NOT YET COMMERCIALLY AVAILABLE FUEL CYCLES

Long Term (20 - 50 years)

Not Yet Commercially Available Fuel Cycle Technologies					
	Fuel Cycle Technology				
LT	Nuclear Fission – Waste Disposal				
	Oil Shale				
	Nuclear Fusion				
	Hydrogen				
	Electrolysis of water from off-peak fossil, nuclear				
	or renewable-source electricity				
	Small and large biomass gasification				
	Direct photochemical conversion of sunlight to hydrogen				
	Direct biological production of hydrogen				
	Direct thermochemical production of hydrogen				
	Petrothermal – Magma				

Nuclear Fission – Waste Disposal

- High-level radioactive waste (HLW) consists of spent fuel or vitrified reprocessing waste (solidified concentrated liquid solutions of nuclear fission products in a glass matrix).
- HLW generates intense levels of both radioactivity and heat that heavy shielding and cooling is required during its handling and storage.
- While stored, both temperature and radioactivity gradually decreased, simplifying their handling and disposal considerably.
- All HLW produced so far is currently being stored; no permanent disposal has yet occurred.

Oil Shale (2,570,756 million barrels)

- Total world oil shale reserves is 2.6 trillion barrels oil.
- Total crude oil and NGL reserves is 1,017 billion barrels as of Jan. 1, 2000; may be gone after 39 years.
- Total natural gas reserves is 5,150 trillion ft^3; may be gone after 61 years.
- Total coal proven reserves is 1,088.6 billion short tons; may be gone in 230 years
- Most oil shales are fine-grained sedimentary rocks containing relatively large amounts of organic matter from which significant amounts of shale oil and combustible gas can be extracted by **destructive distillation**.
- The organic matter in oil shale is composed chiefly of *carbon*, *hydrogen*, *oxygen*, and small amounts of *sulfur* and *nitrogen*.

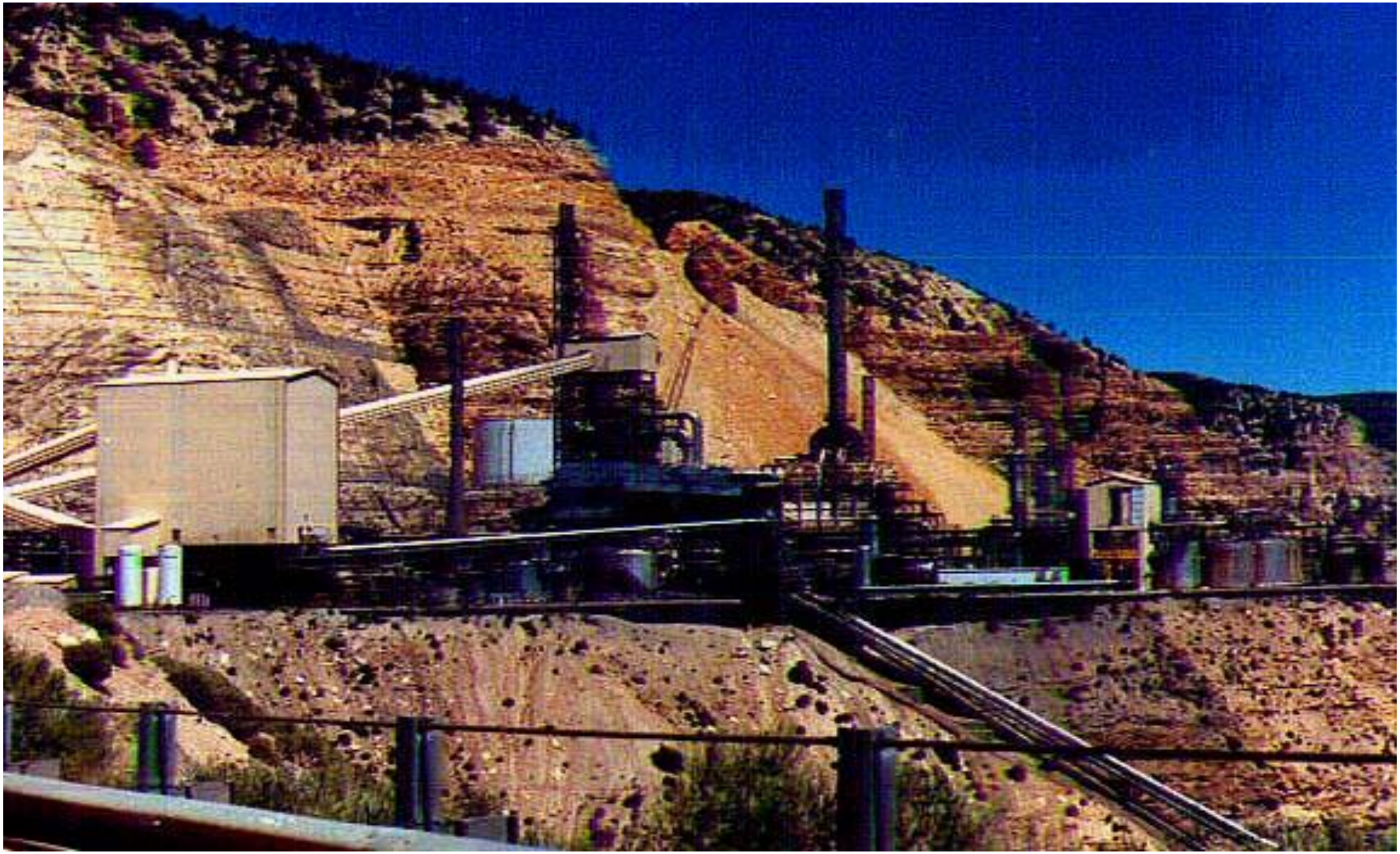
Oil Shale – Recoverable Resources

• Some deposits or portions thereof, such as large areas of the Devonian black shales in eastern United States, may be **too deeply buried to economically mine** in the foreseeable future.

• **Surface land uses may greatly restrict the availability of some oil shale deposits for development**, especially those in the industrial western countries. The obvious need today is new and improved methods for the economic recovery of energy and byproducts from oil shale.

• The bottom line in developing a large oil shale industry will be governed by the price of petroleum-based crude oil. When the **price of shale oil is comparable to that of crude oil because of diminishing resources of crude**, then shale oil may find a place in the world fossil energy mix.

Figure 3—Unocal oil shale facility, Parachute Creek, Colorado. View of the retort on the mine bench at the level of the Mahogany Ledge of the Green River Formation which was the source of the oil shale processed in the plant.



