk management and loss prevention involving humans and the environment have become critically important in planning for the industries.

3.2. Barge Transportation

Many countries in the world have long networks of interconnected inland waterways that are commercially navigable by barge tows. These waterways can serve as cost-effective transportation routes between ports and docks for commodities as well as humans. The United States has an 11,000-mile system of interconnected and intracoastal waterways that can be exploited commercially for barge transportation. These routes have been long used for coal transportation from river terminals in the eastern and midwestern states to utility and non-utility power plants as well as to terminals on the Gulf Coast and at several points on the lower Mississippi River. Nowadays, the waterway system is also utilized for transporting coal produced in the west and taken to river docks at points on the Mississippi River in Missouri and Illinois and on the Ohio River in Illinois. This west-to-east movement of coal is especially prevalent, since the high-sulfur eastern US coal is no longer in high demand due to the restrictions of the Clean Air Act (CAA) Amendments of 1990.

Coal barge tows are particularly important for coal distribution due to the cost competitiveness of a variety of intermodal options such as truck/barge, rail/barge, conveyor/barge, and so on. This advantage is even more pronounced when utility plants are located on navigable waterways. Furthermore, the equipment used for barge transportation is generally inexpensive to construct and maintain, and the energy cost for barge operation itself is also very low. Furthermore, barge transportation is typically through waterways that do not directly affect daily lives of humans.

In the United States, statistics for coal barge traffic for 1997 indicate that the Ohio River was most heavily used, at 134.2 million tons/year, while the Mississippi from Minneapolis (Minnesota) to Mouth of Passes (Gulf of Mexico) was second at 42.4 million tons/year. Considering the total annual US coal production of 950 million tons, the amount going through the Ohio River by barges accounts for a significant portion. In Europe also, the waterborne transportation system is highly developed. Interconnecting rivers and canals provide excellent inland water transportation in central and western Europe. Statistical data for the worldwide barge traffic for coal transportation are not available; however, its importance throughout the world, wherever it is available and practicable, seems undoubtedly high. As long as the tidal and climate predictions are stable for waterways, barge transport serves as a cost-effective and safe option for carrying coal.

In addition to coal transport, barges also move some oil and oil products to ocean and river terminals. In the United States, both river and ocean barges transport significant amounts of oil products along all three US coast lines and into the inland via navigable waterways. Typical river barges for oil transportation carry approximately 1 million gallons each, while ocean barges are substantially larger in capacity and size of navigation equipment as they must go through usually rougher ocean waters. About 1.4 billion gallons of petroleum products are moved annually in the US via waterborne commerce.

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Bibliography

Aceves, S. M.; Martinez-Frias, J.; Garcia-Villazana, O. 2000. Low Temperature and High Pressure Evaluation of Insulated Pressure Vessels for Cryogenic Hydrogen Storage. A document included in Proceedings of the 2000 Hydrogen Program Review, NREL/CP-570-28890. [This paper evaluates the utilization of insulated pressure vessels for hydrogen storage.]

Considine, D. M. 1977. *Energy Technology Handbook.* New York, McGraw-Hill. 1585 pp. [This book is an extensive reference source for a variety of energy related topics.]

Dillon, A. C.; Gennett, T.; Alleman, J. L.; Jones, K. M.; Parilla, P. A.; Heben, M. J. 2001. Optimization of Single-Wall Nanotube Synthesis for Hydrogen Storage. A document from the Metal Hydrides and Carbon for Hydrogen Storage Task of the International Energy Agency, Project C-2, Task 12, also available at http://www.eren.doe.gov/ hydrogen/iea/pdfs/NN0094t.pdf. [This paper describes studies carried out to improve hydrogen storage capability using single-wall carbon nanotubes.]

Lee, S. 1991. *Oil Shale Technology.* Boca Raton, Fla., CRC Press. 271 pp. [This book is a comprehensive reference on oil shale and shale oil related topics.]

——. 1996. *Alternative Fuels.* Philadelphia, Taylor & Francis. 485 pp. [This book discusses current as well as emerging technologies and facts about alternative fuels and their use.]

——. 1997. *Methane and Its Derivatives.* New York, Marcel Dekker. 414 pp. [This book discusses current as well as emerging technologies and facts about methane and petrochemical derivatives.]

Loutfy, R. O.; Wexler, E. M. 2001. Investigation of Hydrogen Storage in Fullerene Hydrides. A document from the Metal Hydrides and Carbon for Hydrogen Storage Task of the International Energy Agency, Project C-2, Task 12, also available at http://www.eren.doe.gov/hydrogen/ iea/pdfs/NN0094u.pdf. [This paper investigates the use of fullerene hydrides for hydrogen storage.]

National Renewable Energy Laboratory. 1995. Hydrogen: The Fuel for the Future. A document prepared for U.S DOE by NREL as part of DOE/GO-10095-099, DE95004024. [This document highlights the potential of hydrogen as an energy carrier of the present and future.]

Odegard, Jr., B. O.; Thomas, G. J. 2001. Testing of High Pressure Hydrogen Composite Tanks. A paper included in Proceedings of the 2001 DOE Hydrogen Program Review, NREL/CP-570-3053. [This paper discusses test results for compressed hydrogen gas storage in high pressure composite tanks.]

