DESIGN OF THERMAL SYSTEMS

INTRODUCTION

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SYSTEM

Prerequisite:

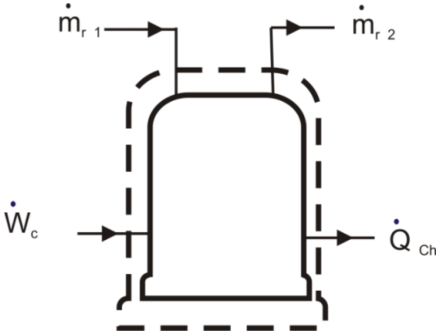
Students should had introductory courses in engineering thermodynamics and heat transfer and are familiar with the basics of fluid mechanics.

Different Thermal systems are:

- **Refrigerator & food freezers,**
- **Air-Conditioning systems,**
- **Cold storages,**
- **Cooking appliances,**
- **Furnaces,**
- **Refrigeration systems,**
- **Thermal power plants.**

- Thermal systems consists of compressors, pumps, turbines, heat exchangers, chemical reactors, and a variety of related devices.
- These components are interconnected to form networks by conduits carrying the *working substances, usually gases or liquids.*

Across all the components of thermal systems, Energy and Heat interaction takes place across each component



Thermal system design has two branches:

- *System design and Component design:*

  System design refers to overall thermal systems and the second to the individual components (heat exchangers, pumps, reactors, evaporator, condenser, compressor, expansion device etc.) that make up the overall systems.,

- *System design may refer to new-plant design (water chiller, Cold storage, Air-conditioning system, Ice factory,) or to design associated with plant expansion, retrofitting, maintenance, and renovation.*

THERMAL SYSTEMS ENGINEERING

- **It is concerned with how energy is utilized to achieve beneficial functions in industry, transportation, and the home.**
- **In industry**, thermal systems are found in **electric power generating plants, chemical processing plants**, and in **manufacturing facilities.**
- Our **transportation** needs are met by various types of engines, power converters, and cooling equipment.
- **In the home, appliances** such as ovens, refrigerators, and furnaces represent thermal systems.
- **Ice rinks, snow-making machines, and other recreational uses** involve thermal systems.

THERMAL SYSTEMS ENGINEERING

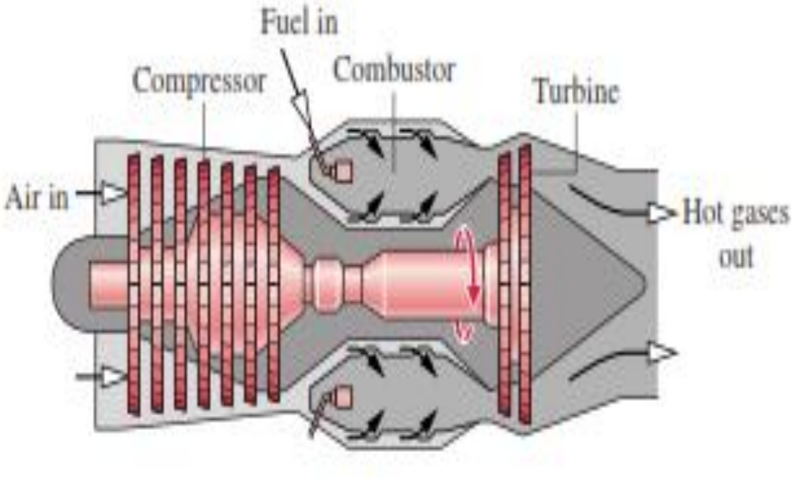
- **Thermal systems involve the storage, transfer, and conversion of energy.**
- **Energy also can be stored within the matter making up the system [Ice bank, Secondary Refrigerant].**
- **Energy can be transferred between a system and its surroundings by work, heat transfer, and the flow of hot or cold streams of matter.**
- **Energy also can be converted from one form to another. For example, chemical energy stored in the fuel can be converted into heat , mechanical energy [Internal combustion engines].**

THERMAL SYSTEMS - APPLICATIONS

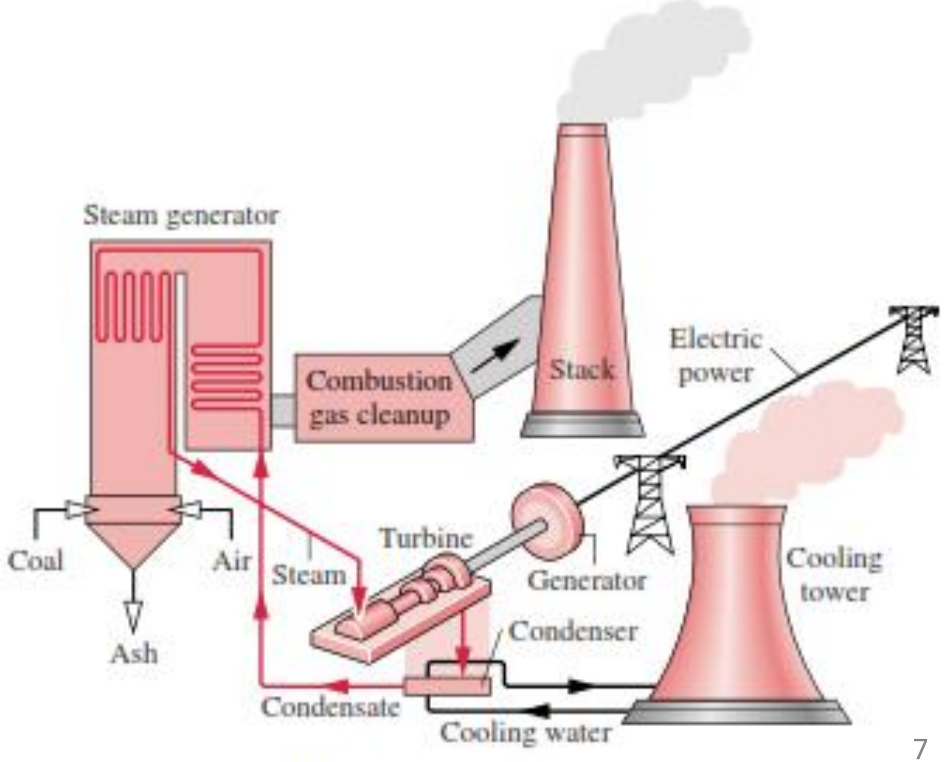
- **Prime movers: internal-combustion engines, turbines**
- **Fluid machinery: pumps, compressors**
- **Fossil- and nuclear-fueled power stations**
- **Alternative energy systems**
- **Fuel cells**
- **Solar heating, cooling and power generation**
- **Heating, ventilating, and air-conditioning equipment**
- **Aerodynamics: airplanes, automobiles, buildings**
- **Pipe flow: distribution networks, chemical plants**
- **Cooling of electronic equipment**
- **Materials processing: metals, plastics, semiconductors**
- **Manufacturing: machining, joining, laser cutting**
- **Thermal control of spacecraft**