OIL SHALE PRODUCTION (1880 – 2000), metric tons

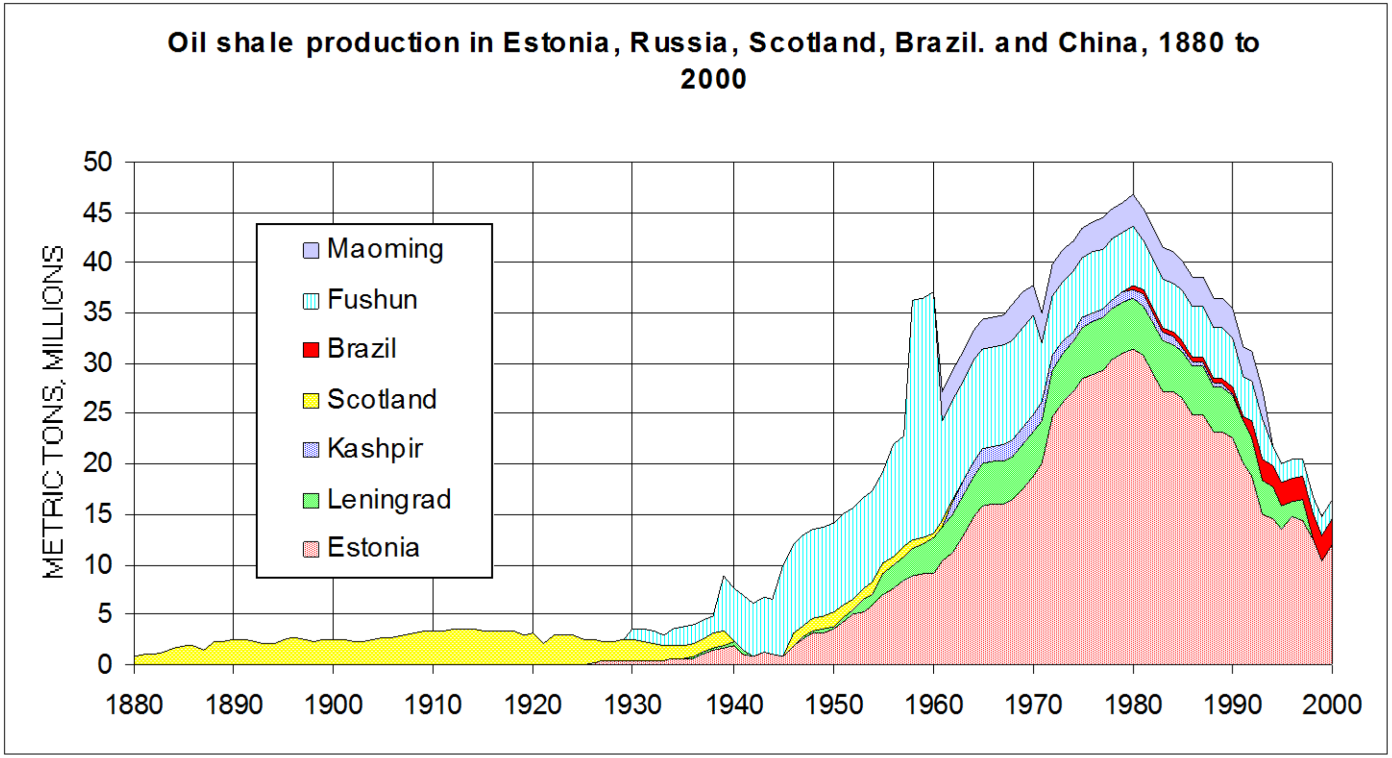


Figure 4.—Oil shale, in millions of metric tons, mined from deposits in Estonia, Russia, Scotland, Brazil, and China between 1880 and 2000. Data for Estonia and Russia from Enno Reinsalu (personal comm., 2000). Data for China from Jialin Qian (personal comm., 2000).

Nuclear Fusion ("Clean" Nuclear Fuel)

- Process by which nuclear reactions between light elements form heavier ones, releasing huge amounts of energy.
- In 1939, H. Bethe suggested that the energy output of the sun and other stars is a result of fusion reactions among hydrogen nuclei.
- In the early 1950s, American scientists produced the hydrogen bomb by inducing fusion reactions in a mixture of the hydrogen isotopes deuterium and tritium, forming a heavier helium nucleus.
- Though fusion is common in the sun and other stars, it is difficult to produce artificially and is very difficult to control; hence, nuclear fusion is still a long-term dream for the 21st century.
- If controlled nuclear fusion is achieved, it might provide an inexpensive energy source because the primary fuel, deuterium, can be extracted from ordinary water, and eight gallons of water could provide the energy equivalent to 2,500 gallons of gasoline.

Renewable Hydrogen Energy System & Hydrogen Storage

- **Hydrogen energy systems** of the future are popularly envisioned as the ultimate green energy source. Its combustion produces only pure water.
- This long-term concept involves producing hydrogen thru solar-driven electrolysis of water or thru off-peak fossil and nuclear electricity sources.
- Other no/low emission methods include biomass gasification, direct photo-chemical conversion of sunlight to hydrogen, direct biological, and thermo-chemical processes.
- Hydrogen is then stored, transmitted as pressurized gas/liquid to generate electricity and provide heating/cooling and pure drinking water thru its use in fuel cells.
- Hydrogen production could eventually be driven by renewable electricity from solar PV arrays, deep-ocean temperature differentials (OTEC) or thermo-chemical (HTGR-based nuclear energy).
- **Hydrogen energy storage** is a simpler and nearer-term opportunity than a complete hydrogen energy system.

Petrothermal - Magma

- Geothermal energy is heat from the earth. The core of our planet is a large mass of molten material called **magma**. It may have temperatures of up to 8,000C. At some locations, the magma comes close to the surface and creates hot spots. When ground water comes in contact with these hot spots, the water turns to steam which is then collected in pipes to run turbines that drive electric generators.

- There are three classifications of geothermal power: (1) **hydrothermal**: associated with steam and hot water; (2) **geopressurized water** (15,000 psia, 325 F or 1,000 bar and 160 C) uses a hydraulic turbine ; and (3) **petrothermal**: dry hot rock (HDR) uses water injection to make steam.

- Thermal energy in the uppermost six miles of the Earth's crust amounts to 50,000 times the energy of all oil and gas resources in the world! US HDR resources alone could supply 30,000 – 500,000 years of US primary energy.

- HDR have not been developed commercially yet because: costs increase exponentially with depth and HDR are much deeper than hydrothermal, and risks over uncertainties on reservoir flow, thermal drawdown and water loss.