Patterson, P. D.; Birky, A. K.; Maples, J. D.; Moore, J. S. 2000. Future World Oil Prices and the Potential for New Transportation Fuels. A paper presented at the TRB Seventy-ninth Annual Meeting, also available at http://www.ott.doe.gov/facts.html. [This paper presents projections of oil price and production as well as Gately world oil model.]

Speight, J. G. 1991. *The Chemistry and Technology of Petroleum.* 2nd edn. New York, Marcel Dekker. 760 pp. [This book is a comprehensive reference for the chemistry and technology of petroleum.]

——. 1993. *Gas Processing: Environmental Aspects and Methods.* Oxford, Butterworth Heinemann. 338 pp. [This book presents in great detail the natural gas processing with special emphasis placed on the environmental aspects and treatment methods.]

——. 1994. *The Chemistry and Technology of Coal.* 2nd edn. New York, Marcel Dekker. 528 pp. [This book is a comprehensive reference for the chemistry and technology of coal.]

Speight, J. G.; Lee, S. 2000. *Environmental Technology Handbook,* 2nd edn. Philadelphia, Taylor & Francis. 333 pp. [This handbook is a comprehensive guide for all scientific and technological aspects of the environment and environmental technologies.]

Tata Energy and Resources Institute, 2001. TERI Teams Up with Pakistani Institute to Conduct Feasibility Study. [A news release available from Tata Energy and Resources Institute, New Delhi, India.]

Venneri, F. 2000. Zero Emission Coal to Hydrogen. A document from the Energy and Sustainable Systems Program Office, Los Alamos National Laboratory, New Mexico, USA. [This paper introduces a new process to produce hydrogen from a coal and water slurry, which can then be converted into electricity.]

Whaley, T. P.; Long, G. M. 1996. Pipelines in Kirk-Othmer. *Encyclopedia of Chemical Technology.* 4th edn, Vol. 19, pp. 91–112. New York, Wiley. [This paper is a comprehensive summary of pipeline technology for the oil and gas transportation.]

Yvon, K. 2001. High Pressure Synthesis of New Hydrogen Storage Materials. A document from the Metal Hydrides and Carbon for Hydrogen Storage Task of the International Energy Agency, Project C-2, Task 12, also available at http://www.eren.doe.gov/hydrogen/iea/pdfs/ NN0094n.pdf. [This paper deals with synthesis of novel lightweight metal hydrides for hydrogen storage.]

Biographical Sketch

Dr Sunggyu Lee, Chairman and C. W. LaPierre Professor, Department of Chemical Engineering, University of Missouri-Columbia, Columbia, Mo., USA.

Dr Lee earned his Bachelor's and Master's degree in Chemical Engineering from Seoul National University, Seoul, Korea, in 1974 and in 1976, respectively. He received his Ph.D. degree from Case Western Reserve University in 1980. Dr Lee joined The University of Akron as Assistant Professor of Chemical Engineering in 1980. From 1988, he held the title of Robert Iredell Professor, an endowed chair-professorship, and served as Department Head for nine years. He served also as the Director of the Process Research Center (PRC), one of the state supported Centers of Excellence. He left Akron to join the University of Missouri in 1997 and currently holds titles of Chairman and C. W. LaPierre Professor of Chemical Engineering.

At Akron, Dr. Lee was the recipient of numerous prestigious awards, including the Outstanding Teacher Award in 1987, the Outstanding Researcher Award in 1993, and the first recipient of the Louis A. Hill Award for outstanding professional achievement in 1987. He is the only professor in the University (Akron) history to have received both teaching and research awards from the University Alumni Association. He received a Distinguished Alumni Award from the College of Engineering, Seoul National University in 1994. He is a member of National Academy of Engineering of Korea (NAEK).

He has authored five books, has four more books in progress, nine major research monographs, 125 refereed journal publications, over eighteen US patents and over 100 foreign patents, and 281 proceedings and conference articles. He has delivered ninety invited seminars and lectures to academia and industries. He has taught a total of twenty-six different subjects at both undergraduate and graduate levels. He has received research grants and contracts totaling over $12 million, of which $8.8 million as a principal investigator. He served as Major Advisor to forty-seven Masters, twenty-six Ph.D.s, and twenty-one post-doctoral fellows. He has also designed and helped design twenty-one pilot plants and eight commercial and demonstration plants. He serves as Editor of *Reviews in Process Chemistry and Engineering* (RPCE), and US Editor of *Korean Journal of Chemical Engineering* (KJChE), and is a member of the Editorial Board of *Energy Sources.* He also serves on the Advisory Board of International Pittsburgh Coal Conference. He has served as consultant to over forty major industries.

His specialties are in the areas of industrial reaction engineering and process engineering. To be specific, his expertise areas include C_1 Chemistry, clean coal technology, methanol and DME synthesis, gasoline and oxygenates, environmental technology, oil shale pyrolysis, supercritical fluid technology, low temperature materials processing, reactive polymer processing, scale-up and pilot plant studies, and high pressure reactor design.