Thermal systems - applications

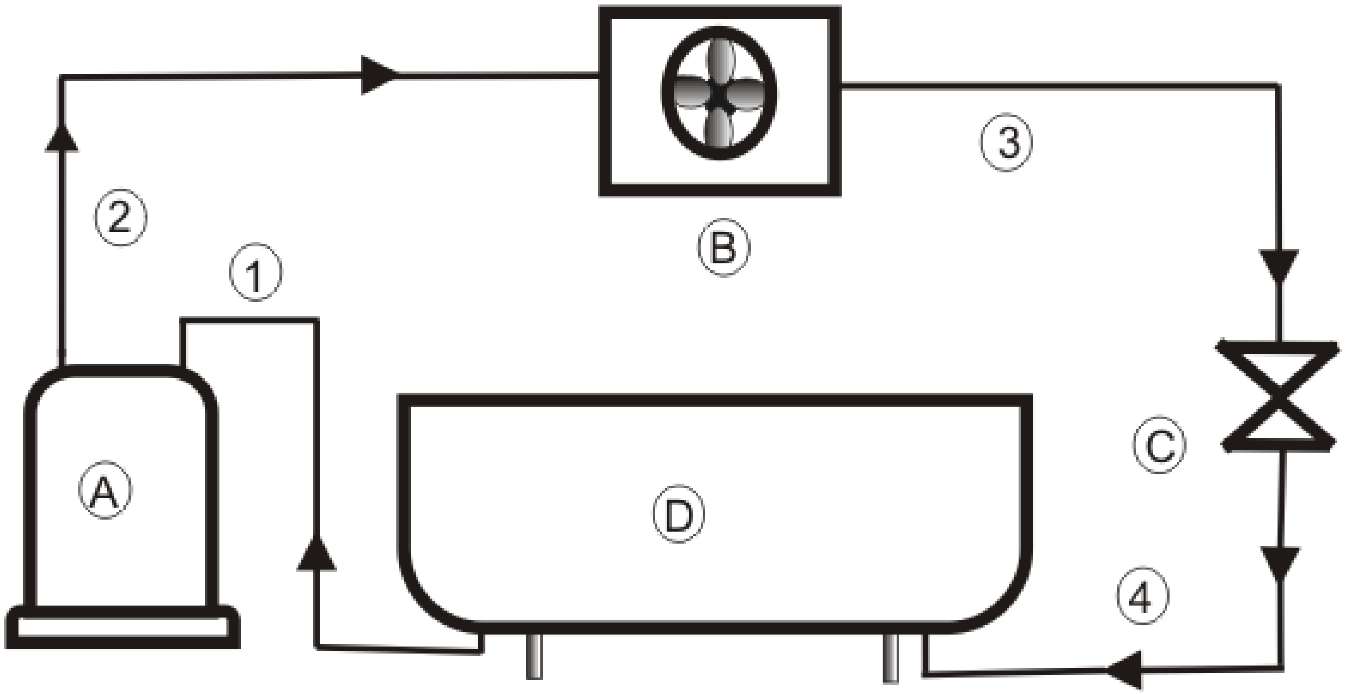
- Thermal systems involving conversion of energy in fossil fuels to achieved a desired outcome. Components of these systems also involve work and heat transfer.
- Across each component of thermal systems heat and energy interactions takes place.



Turbojet engine

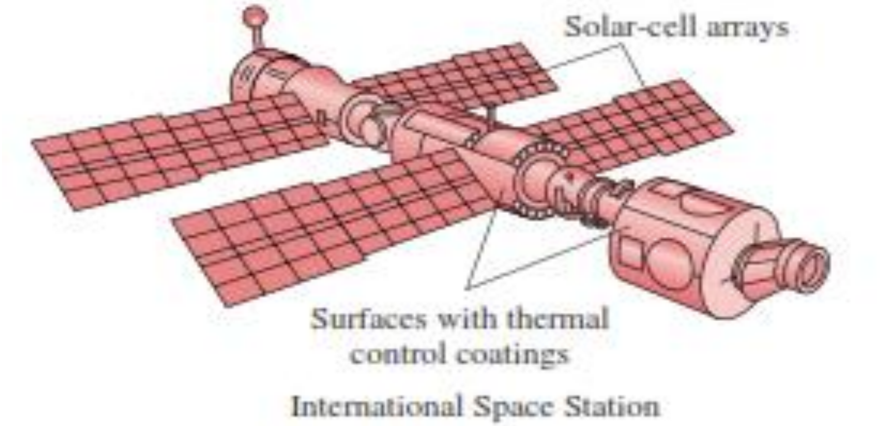


Electrical power plant

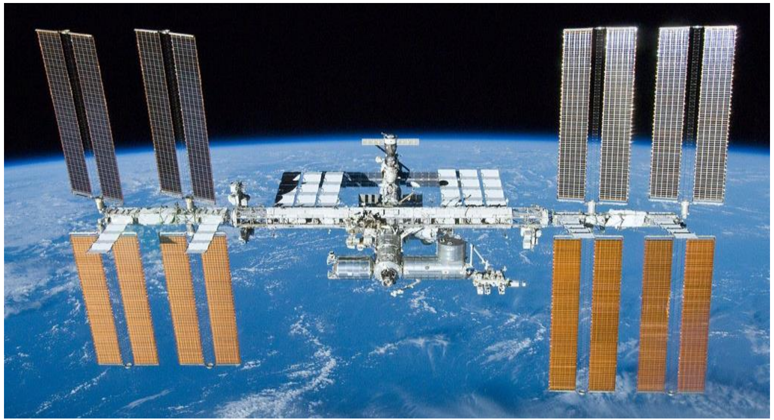


Block Diagram of Bulk Milk Cooler

- **For life support on the International Space Station, solar energy is converted to electrical energy and provides energy for plant growth experimentation and other purposes.**



International Space Station



- **The International Space Station (ISS) is a space station, or a habitable artificial satellite, in low Earth orbit.**
- **The ISS serves as a microgravity and space environment research laboratory in which crew members conduct experiments in biology, human biology, physics, astronomy, meteorology, and other fields.**
- **The station is suited for the testing of spacecraft systems and equipment required for missions to the Moon and Mars.**

THERMAL SYSTEMS CASE STUDIES

- **Thermal systems typically consist of a combination of components that function together as a whole.**
- **The components themselves and the overall system can be analyzed using principles drawn from three disciplines: Thermodynamics, Fluid Mechanics, and Heat Transfer.**
- **The nature of an analysis depends on what needs to be understood to evaluate system performance or to design or upgrade a system.**
- **Engineers who perform such work need to learn thermal systems principles and how they are applied in different situations.**

THERMAL SYSTEMS CASE STUDIES

- **Domestic Hot Water Supply**
  - **The installation that provides hot water for your shower is an everyday example of a thermal system.**
  - **A typical system includes: a water supply, a hot-water heater, hot-water and cold-water delivery pipes, a valve and a shower head.**
  - **The function of the system is to deliver a water stream with the desired flow rate and temperature.**