NOT YET COMMERCIALLY AVAILABLE POWER GENERATION TECHNOLOGIES

Long Term (20 - 50 years)

Not Yet Commercially Available Power Generation Technologies					
	Power Generation Technologies Levelized Cost in Nominal 1996 $	**Baseload 60 - 75 %**	**Intermediate 20 - 35%**	**Intermittent Varies**	**Peaking 0 - 5%**
LT	Nuclear Fission High Temp. Gas-Cooled Reactor (HTGR)				
	Nuclear Fission Liquid Metal Fast Breeder Reactor (LMFBR)				
	Nuclear Fusion High Temperature				
	Ocean Energy Ocean Thermal Energy Conversion (OTEC)			14.6 - 26.7	
	Fuel Cells Alkaline (AFC)				
	Stored Hydrogen from electrolysis of water				
I	*Coal* Brayton Cycle Indirectly Coal-Fired Combined Cycle				
	Magnetohydrodynamics				
	Nuclear Fusion Cold Fusion				
	Solar Thermal Electric Salt Ponds (electricity and water)	9.8 - 12.3			

Nuclear Fission High Temp. Gas-Cooled Reactor (HTGR)

- Planned HTGRs are graphite moderated and helium cooled. In a recent version, being designed by the General Atomics Corporation, *hot helium directly drives a gas turbine*, in contrast to earlier designs where the hot gas is used to produce steam for a steam turbine.
- HTGRs use a rugged fuel form, capable of withstanding high enough temperatures for the reactor to be cooled by radiation if the helium flow is interrupted -- an important passive safety feature.
- At present, HTGR development is not receiving U.S. federal support, and is thus dependent on General Atomics resources, plus foreign contracts, to bring the designs to completion.

Nuclear Fission Liquid Metal Fast Breeder Reactor (LMFBR)

- Present-day burner reactors produce some Pu^{239} from the U^{238} in the fuel. Such a system would convert the abundant U^{238} (99.3% of natural uranium ore, balance of 0.7% is U^{235}) to fissionable Pu^{239}. The fast breeder reactor is a logical step in **conserving uranium reserves** and keeping fuel costs down.
- But the potentially greater availability of plutonium would create **increased proliferation dangers of nuclear weapons**.
- The liquid metal coolant of the reactor also moderates or slows down the neutrons, but since it becomes radioactive also, an **intermediate coolant** (Na or NaK) guards against reactions between the radioactive primary coolant loop and water in the secondary steam generator loop.

Nuclear Fusion High Temperature

- A different type of nuclear reaction, called fission, was long ago harnessed to create the atomic bomb and is used in nuclear power plants. **Fission splits heavy atoms**, such as uranium, to release energy.
- Nuclear **fusion is a process that joins atoms** together. Inside the Sun, for example, hydrogen is fused to create heavier elements. In the process, energy is released.
- Commercial fusion could solve the world's power woes, some scientists have long claimed, and it would do so safely, with little or **no harmful byproducts like the radioactive waste** that comes from fission.
- Many schemes have been developed, from using magnetism to lasers to create high-speed, **high-temperature** collisions among atoms.

Ocean Energy Ocean Thermal Energy Conversion (OTEC)

- Absorption of solar radiation by the seas and oceans, which constitutes 70% of the earth’s surface, causes **ocean currents and moderate temperature gradients** from the water surface downward, especially in tropical waters (surface at 27 C and heat sink 1 km below at 4 C). Oceans serve as storage of solar input.
- **Temperature gradient can be utilized in a heat engine** to generate power – Ocean thermal (temperature) energy conversion or OTEC: open Claude and closed Anderson cycles.
- Because the temperature difference is very small, even in the tropics, **OTEC systems have very low efficiencies** (at most 2%) and consequently have high capital costs.
- Average terrestrial incidence on the waters at 50% average clearness is 1,353 x 0.50 = 676 W/m^2 of which only 14% is **absorbed by oceans: 676 x 0.14 = 95 W/m^2**.

Fuel Cells Alkaline (AFC)

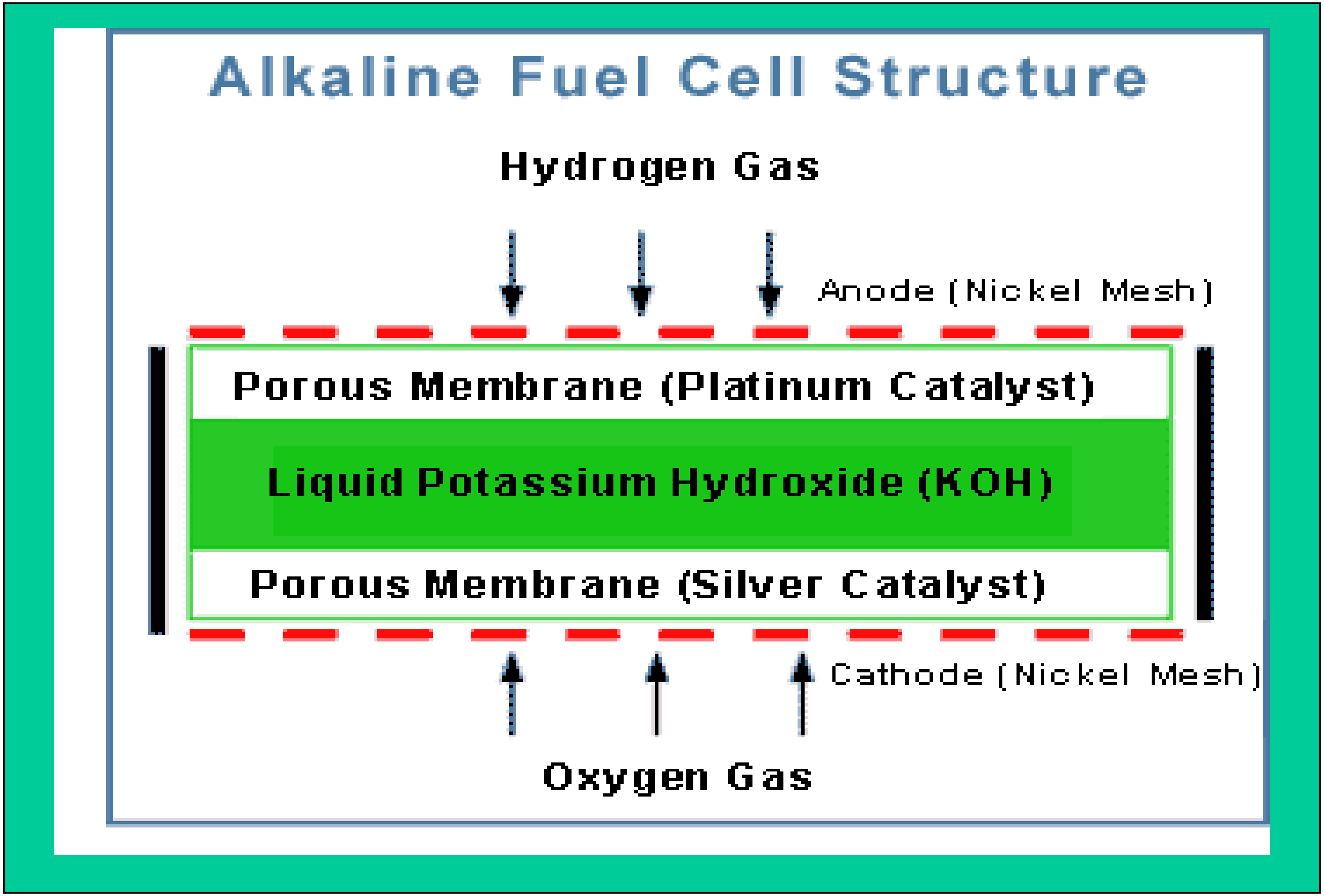
- Fuel cells are devices which convert hydrogen and oxygen into electricity and water. It is exactly the opposite of the electrolysis of water – which breaks up water into hydrogen and oxygen when electricity is applied.

