Energy 102 - Heat Engines

The Laws of Thermodynamics pretty well limit the way we can utilize energy. The First Law (EL-I) says we can't create or destroy energy, only change it from one form to another. We are further restricted by the Second Law (EL-II) which says if a form change is made, it degrades some of it into Unavailable Energy (UE), i.e. unavailable to do 'Work'. Then there is the Third Law (EL-III) which dictates that any manipulation of energy is subject to both EL-I and EL-II.

A common way we change stored 'chemical' energy to useful Work is by combustion in a 'Heat Engine'. . The first successful engine is attributed to Thomas Newcomen in 1712 with his Newcomen Engine, which was steam powered and used to pump seepage water out of coal mines in England. [An animated diagram of that engine may be found at: http://en.wikipedia.org/wiki/Newcomen_steam_engine [1]]. It is recognized as the first efficient workable steam engine. James Watt is generally called the 'Father' of the steam engine, but his 1770 engine was only an improved Newcomen Engine modified for powering machinery in factories. Robert Fulton was another big name in steam engines. His contribution was the adaptation of the Watt engine for use on ships by connecting its output shaft to 'water paddle wheels' mounted on each side of the ship.

There is no question the overwhelming majority of 'mechanical' energy utilized in this country has as its source the output of Heat Engines, i.e. devices that convert stored solar energy in fossil fuels to 'mechanical work'. One type of these heat engines is the 'internal combustion' engine (ICE) and billions are in use in things like: automobiles, motorcycles, ATVs, go-carts, snowmobiles, trucks, stationary/peak load electrical power plants, aircraft, marine vessels, locomotives, off road construction equipment, farm machinery, portable tools (chain saws, water pumps, pneumatic compressors, pavement saws, etc.). Their size ranges from tiny model airplane engines small enough to fit in the palm of the hand and perhaps producing 1/100 horsepower (hp) (7 watts) . . . to gigantic stationary power plant/marine vessel diesel engines, 60 ft. long with 14 cylinders, each 39 inches in diameter, and producing 100,000 hp (75,000 kw).

Their fuels can be of many forms, including: coal, crude oil, diesel fuel, gasoline, ethanol/methanol, natural gas, and petroleum gas. Being of an 'open cycle' type, they all use air as their 'working substance'. Their working principles are one of

three forms:
1. Reciprocating pistons operating a crankshaft to produce a rotating shaft output with a pulsating energy output (usually smoothed with an inertia flywheel).
2. A continuous ‘axial flow’ along the output shaft, producing a continuous energy output (gas turbines).
3. A continuous high velocity flow of air/exhaust gas output, producing a reactive thrust force (jet engines).

ICEs operate on a variety of ‘open cycles’ containing as many as 6 ‘processes’ per cycle. These processes generally take the form of: intake of air, compression of the air, addition of heat to the compressed air, expansion of the hot gases in a ‘work’ producing process, and exhaust of the hot gases.

The other major group of Heat Engines is of the ‘Closed Cycle’, ‘External Combustion Engine’ (ECE) type. These represent the majority of electrical power generation plants in the world. Physically they generally use water as the ‘working substance’ although some of the early experimental nuclear units used mercury. In the US, the most common fuel for these units is coal, followed by natural gas, crude oil, and other petroleum types . . . in that order. There are small units, associated with manufacturing facilities, using combustible waste from their manufacturing process and cities with garbage/trash incinerator units or landfills (methane makers), generating power for their own use.

Starting in about the 1960s it became popular to build large commercial power plants at or very near their fuel sources (coal fields/mines and natural gas fields) to reduce fuel transportation costs, which were much more expensive than the costs of power distribution system extensions.

A moderately large commercial water/steam power plant might consist of a huge (perhaps 10 stories high) pressurized (3000 psi) steam generator/boiler, where the liquid water is pumped in, heated to the boiling point (700 deg, F at that pressure) and in most cases the generated steam is ‘superheated’ up to perhaps 1000 deg. F. A good sized boiler might be supplying 10,000,000 lbs. of steam per hour, containing the ‘Total Energy’, to multi-megawatt capacity turbine/generator(s) in a separate building. After going through the high pressure section of a steam turbine, it may be ‘extracted’ and sent back to the ‘reheat’ section of the boiler. After its reheat back to 1000 deg. F., it is piped back to the turbine low pressure section. After leaving the turbines where it has had its ‘Available Energy’ transformed to shaft horsepower by the turbine and then to Mw of electrical energy by the generator. The ‘spent’ steam containing the ‘Unavailable Energy’ goes through a ‘condenser’ heat exchanger where it passes over pipes containing cold running water which condenses the steam back to a liquid. This condensed steam is pumped back to the boiler as ‘feed water’ to begin its journey again . . . and so it goes round and round 24/7/365 until scheduled maintenance time.