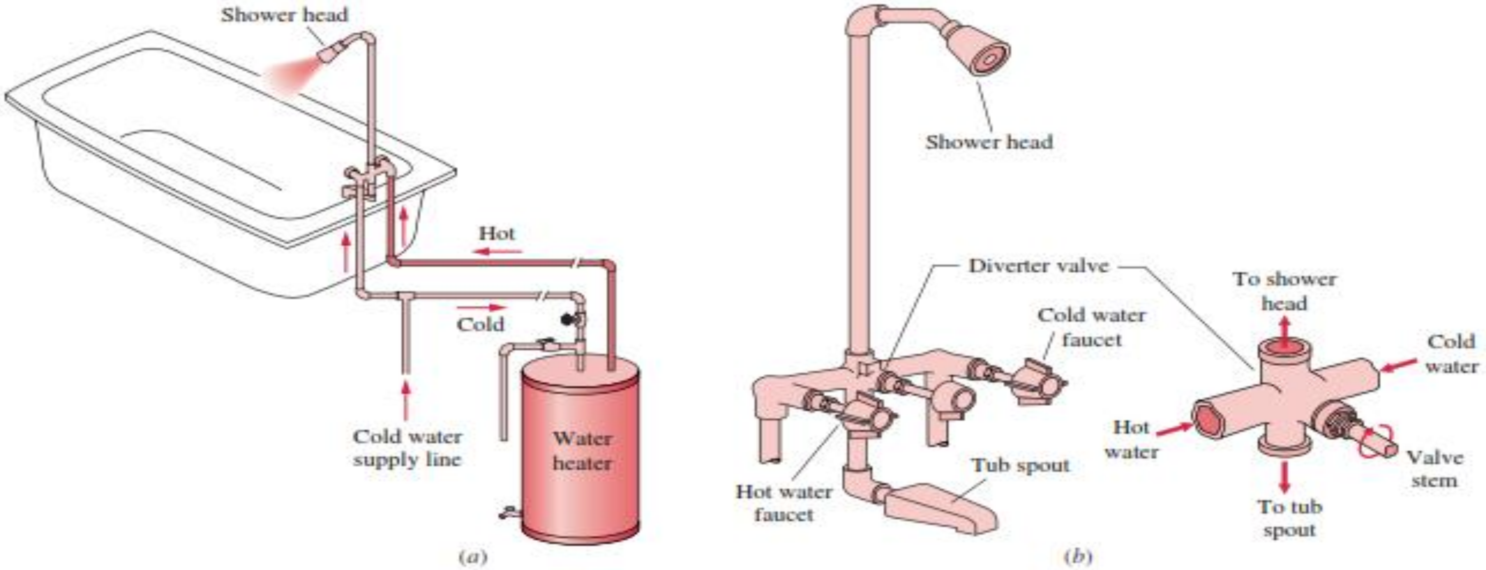
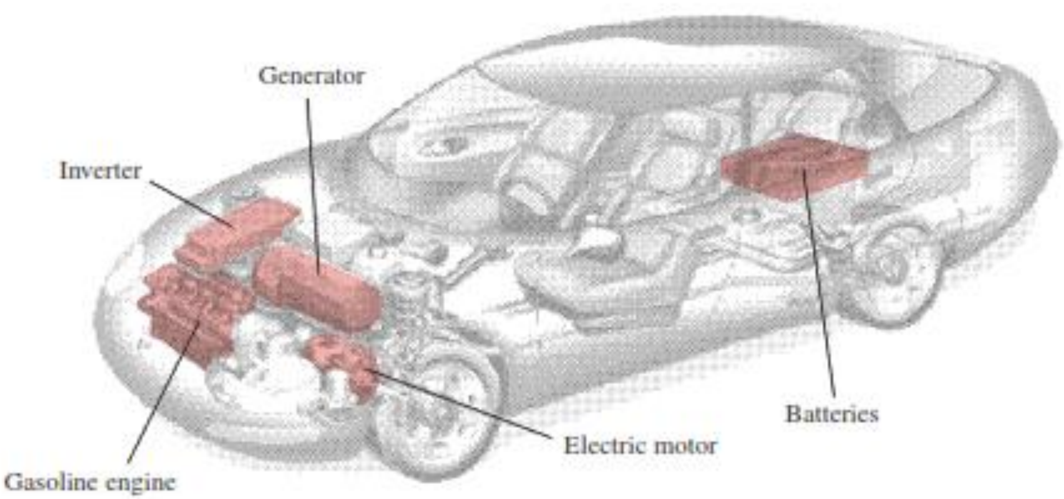


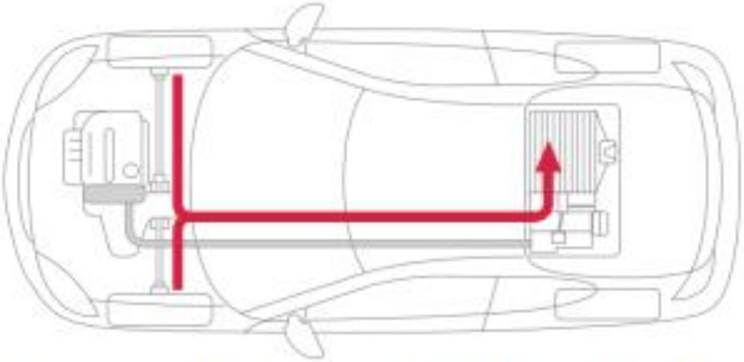
Figure 1.2 Home hot water supply. (*a*) Overview. (*b*) Faucet and shower head.

THERMAL SYSTEMS CASE STUDIES (contd…)

- **Hybrid Electric Vehicle**



(*a*) Overview of the vehicle showing key thermal systems



(*b*) Regenerative braking mode with energy flow from wheels to battery

Figure 1.3 Hybrid electric vehicle combining gasoline-fueled engine, storage batteries, and electric motor. (Illustrations by George Retseck.)

- It utilize two or more sources of power within a single vehicle to achieve good fuel economy.
- The aspects of deals with energy conversion, energy accounting, and the limitations on how energy is converted from one form to another.
- Within the engine, air, fuel, engine coolant, and oil are circulated through passageways, hoses, ducts, and manifolds. **These must be designed to ensure that adequate flow is obtained.** The fuel pump and water pump also must be designed to achieve the desired fluid flows.

THERMAL SYSTEMS CASE STUDIES

- **Heat transfer principles** guide the design of the **cooling system, the braking system, the lubrication system,** and numerous other aspects of the vehicle.
- **Coolant circulating** through passageways in the engine block must absorb energy transferred from hot combustion gases to the cylinder surfaces so those surfaces do not become too hot.
- **Engine oil and other viscous fluids** in **the transmission and braking systems** also can reach high temperatures and thus must be carefully managed for retaining properties of lubricants.
- **Hybrid electric vehicles provide examples of complex thermal systems**. As in the case of hot water systems, the principles of thermodynamics, fluid mechanics, and heat transfer apply to the **analysis and design of individual parts, components, and to the entire vehicle.**

ANALYSIS OF THERMAL SYSTEMS

- Important engineering functions are to **design and analyze** things intended to **meet human needs.**
- **Engineering *design*** *is a* ***decision-making process in which principles drawn from*** engineering and other fields such as **economics and statistics** are applied to devise a system, system component, or process.
- Fundamental elements of design include establishing **objectives, analysis, synthesis, construction, testing, and evaluation.**

ANALYSIS OF THERMAL SYSTEMS

- The first step in analysis is the identification of the system and how it interacts with its surroundings.
- Analysis of thermal systems uses, directly or indirectly, one or more of four basic laws:

1. *Conservation of mass*
2. *Conservation of energy*
3. *Conservation of momentum*
4. *Second law of thermodynamics*

THE THREE THERMAL SCIENCE DISCIPLINES

- Thermal systems engineering typically requires the use of three thermal science disciplines: **Thermodynamics, Fluid mechanics, and Heat transfer**.
- **Thermodynamics** provides the foundation for analysis of thermal systems through the conservation of mass and conservation of energy principles, the second law of thermodynamics, and property relations.
- *Fluid mechanics and heat transfer provide additional concepts, including* the empirical laws necessary to specify, for instance, material choices, component sizing, and fluid medium characteristics.

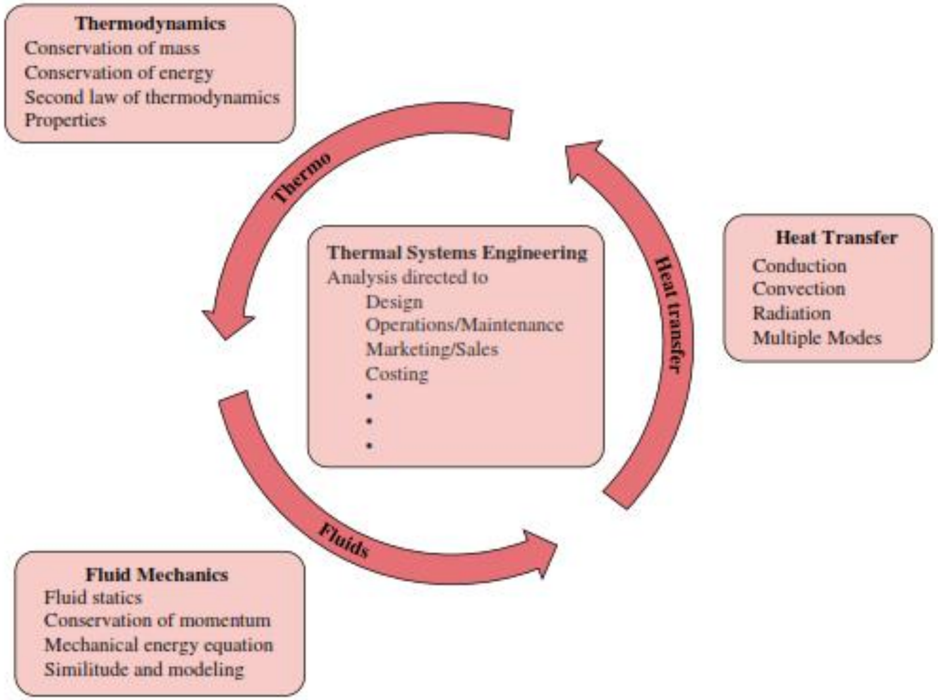


Figure 1.5 The disciplines of thermodynamics, fluid mechanics, and heat transfer involve fundamentals and principles essential for the practice of thermal systems engineering.