- Conventional mechanical and thermal cycles convert the fuel energy content to only 30 – 60% electricity. Fuel cells can convert energy up to 83% efficiency and is totally emission free – no SO_2, NO_X, CO, UHC and CO_2 – only plain drinking water H_2O.

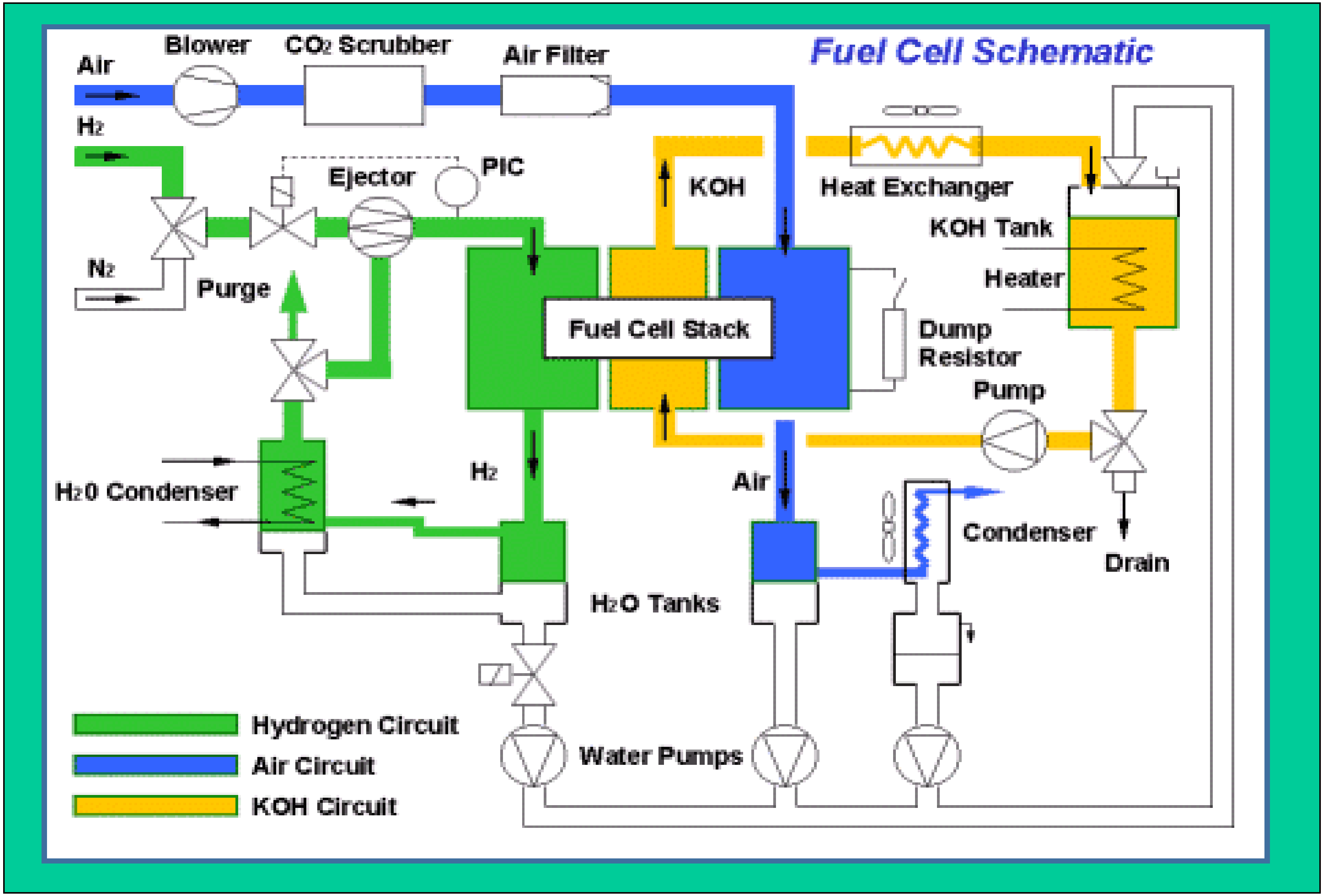
- The electrolyte used is potassium hydroxide (KOH) – the same chemical used in Duracell batteries. It operates at 70 C to give full power.

- Used primarily in space programme to provide electricity and drinking water; the crew brings only liquid H_2 and O_2.