The heated condenser cooling water carrying the Unavailable Energy, is piped to ‘Cooling Tower(s)’. These Towers can take several different forms but modern day (particularly nuclear plants) are usually huge circular wine carafe shaped structures (called hyperboloids), separate from the Boiler and turbine/generator house

structures. In operation, they look like they have smoke coming out of them. The ‘smoke’ is literally a ‘cloud’ or mist of that condenser cooling water containing the Unavailable Energy, on it’s way to be ‘rejected’ into the atmosphere. The heated cooling water is sprayed out in the top of the tower, which may have fans blowing ambient air in at the bottom of the tower and upward to mix with the sprayed water. The necked down area of the hyperboloid acts like a venturi tube, accelerating the air upward. It also decreases the ambient pressure slightly, facilitating a higher evaporation rate of the hot water droplets traveling through the air blast. As they fall, their surface evaporates, cooling them and the vapor carries the Unavailable Energy into the atmosphere. The cooled droplets fall down to the bottom collection pond and the cooled water is pumped back through the heat exchanger to get another load of Unavailable Energy. Some plants have large artificial lakes or ‘lagoons’ as thermal ‘sinks’ instead of cooling towers. In these, the hot cooling water is simply pumped into the lagoon, where surface evaporation, surface water conducting heat to the cooler ambient air, and nighttime radiation to space all act to cool the lagoon, whose cool bottom water is being pumped back through the heat exchanger. There is, of course, a large amount of cooling water loss by evaporation, which has to be made up from an external source, quite often from ground wells or a nearby stream. Plants are often built on the banks of rivers or shores of oceans and lakes, for easy access to large quantities of cooling water.

Nuclear plants are of similar construction and operated in the same fashion, except the fossil fuel boiler is replaced with a reactor and usually inter-stage heat exchangers to isolate the low level radioactive water passing through the reactor from the turbine steam and cooling water loops. The Reactor Containment Building is a very substantial structure. It is usually an extremely thick steel reinforced concrete dome, designed to contain not only minor internal explosions, but withstand external 150 mile mph tornado winds and wind driven timbers, automobiles, etc. I also was once told it had to withstand the direct vertical impact of a loaded 747 airliner traveling at terminal velocity.

These type of closed cycle ECEs in the US are responsible for providing about 3.5 Petawatt hrs (that’s 15 zeroes) a year of electrical energy. Converting that into more common terms, it is 3.5 trillion Megawatt hours. In ME terms it is about 12,000 Quadrillion BTU, 12,000 ‘QUAD’, or just 12,000 ‘Q’. As a matter of interest, that is about 80% of all electrical power generated in the US.
(U.S. Energy Information Administration/Electric Power Annual 2008)

We can identify processes of a thermodynamic heat engine cycle for this ECE just as we did for the ICEs, the difference is, the processes are done to the working substance in different physical locations. Starting with the water entering the boiler, it must be pressurized to get into the boiler, so the first process is a ‘feedwater’ pressurization to the boiler pressure. The next process is adding heat to the water in the boiler by an external combustion process until it reaches its boiling point and then until it is all water vapor (‘dry’ steam). It is then sent to a steam turbine where the thermal Available Energy in the steam is converted to mechanical energy. The now lower energy steam, having transferred its Available Energy to the turbine shaft, could be dumped out, but boiler water is not just plain tap water. It must be treated so as not to cause corrosion (rust) in the system, and not to leave mineral

deposits (scale) in the boiler, which retards heating it to steam. So it is saved and sent back to the boiler to raise its thermal energy level back up. But to get it into the boiler, it must be pressurized, and since it is still steam, it would require a very large gas compressor and as much Work to re-pressurize it as it gave out in the turbine. Also, the Second Law comes into play here. The Unavailable Energy portion of the Total Energy added in the boiler, must be ‘rejected’, so rather than waste all that treated water as low pressure steam (millions of pounds per hour) it is condensed back to a liquid in a constant pressure process (rejecting the Unavailable Energy) and reused. It does use a lot of cooling water, much of which is recycled, but saves the cost of treating millions of pounds per hour of new boiler water.

Much of the history of technological advances, is based upon the work of some tinkerer or dreamer who gets an idea for a 'gadget' such as an electric generator, a light bulb, or an ICE . . . and thru a lot of 'perspiration', an expenditure of all their (and their family's) resources, manages by trial and error to make it work. At that point, they attract scientists who then develop the theories as to why it works and formalize those theories, often connecting their own name to the 'gadget'. So the ICE and ECE 'gadgets' have received a great deal of this theoretical analysis. These analyses have been very helpful in achieving vast improvements in those gadgets. For a Heat Engine, they have taken the form of a 'theoretical cycle', which consists of a number (usually four) of sequential idealized thermodynamic processes, that closely simulate what happens in the real engine. These cycles for the three most common ICEs are:
1. Otto Cycle: for the Spark Ignition (SI) reciprocating piston gasoline engine.
2. Diesel Cycle: for the Compression Ignition (CI) reciprocating piston fuel oil engine.
3. Brayton (Joule) Cycle: for the Gas Turbine (GT) rotary engine.

The Rankine Cycle is the main model for an ECE using a "Two Phase" (liquid/vapor) working substance.

The Stirling Cycle is the main model for an ECE using a gas as a working substance.

There are several other model cycles that are used for special purposes. The most notable, for a Heat Engine, is the Carnot Cycle, which theoretically has the most Work output for a given thermal energy input and the minimum and maximum temperatures achievable (highest 'Thermal Efficiency'). It is an engine which is extremely difficult and expensive to build, but the Rankine Cycle engine can be built much easier and with nearly the same efficiency as the Carnot, particularly with the marvelous sophisticated automatic control systems now available.

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[1] http://en.wikipedia.org/wiki/Newcomen_steam_engine