- For example, thermodynamic analysis can tell you the final temperature of a hot work piece quenched in an oil, but the *rate at which it will cool* is predicted using a heat transfer analysis.

THE THREE THERMAL SCIENCE DISCIPLINES

- Fluid mechanics is concerned with the behavior of fluids at rest or in motion.
- Two fundamentals that play central roles in our discussion of fluid mechanics are the **conservation of momentum principle.**

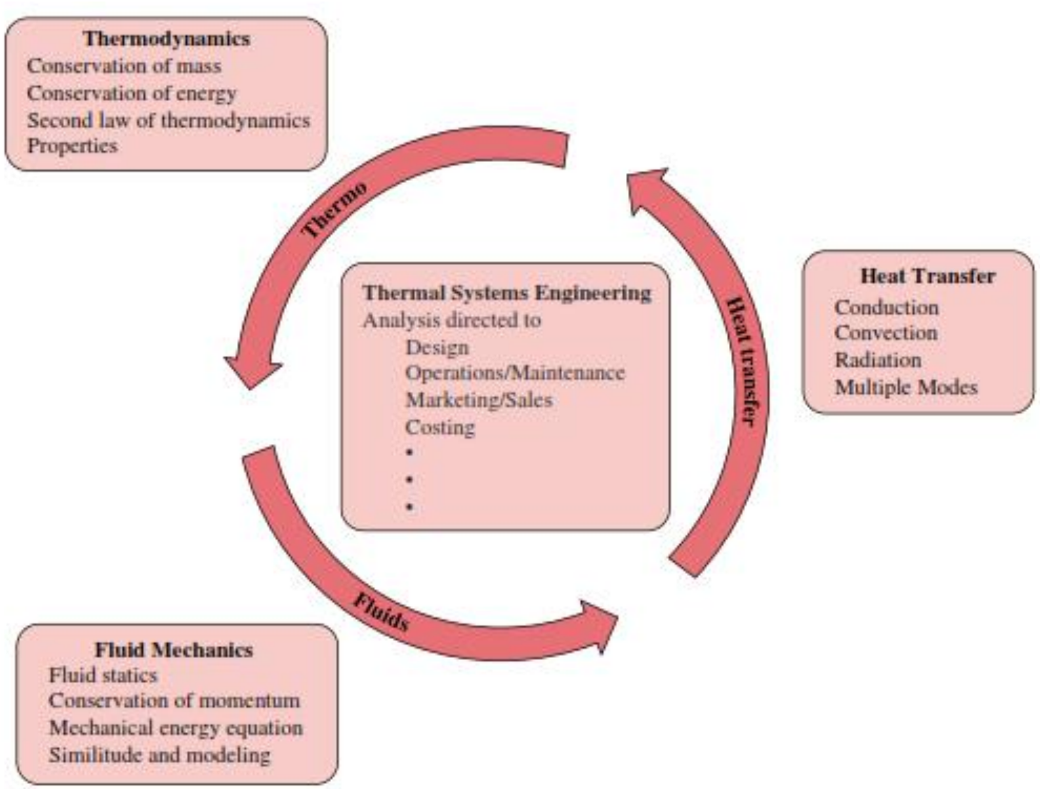


Figure 1.5 The disciplines of thermodynamics, fluid mechanics, and heat transfer involve fundamentals and principles essential for the practice of thermal systems engineering.

- ❑ Principles of fluid mechanics allow the **study of fluids flowing inside pipes (internal flows) and over surfaces (external flows) with consideration of frictional effects and lift/drag forces.**

THE THREE THERMAL SCIENCE DISCIPLINES (contd…)

- *Heat transfer is concerned with energy transfer as a consequence of a temperature difference.*
- There are three *modes of heat transfer.* ***Conduction*** *refers* to heat transfer through a medium across which a temperature difference exists.
- ***Convection*** refers to heat transfer between a surface and a moving or still fluid having a different temperature.
- The third mode of heat transfer is termed **thermal *radiation*** *and represents* the net exchange of energy between surfaces at different temperatures by electromagnetic waves independent of any intervening medium.
- For these modes, the heat transfer rates depend on the *transport properties of substances, geometrical parameters, and temperatures.*

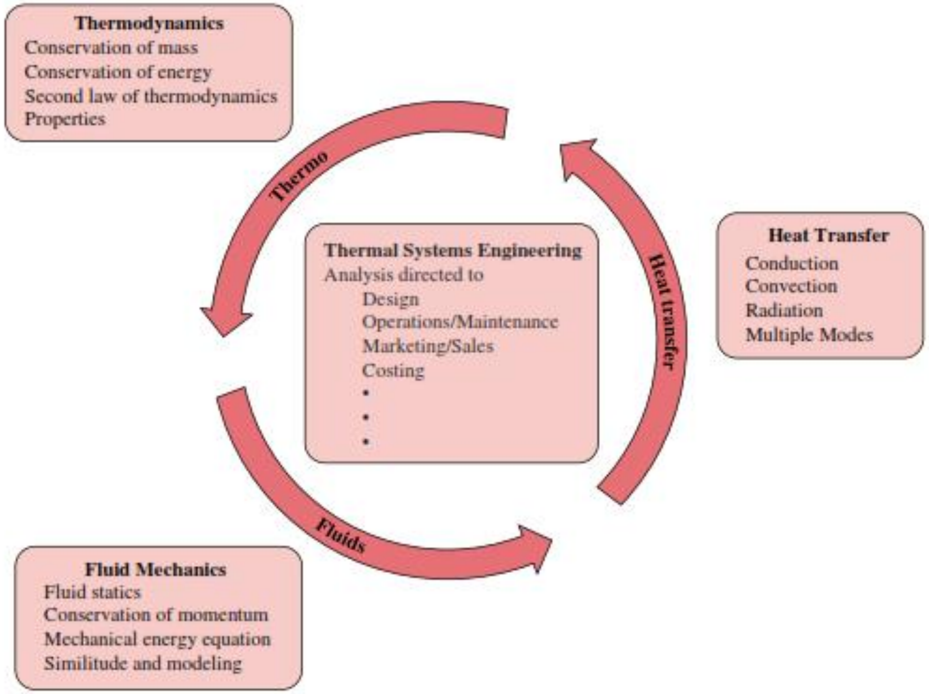


Figure 1.5 The disciplines of thermodynamics, fluid mechanics, and heat transfer involve fundamentals and principles essential for the practice of thermal systems engineering.

- Many applications involve more than one of these modes; this is called ***multimode*** **heat transfer.**

WORKABLE, OPTIMAL AND NEARLY OPTIMAL DESIGN

- **Thermal Design** - a creative process by which new methods, devices, and techniques are developed to solve new or existing thermal problems.

A critical early step in the design of a system is to pin down what the system is required to do and to express these requirements quantitatively, that is, to formulate the design specifications.

A workable or acceptable design - one that satisfy the given requirements and constraints. A workable design is simply one that meets all the specifications.

- Optimal design -The workable design which is in some sense the "best." Several alternative notions of best can apply depending on the application: optimal cost, size, weight, reliability, and so on. Although the term optimal can be defined as the most favorable or most conducive to a given end, especially under fixed Conditions.

- **'Optimal' meaning** - most favorable or most favorable to a given end, especially under fixed conditions.

- ***Nearly optimal* design -** a design that is close to optimal.

- Due to system complexity and uncertainties in data and information about the system, a true optimum is generally impossible to determine.