Fuel Cells Alkaline (AFC) - 2



Fuel Cells Alkaline (AFC) - 3



Fuel Cells Alkaline (AFC) - 4

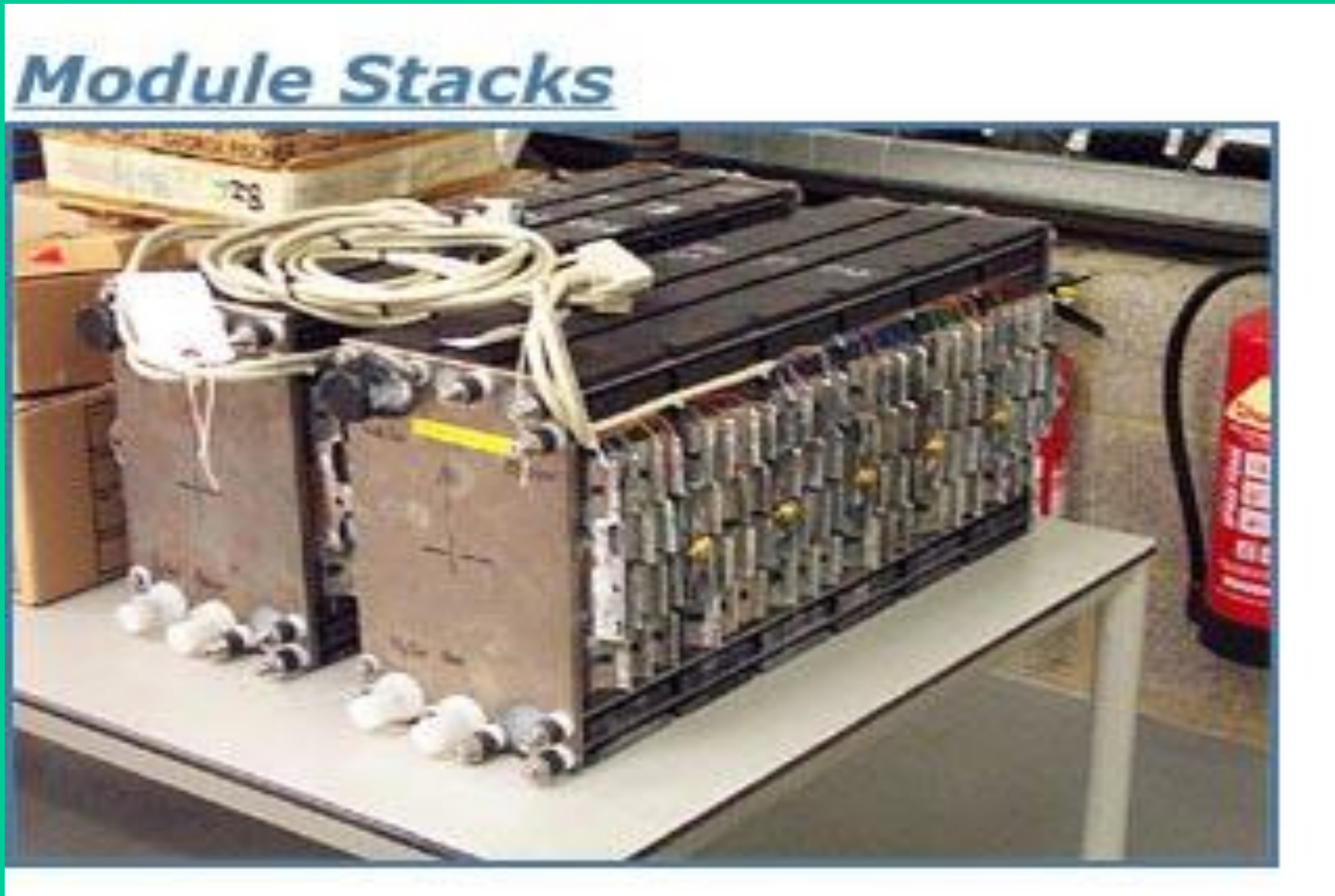
• Speed of response is determined by service gas pressures. In this system gas pressures are low (1/20 bar) and response time around 10 seconds. The Fuel Cell is consequently used with a battery to supply transient loads.

• Each fuel cell plate gives 0.93 volts at no load and 0.66 volts at full load. Each plate gives 25 amperes. Modules are matrices of six plates in series and four plates in parallel, each module providing 5.6 volts no load and 4 volts at 100 amperes full load. A 2.5 kW Fuel Cell consists of a single stack of six modules in electrical series.

• Gives very high efficiency when lightly loaded and around 50% efficiency at full load and at half load with around 70%+ efficiency. This results in low levels of waste heat and economy in gas usage.

• Main consumer of control power is the air compressor which is why the system operates at low pressure.

Fuel Cells Alkaline (AFC) - 5

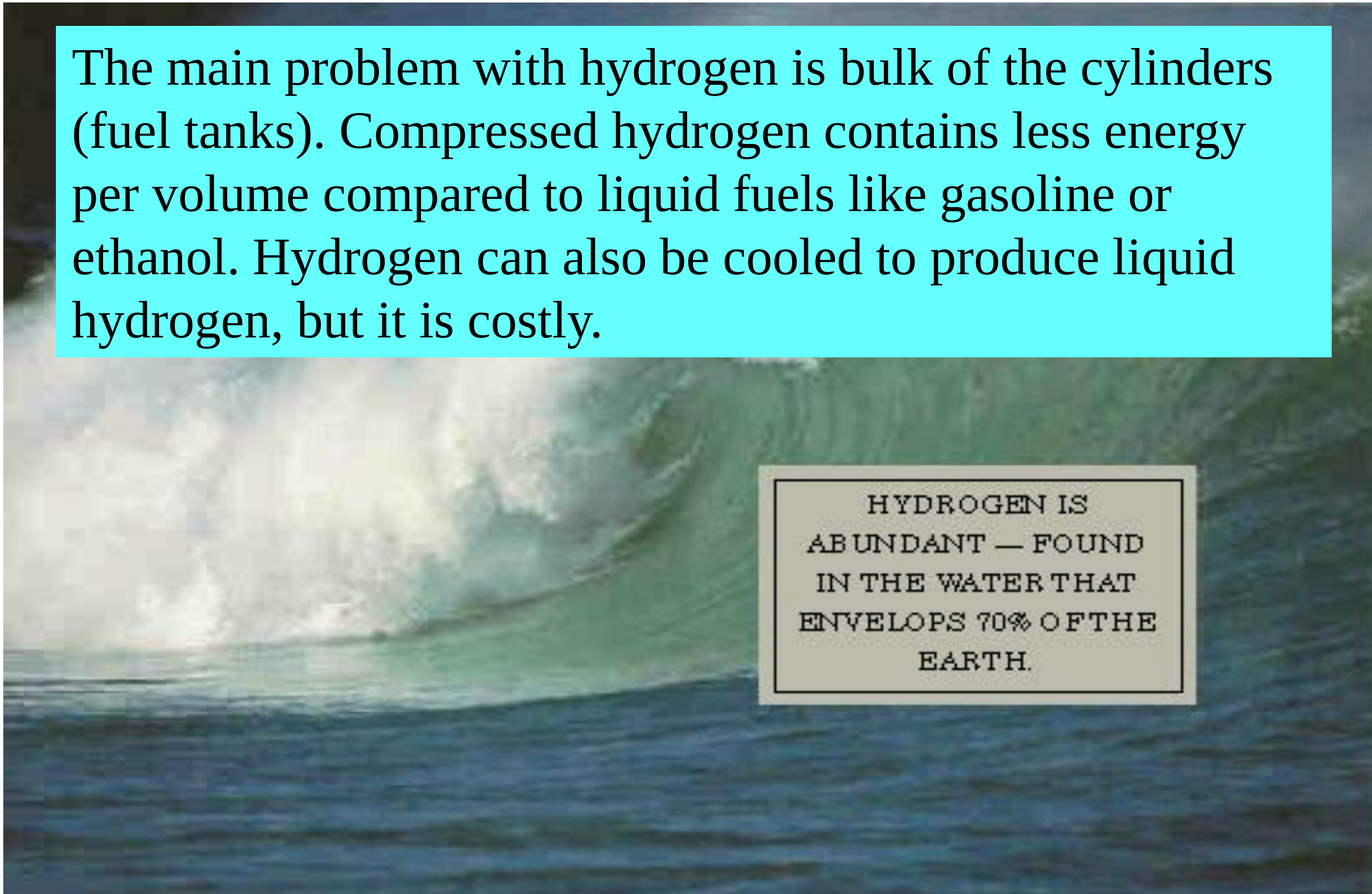


Stored Hydrogen – from electrolysis of water and biomass gasification

- By the 21st century, hydrogen will join electricity as the primary energy carriers in the world. Both energy carriers will ultimately come from renewable (and nuclear) energy sources, although fossil fuels will provide a long term transitional source. Hydrogen can be transported as a gas or liquid in pipes as well as in trucks, trains or barges.
- A long-term energy strategy, using an "energy system" based on sustainable and abundant sources, will eliminate dependency upon both limited and politically volatile fossil fuel supplies.
- Being a non-carbon fuel, the exhaust is free of carbon dioxide, which some scientists believe may eventually cause the world's climate to change.

Stored Hydrogen – its source is abundant and limitless – water from oceans & seas (2)

The main problem with hydrogen is bulk of the cylinders (fuel tanks). Compressed hydrogen contains less energy per volume compared to liquid fuels like gasoline or ethanol. Hydrogen can also be cooled to produce liquid hydrogen, but it is costly.



Stored Hydrogen : electricity & hydrogen – an energy loop that is renewable & clean (2)

- Our Energy System is composed of: energy sources, currencies, technologies and services. Energy sources are things like coal, crude oil, natural gas, hydraulic power, uranium, sunlight, and wind. Energy currencies are similar to monetary currency.
- **Just as money allows financial transactions to take place, energy currencies allow energy transactions to take place.**
- Two energy currencies hold the greatest promise for a renewable energy future: electricity and hydrogen. Electricity is clean and fast, but cannot be effectively stored. Hydrogen can be readily stored and transported. **Hydrogen can make electricity, and electricity can make hydrogen**. Together, they create an energy loop that is *completely renewable and harmless to the environment*.

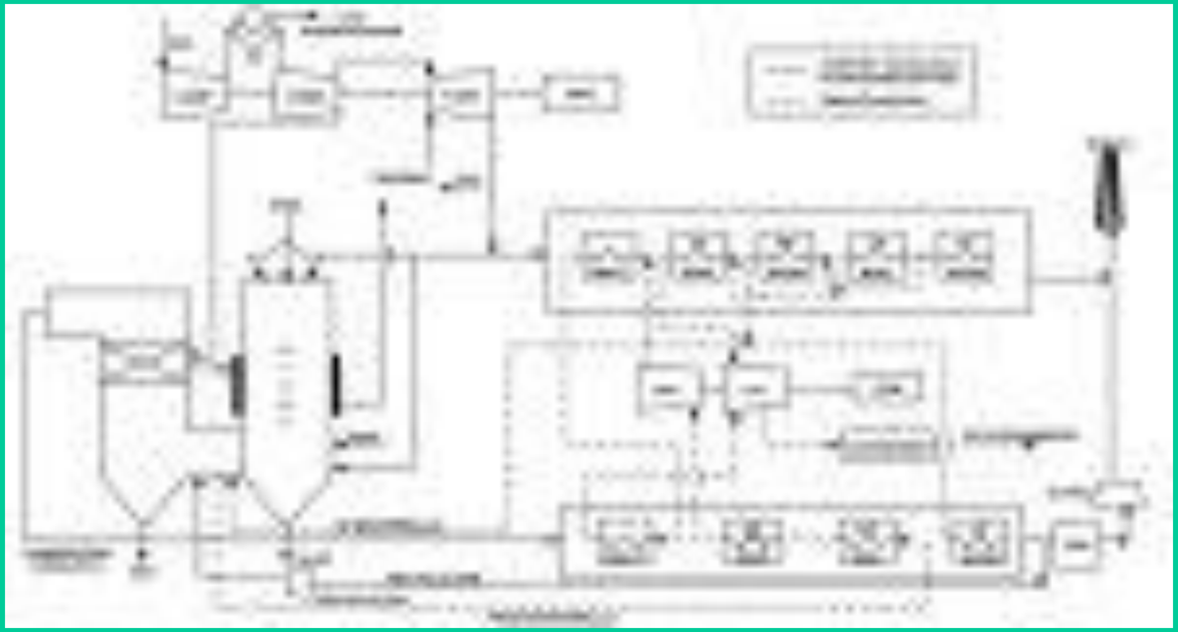
Coal Brayton Cycle Indirectly Coal-Fired Combined Cycle

• Indirectly fired power system (IFPS) uses an indirectly fired GTCC, where heat is provided to the GT by high-temperature heat exchangers to achieve even **higher efficiency and lower emissions**.

• It **maximizes the use of domestic solid carbon feedstocks** while effectively addressing global environmental concerns due to carbon dioxide emissions.

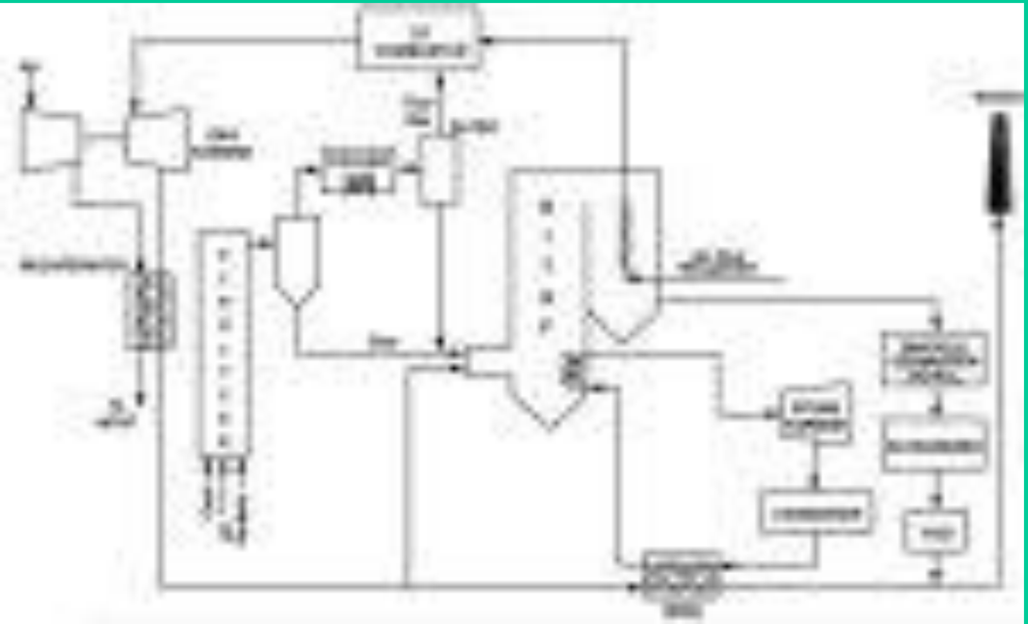
• It has an **inherently high thermal efficiency** (47-55% LHV), since it takes advantage of the combined efficiency of a GT Brayton cycle that operates along with a Rankine steam bottoming cycle. Since the coal combustion gases do not flow into the GT, **cleaning of combustion gases at high temperatures is not necessary**.