LIFE-CYCLE DESIGN:

- **Engineering design requires highly structured *critical thinking and active Communication among the members of the design team, that is, the group of* individuals whose responsibility is to design a product or system.**

Overview of the Design Process

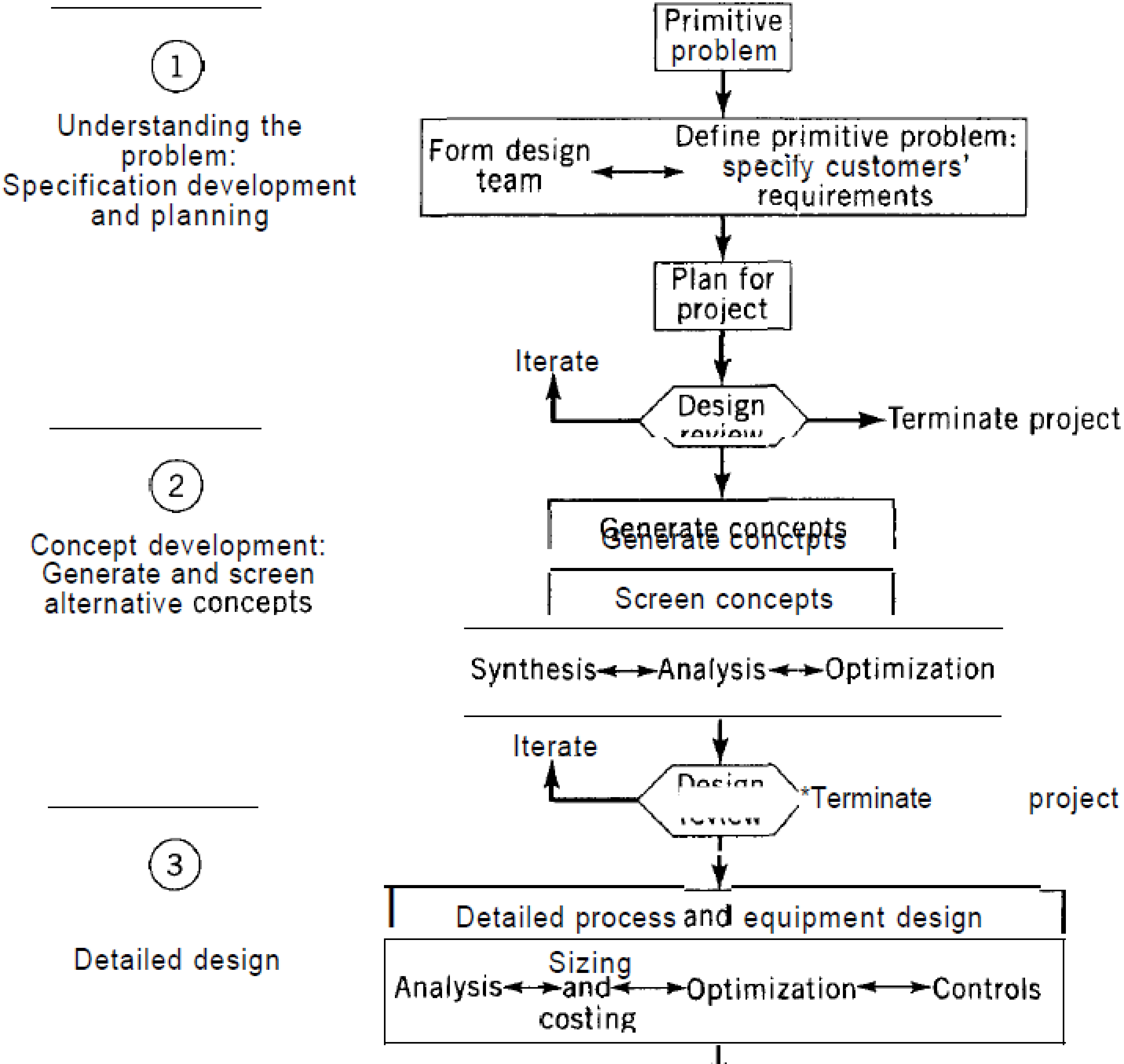
Figure **shows a flow chart of the design process for thermal systems.**

Five distinct stages are indicated:

1. Understanding the problem
2. Concept development
3. Detailed design
4. Project engineering
5. Service

- The flow chart starts from a general statement of use or opportunity, the ***primitive problem, through placing the system into service and its*** ultimate retirement from service. This sequence may be called as ***life-cycle design [Concept- Design-Manufacturing-Use for intentional application – Retirement from service and recycle]***

- The design process involves a wide range of skills and experience. Normally these are well beyond the capabilities of **a single individual and call** for a group effort. This is the role played by the design team.
- A strategy known as ***concurrent design addresses both the makeup of the design team*** and the interactions between team members.
- A main principle of concurrent design **is that all departments of a company be involved in the design process f**rom the very beginning so that decisions can be made earlier and with better knowledge, avoiding delay and errors and shortening the design process.



① Understanding the problem: Specification development and planning

Primitive problem

Form design team ↔ Define primitive problem: specify customers' requirements

Plan for project

Iterate

Design review

Terminate project

② Concept development: Generate and screen alternative concepts

Generate concepts

Generate concepts

Screen concepts

Synthesis ↔ Analysis ↔ Optimization

Iterate

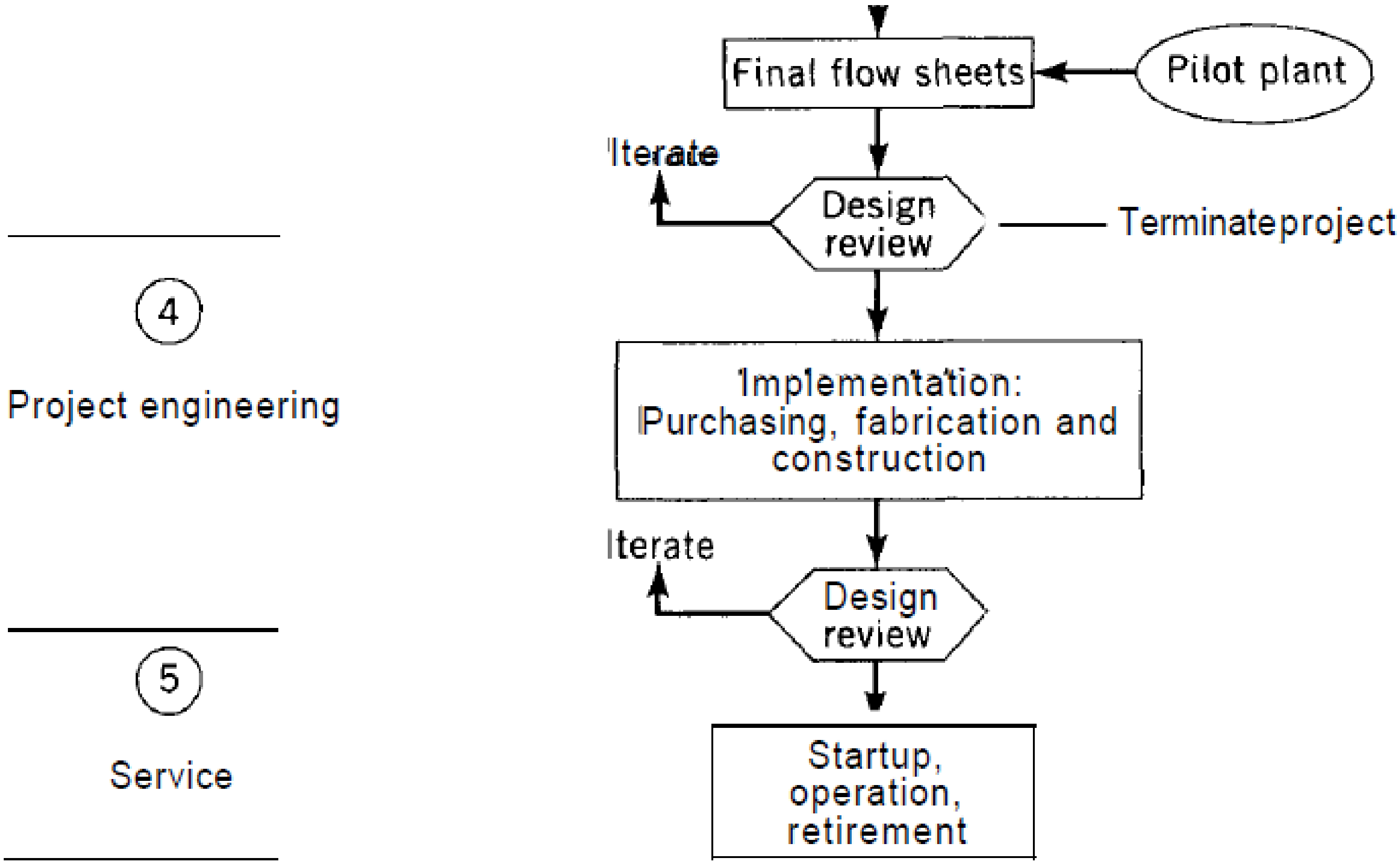
Design review

*Terminate project

③ Detailed design

Detailed process and equipment design

Analysis ↔ Sizing and costing ↔ Optimization ↔ Controls



Life- Cycle Design Flow Chart

THERMAL SYSTEM DESIGN ASPECTS:

some of the key design aspects within the context of thermal systems are :