Coal Brayton Cycle Indirectly Coal-Fired Combined Cycle (2)



UTRC-type IFPS – Air compressed to turbine inlet temperature is heated in a coal-fired high-temperature air furnace, augmented with clean fuel like natural gas to reach GT inlet temperature. The vitiated air expands in the GT and turbine exhaust goes to heat recovery boiler to raise steam to power ST generator.

Coal Brayton Cycle Indirectly Coal-Fired Combined Cycle (3)

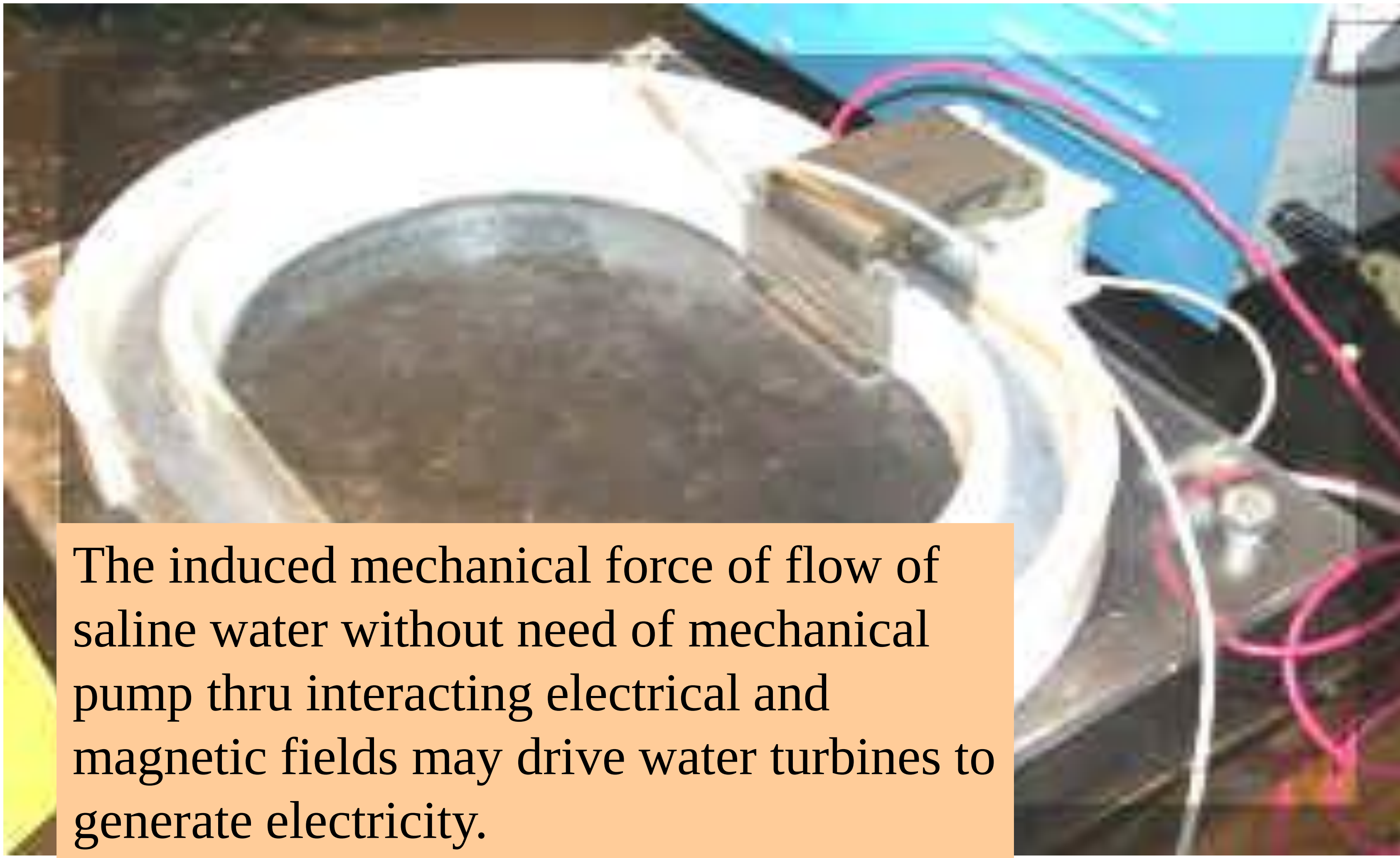


FW-type IFPS – Foster-Wheeler type IFPS uses a pyrolyzer to develop a low-Btu syngas (synthetic gas from coal) for the GT. This develops a char discharge, which is burned in a wall-fired type combustor in a furnace that includes a high-temperature air heater that uses pendant air heaters.

Magnetohydrodynamics

- Magnetohydrodynamics (MHD) is the use of interacting electrical and magnetic fields to produce flow or motion. The **Lorentz Force Law** (also known as *Right Hand Rule*) is an equation that describes the effects of a charged particle moving in a constant magnetic field: $\mathbf{F = q\ v\ B\ sin(\theta)}$.
- As defined, MHD is a phenomenon where the mechanical force of flow is induced on a conductive fluid when it is placed in electrical and magnetic fields.
- MHD is unique from all other propulsion systems in that it utilizes interacting electric and magnetic fields to produce movement of salt water, for instance, without any moving components, such as motors or pumps.

Magnetohydrodynamics (2)



The induced mechanical force of flow of saline water without need of mechanical pump thru interacting electrical and magnetic fields may drive water turbines to generate electricity.

Nuclear Fusion "Cold Fusion"

- The other so-called "**cold fusion**" efforts were widely reported but never reproduced, and therefore scientists considered them flawed. The new device uses **sound waves** and **bubbles**.
- "*In such a device, a small gas bubble trapped in liquid is imploded using high pressure sound waves*," explains Fred Becchetti, a University of Michigan scientist in an on-line paper. "*The imploding bubble reaches sufficiently high temperatures and pressures to emit a burst of light*."
- The device created a bubble that reached 10 million degrees Kelvin -- as hot as the center of the Sun -- and also appears to have emitted **high-energy neutrons** -- the telltale sign of fusion.
- Using the same tabletop device, Dan Shapira and Michael Saltmarsh reported in on-line paper *Science* that they found "***no evidence***" for the telltale high-energy neutrons.

Nuclear Fusion "Cold Fusion" (2)

- Fusion energy represents a promising alternative to fossil fuels and nuclear fission for world energy production.