- **Environmental Aspects**

  Compliance with governmental environmental regulations has customarily featured an *end-of-the-pipe approach that addresses mainly the pollutants* emitted from stacks, ash from incinerators, thermal pollution, and so on. Increasing attention is being given today to what goes *into the pipe.*

  In *design for the environment (DFE)*, designers are called on to anticipate negative environmental impacts throughout the life cycle and engineer them out. In particular, efforts are directed to reducing the creation of waste and to managing materials better, using methods such as changing the process technology and/or plant operation, replacing input materials known to be sources of toxic waste with more caring materials, and doing more in-plant recycling.

Compliance with environmental regulations should be considered through**out** the design process and not deferred to the end when options might be foreclosed owing to earlier decisions. Costs to control pollution are generally much higher if left for resolution after the facility has begun operation.

Design engineers should keep current on what is legally required by the federal EPA (Environmental Protection Agency) and OSHA (Occupational Safety and Health Administration) and corresponding state and local regulatory groups.

Depending on the nature of the processes taking place in the system, several types of pollution control may be needed: air, water, thermal, solid waste, and noise pollution.

- *Air pollution control equipment falls into two general types: particulate removal by mechanical means, such as cyclones, filters, scrubbers, and precipitators,* and *gas component removal by chemical and physical means, including* absorption, adsorption, condensation, and incineration. For *liquid waste effluents, physical, chemical, and biological waste treatment measures* can be used.
- *Thermal pollution resulting from the direct discharge of* warm water into lakes, rivers, and streams is commonly ameliorated by cooling towers, cooling ponds, and spray ponds.
- For effective and practical *noise* control it is necessary to understand the individual equipment and process noise sources, their acoustic properties and characteristics, and how they interact to cause the overall noise problem.

- Safety should be designed in from the beginning of the life-cycle design process. **A tolerance** to failure is an important feature of every system. One approach for instilling such a tolerance involves testing the response of each component via computer simulation at extreme conditions that are not part of the normal operating plan.
- Personnel safety is an area where there can be no compromise. Safety studies should be undertaken throughout the design process.
- Hazards have to be anticipated and dealt with; exposure to toxic materials should be prevented or minimized; machinery must be guarded with protective devices and placarded against unsafe uses; and first-aid and medical services must be planned and available when needed. The design team should use safety checklists for identifying hazards

Reliability is a crucially important feature of systems and products of all kinds. Reliability is closely related to *maintainability and availability.*

Reliability is the probability that a system will successfully perform specified functions for specified environmental conditions over a prescribed operating life.

COMPUTER-AIDED THERMAL SYSTEM DESIGN

As thermal system design involves considerable analysis and computation, including the mathematical modeling of individual components and the entire system, use of computers can facilitate and shorten the design process. Although not realized uniformly in each instance, benefits of computer-aided thermal system design may include increased engineering productivity, reduced design costs, and results exhibiting greater accuracy and internal consistency.

CONCEPT CREATION AND ASSESSMENT:

Important stage of the design process is creating and evaluating alternative design concepts. Only general guidelines can be suggested.

Conceptual designers rely heavily on their practical experience and inherent creativity.

All ideas generated during a brainstorming session should be recorded, even if at first glance some may look impractical or unworkable.

The goal should be to generate as many ideas as possible but not evaluate them. Team member should not be allowed to comment critically until the brainstorming session ends.

Concept Screening:

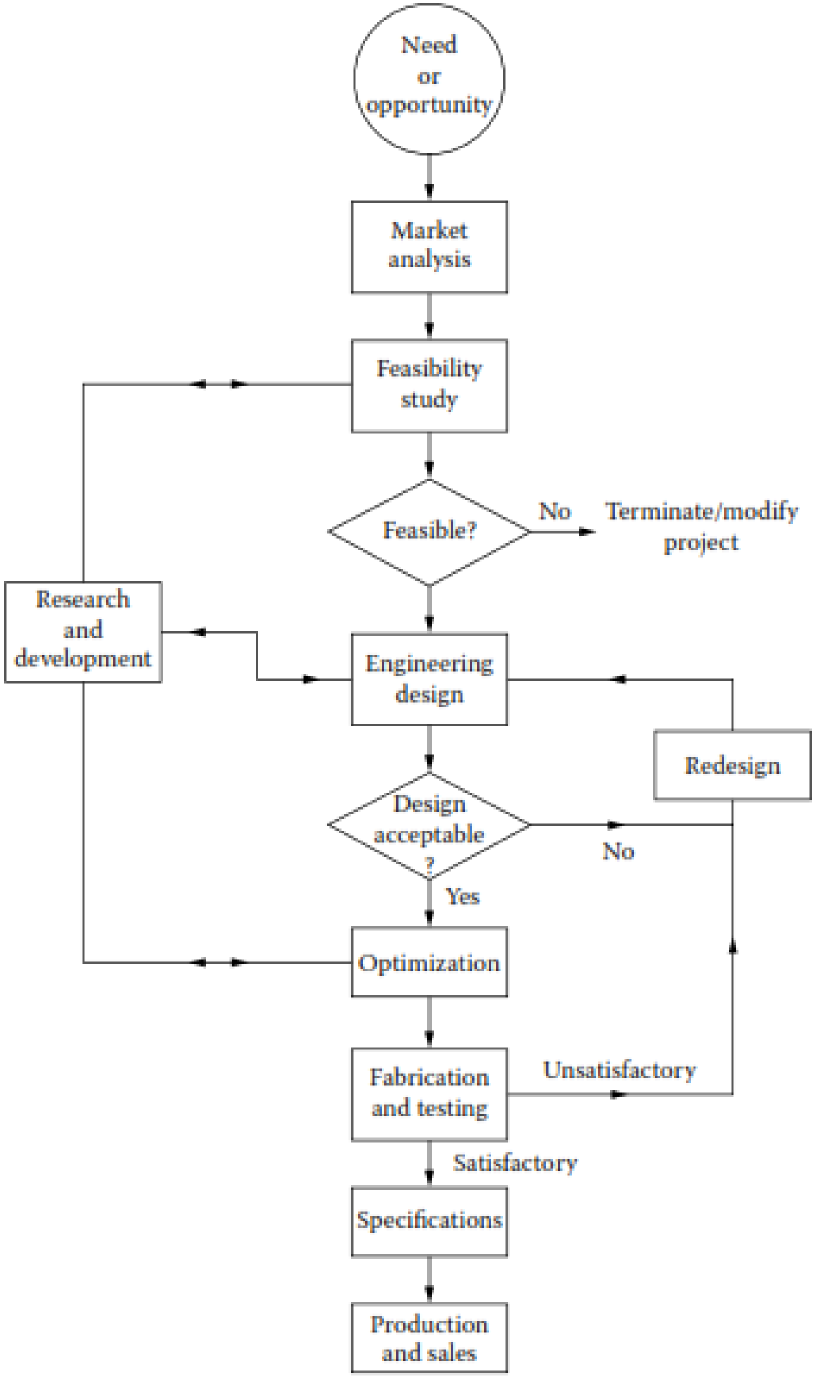
Best alternative is simply screened out from all ideas.

Decision Matrix:

The decision matrix is a formal procedure for evaluating alternative concepts. This method can be used for screening at any stage of the design process.

Each team member would rate the alternatives numerically against criteria related to the musts and wants.

METHODOLOGY OF DESIGN



Opportunity – Positive suggestion.

Need – Suggest a defensive action.

Difficult to distinguish between two.

Market Analysis –

How big the market is, what price range will it bear, and what possible expenses involved in taking the concept to completion are.

Feasibility Study –

Measure of success – Criterion – Return on Investment

Chances of Success – based on probabilistic analysis of various items on the enterprise such as finance, design, R&D, manufacturing, testing, government approvals, sales, advertising, and marketing.

Feasibility – whether the enterprise is possible at all, reasons may or may not be technical.

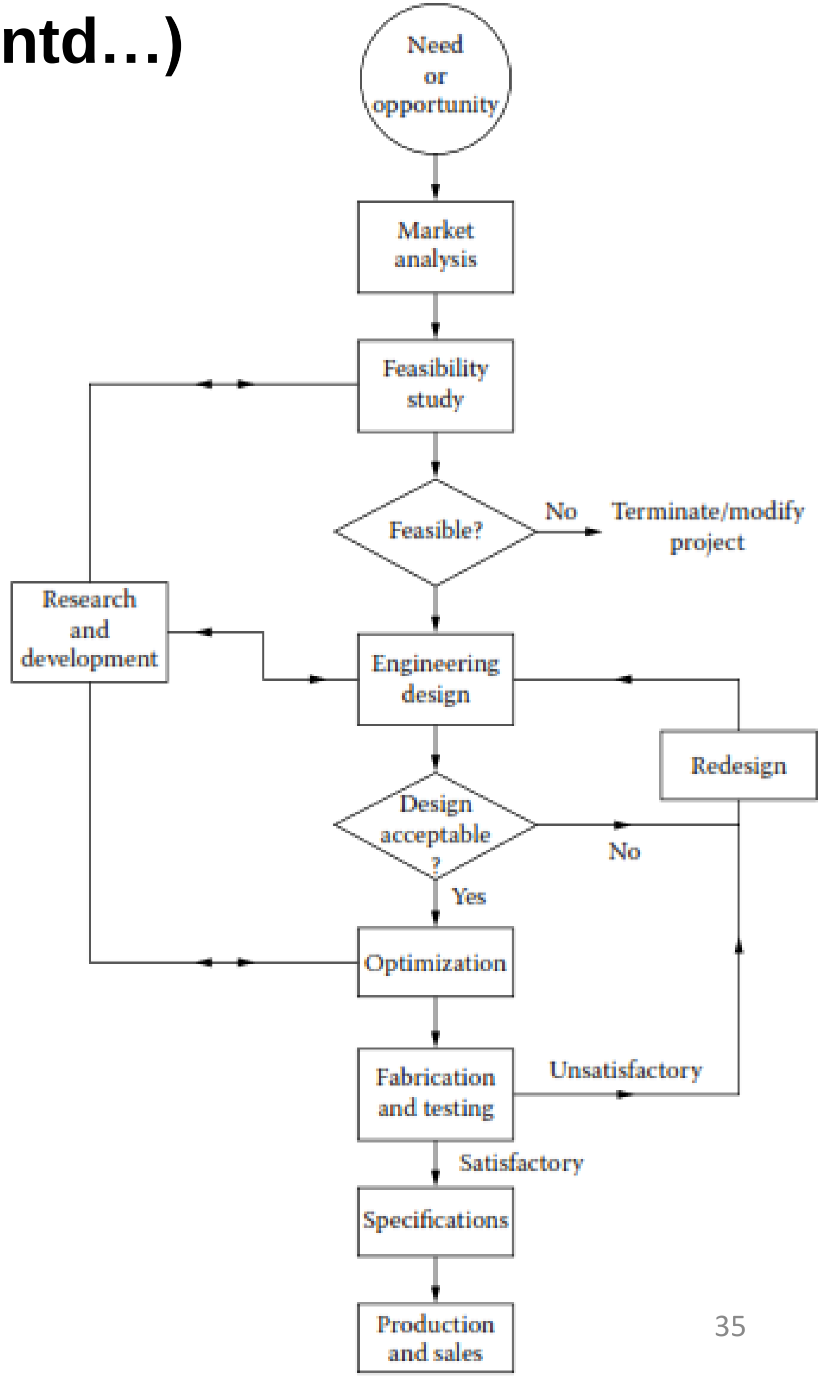
METHODOLOGY OF DESIGN (contd…)

Engineering design –

- ❑ Involves consideration of technical details of the basic concept and creation of new or improved process or system for the specified task.
- ❑ determine specifications of various components of system, range of operating conditions that would yields desired output
- ❑ Starts with basic concepts, then models and analyzes various constituent of the system; synthesizes information on materials, existing system, and results from different models; evaluate the design with respect to performance; finally communicate the design specifications for fabrication and prototype development.

Optimization –

- ❑ Related to profit, cost, product quality, and output.



THERMAL SYSTEM DESIGN ASPECTS

1. Environmental Aspects

- Pollutants emitted from stack, ash from incinerators, thermal pollution, Air Pollution, Liquid pollution, Noise Pollution, Solid waste.
- Design for environment (DFE) – environmentally preferred aspects of a system are preferred as design objectives rather than constraints.
- Compliances with environmental regulations – EPA (Environmental Protection Agency), OSHA (Occupational Safety and Health Administration).
- Formulation of Environmental Impact Statement – providing a full disclosure of project features likely to have adversely environmental effects.

THERMAL SYSTEM DESIGN ASPECTS (contd…)

2. Safety and Reliability

Safety

- ❑ Safety should be designed in form the beginning of the life cycle design process.
- ❑ Personal safety is an area where there can be no compromise.
- ❑ Published codes and standards must also be considered.
- ❑ The ASME Performance Test Codes, NRC (Nuclear Regulatory Commission), The US armed forces standards MIL-STD 882B – Safety in Military equipment's, TEMA (Tubular Exchanger Manufacturers Association), and APA (American Petroleum Association) – Shell and tube heat exchangers design,

Reliability

- ❑ Reliability must be designed in from the beginning and considered at each decision level.
- ❑ It is closely related to maintainability and availability.
- ❑ It is the probability that a system will successfully perform specified functions for specified environmental conditions over a prescribed operating life.

THERMAL SYSTEM DESIGN ASPECTS (contd…)

3. Background information and Data Sources

- ❑ Design engineers should make special efforts to keep current on advances in their fields and allied fields.
- ❑ Online databases- Online Technical Journals, Conference, Technical Periodicals etc.

4. Performance and Cost data

- ❑ Equipment performance and cost data are required at various stages of design process.
- ❑ Theses data might be obtained from vendors located via the **Thomas Register** or other sources.
- ❑ Detailed cost estimates are conducted by specialist usually in a cost estimating department.
- ❑ The design engineer must also estimate the final product cost.

CONCEPT CREATION AND ASSESSMENT

- ❑ Related to **creating and evaluating alternative design concepts.**
- ❑ Conceptual designers **rely heavily on their practical experience and innate creativity**, and these qualities are not readily transferable.
- ❑ These are actually ongoing design activities not limited to any particular stage of the design process.

1. Concept generation: "How?" not "What?"

a) Generate all of the steam required in a boiler and purchase the required power from the local utility.

b) Cogenerate steam and power. Generate all of the steam required and:

i) Generate the full electricity requirement.

ii) Generate a portion of the electricity requirement. Purchase the remaining electricity needed from the utility.

iii) Generate more than the electricity requirement. Sell the excess electricity to the utility.