- If successful, it offers a renewable, clean, non-radioactive and non-polluting way of producing power using heavy water at low temperatures.

- Research into the possibility of cold fusion, by Fleischmann and others, nonetheless continues, because of intriguing but inconclusive experimental results such as claims of production of excess heat, helium, or tritium when heavy water reacts with metals.

- Cold-fusion proponents believe that the fusion mechanism is different from that of hot fusion in that it encompasses some type of unusual nuclear reaction in the metal lattice involving deuterium and possibly other atoms.

- Several dozen models to explain the observed phenomena have been advanced, but none accounts for the full range of experimental observations.

Solar Thermal Electric Salt Ponds (electricity and water)

• A *salinity gradient solar pond* (SGSP) is an integral collection and storage device to tap solar energy. By virtue of having a built-in thermal energy storage, it can be used irrespective of time and season.

• In an ordinary pond or lake, when the sun's rays heat up the water, this heated water, being lighter, rises to the surface and loses its heat to the atmosphere. The net result is that the pond water remains at nearly atmospheric temperature.

• Solar pond technology inhibits this phenomena by dissolving salt into the bottom layer of this pond, making it too heavy to rise to the surface, even when hot. The salt concentration increases with depth, thereby forming a salinity gradient.

• Sunlight, which reaches the bottom of the pond, remains trapped there. The useful thermal energy is then withdrawn from the solar pond in the form of hot brine and is used as industrial process heat.

Salt Pond (2)

The 6000-m^2 in Bhuj, the first large-scale pond in industrial environment to cater to actual user demand, supplied totally about 15,000 m^3 (15 million liters) of hot water to the dairy at an average temperature of 75^{o}C between September 1993 and April 1995. It is estimated that the beneficiary of the project, Kutch Dairy, can save over 935 metric tons of lignite per year if the solar pond is used to its full capacity. This translates into monetary savings of of $19,000/yr.

Salt Pond (3)

The heat extraction system consisted of brine suction and discharge diffusers, a brine pump, associated piping, controls, and instrumentation. Both the suction and the discharge diffusers were installed on the same side of the pond. Keeping in view the problem of fouling, a shell-and-tube type heat exchanger was chosen. Brine was on the tube side, which was made of cupro-nickel. The pond is capable of delivering 80,000 liters of hot water daily, at 70 degrees C or above.

Salt Pond (4)

• Total **cost of construction** of the Bhuj Solar Pond was $90,000 (1997 prices), including the heat exchanger, piping etc. This corresponds to a unit cost of $15 per m^2 of the pond area as compared to $30 per m^2 of the Beth `ha Arava (Israel) solar pond in 1984.

• Further improvements, especially on the **lining method**, are expected to reduce the costs even more.

• Thus, the **simple payback period works out to less than 5 years** without any subsidy or tax incentives. The economics become even more attractive if the fuel replaced is not lignite but either oil or coal.

• Since **brine transparency** is one of the crucial factors as far as the thermal behavior of the pond is concerned, several steps were taken to maintain it at an optimal level. These included *surface skimming*, *flocculation* of suspended particles, and *algae control* by adding hydrochloric acid and copper sulfate.

Stored Hydrogen - Direct photochemical

- Direct photochemical process involves conversion of sunlight to hydrogen without electricity as intermediate step.
- Advantages of the photochemical alternative include atom economy, convenient and stable starting materials, and generality with regard to the aldehyde component. A major facet that needs attention if this reaction can truly be considered environmentally benign is the solvent. Presently, hydrocarbon solvents or acetonitrile are employed. The reaction fails in water, probably a consequence of the insolubility of the starting materials.
- An alternative would be to conduct the reaction in a supercritical solvent such as supercritical carbon dioxide. This possibility has clear advantages in terms of the ease of product isolation. The photochemical reactions described above have been shown to occur in supercritical carbon dioxide. This work is being done in collaboration with Professor James Tanko at the Virginia Polytechnical Institute.

Stored Hydrogen – Direct biological

- A biological fuel cell is a device that directly converts biochemical energy into electricity. The driving force of a biological fuel cell is the redox reaction of a carbohydrate substrate such as glucose and methanol using a microorganism or an enzyme as catalyst.

- Working principle is similar to that of chemical fuel cells. The main differences are that catalyst in the biological fuel cell is microorganism or enzyme, therefore noble metal is not needed, and its working conditions are mild: neutral solution and room temperature.

- For example, complete oxidation of one gram of methanol by an enzyme gives theoretically 5000 mAh of electric energy.

- When considering energy supply for portable applications, fuel cells have some disadvantages. Reaction conditions are usually harsh: high temperature and pressure, maybe strongly acidic or alkaline solutions

Stored Hydrogen – Direct biological (2)

- Most applications use platinum as catalyst, it is expensive, resources are limited, and it is easily poisoned by CO, which can be formed if the used fuel is not pure hydrogen. Direct methanol fuel cell (DMFC) is reported to be most promising for portable applications among chemical fuel cells.
- The biological fuel cell developed in the Automation Technology Laboratory at HUT is an interesting and promising addition to already existing fuel cell types (PAFC, PEM, MCFC, SOFC, AFC).
- In contrast to chemical fuel cells, the biological fuel cells have mild reaction conditions (ambient temperature, normal pressure, and neutral pH) and platinum is not needed.
- Instead of platinum, the catalyst is either a microorganism or an enzyme.
- The biological fuel cell converts the chemical energy of carbohydrates, such as sugars and alcohols, directly to electric energy.

Stored Hydrogen – Thermochemical from water, hydrogen sulfide and ammonia

• Thermochemical production of hydrogen involves high-temperature reactions using heat from solar or HTGR-based nuclear energy.

• The three areas are:

- solar thermochemical cycles for splitting water
- thermochemical cycles for splitting hydrogen sulfide, and
- catalyzed micro-reformer for splitting ammonia.

• The feasibility of the three technology areas from technical, economic and environmental viewpoints is being studied in a project is funded by USDOE.

Stored Hydrogen – Thermochemical from decomposition of hydrocarbon (2)

• Another project is the production of hydrogen for application in vehicles through the use of thermocatalytic decomposition of hydrocarbon fuels. The two fuels presently being evaluated are natural gas and gasoline.

• The technical approach is based on a single-step decomposition pyrolysis of the hydrocarbons over carbon catalysts in a water-free environment.

• This approach significantly simplifies the process and eliminates the need for a water-gas shift reactor, CO_2 removal and catalyst regeneration.

• Clean carbon is produced as a valuable by-product of the process. Preliminary economic assessment of the process has indicated that the hydrogen can be produced at a cost of $5/MMBtu (if carbon is sold at $100/ton), which is less than that for the steam reforming process coupled with CO_2 sequestration. The project is funded by USDOE.