CONCEPT CREATION AND ASSESSMENT (contd…)

2. Concept Screening

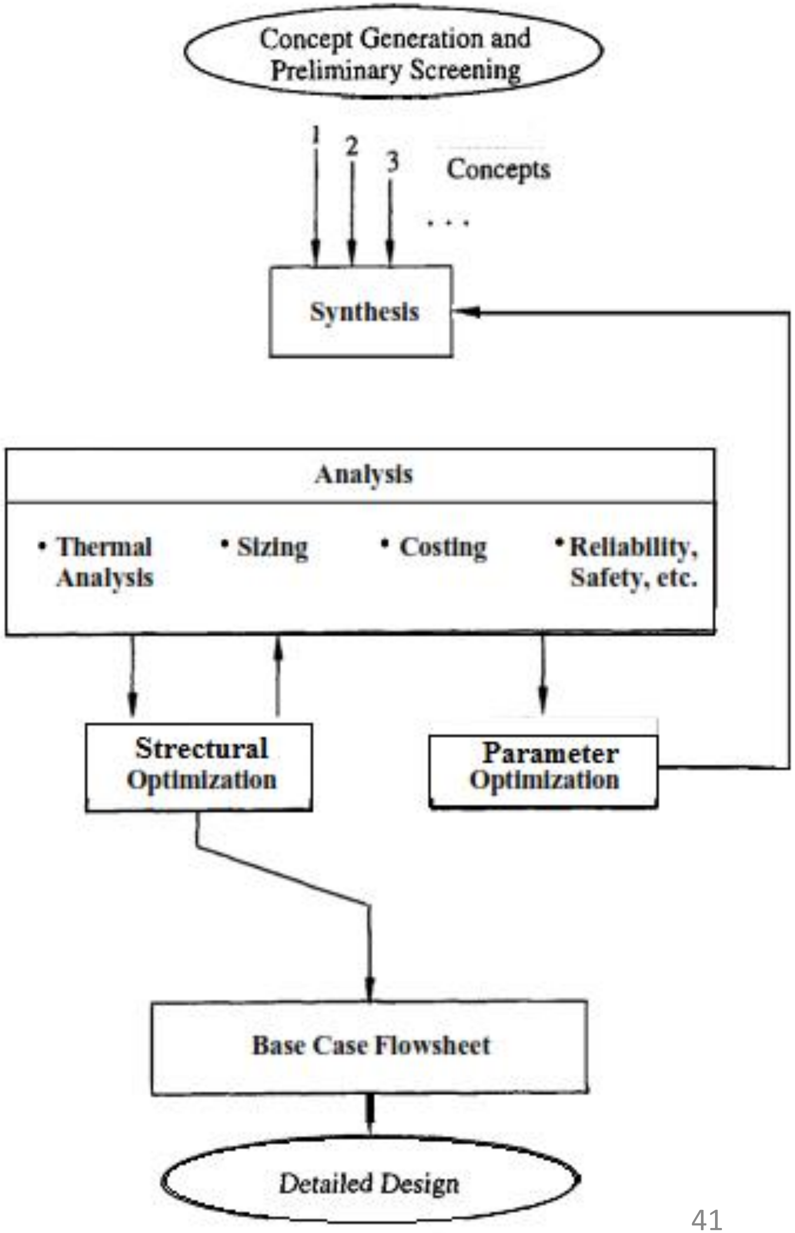
- ❑ As the design of a thermal system is a significant undertaking involving considerable time and expense, no design effort should be wasted on alternatives lacking merit. Accordingly, the alternative concepts must be screened to eliminate all but the most worthwhile.
- ❑ Choose a best alternative depending on appropriate technology (mature, state-of-the-art or modification in existing or latest proven), cost, safety and reliability etc.
- ❑ Let us suppose that after preliminary screening the following alternatives have been retained for further screening and evaluation.

- Produce all the steam required in a natural gas-fired boiler. Purchase the electricity from the local utility.
- Employ a coal-fired steam turbine cogeneration system.
- Employ a natural gas-fired gas turbine cogeneration system.
- Employ a natural gas-fired combined steam and gas turbine cogeneration system.

CONCEPT CREATION AND ASSESSMENT (contd…)

3. Concept Development

- Here, each alternative passing the screening procedure to further screening until the preferred design serving as the focus of the detailed design stage **emerges. This is known as the** *base-case design.*
- It has three interrelated steps : **synthesis, analysis, optimization.**



CONCEPT CREATION AND ASSESSMENT (contd…)

3. Concept Development (contd…)

a) Synthesis

- *It is concerned* with putting together separate elements into a whole.
- The particular equipment items making **up the overall thermal system and their intercon**nections are specified.

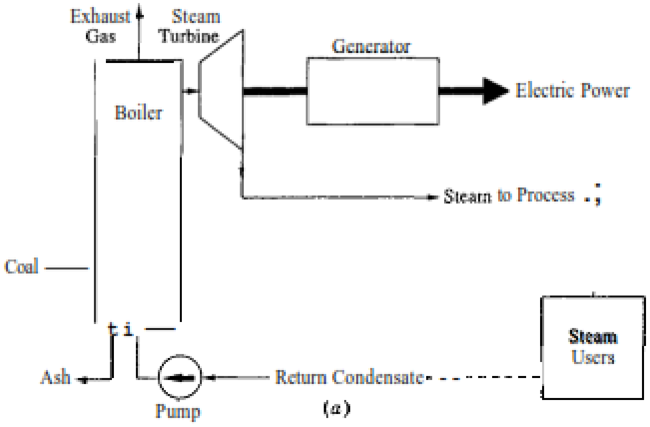


Fig.1 Coal-fired steam turbine cogeneration system

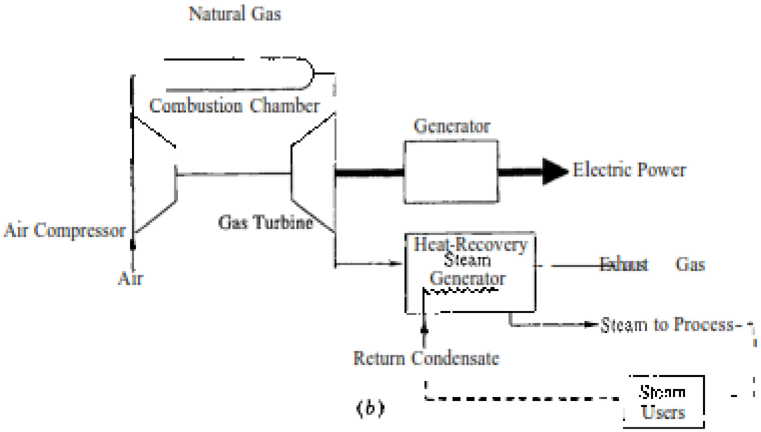


Fig. 2 Natural gas-fired gas turbine cogeneration system

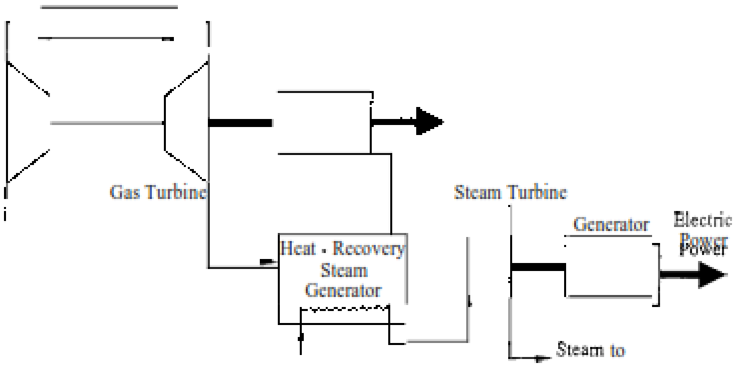


Fig. 3 Natural gas-fired combined steam and gas turbine cogeneration system

CONCEPT CREATION AND ASSESSMENT (contd…)

3. Concept Development (contd…)

b) Analysis

- *Analysis gen*erally entails thermal analysis (solving mass, energy, and exergy balances, as required), costing and sizing equipment on at least a preliminary basis, and considering other key issues quantitatively

c) Optimization

Structural Optimization - the equipment inventory and/or interconnections among the equipment items are altered to achieve a superior design.

Parameter Optimization - the pressures, temperatures, and chemical com-positions at various state points and/or other key system variables are deter- mined, at least approximately, with the aim of satisfying some desired objective - minimum total cost of the system product(s).

Parameter meaning– here, independent variables.