2. Cold Fusion Energy Production

An earlier blog discussed the potential benefits of cold fusion as a green energy source and provided links to several small U.S. companies that are attempting to develop systems to utilize cold fusion or low energy nuclear reactions (LENR). The purpose of this blog is to discuss ideas about possible sources of energy from cold fusion.

In the process of performing cold fusion experiments, scientists have determined that more energy is produced than can be accounted for by chemical reactions. Chemical reactions involve electron volts (eVs) of energy per reaction, while nuclear reactions typically involve millions of electron volts (MeVs) of energy per reaction. One electron volt = 1.6×10^{-19} joule; but, one MeV = 1.6×10^{-13} joule, which is a million times larger. In addition, scientists have observed that various types of atoms can be produced and that these might be produced by nuclear fusion, nuclear transmutation, nuclear fission, or a combination of these three types of reactions.

Chemical Reactions.
It is important first to discuss how energy (heat) is produced in chemical reactions. Atoms bond together to form molecules because in doing so they attain lower energies than they possessed as individual atoms. That is, the bonded atoms or molecules have an energy that is less than the sum of energies of the initial atoms. A quantity of energy is released that is equal to the difference between the energies of the atoms bonded together to form molecules and the energies of the initial atoms or molecules. The energy is usually released as heat. When atoms combine to make molecules, energy is always given off, and the compound has a lower overall energy.

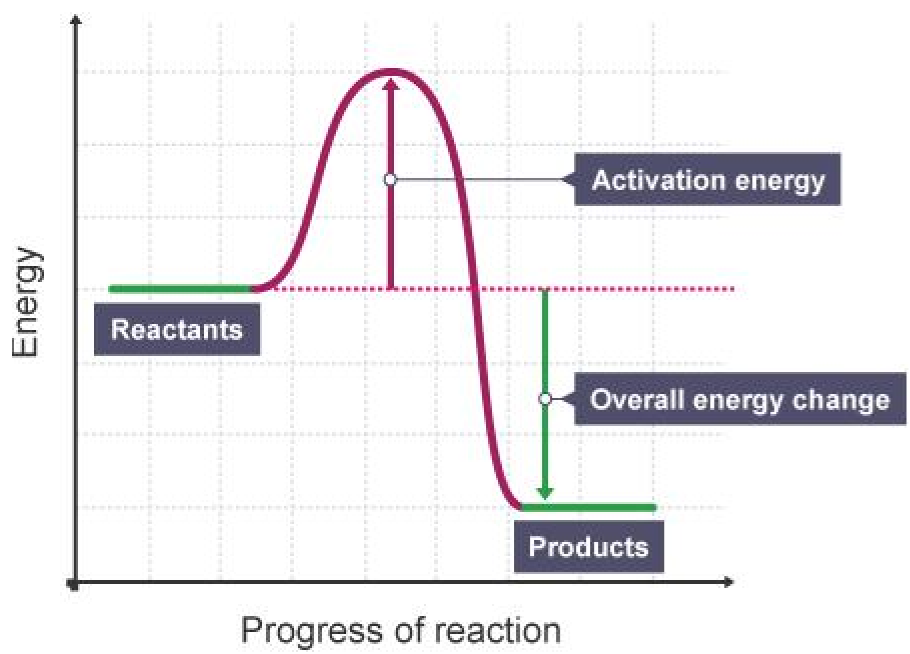
The web provides a lot of information on how chemical reactions work. See, for example:

https://www.youtube.com/watch?v=DUtUNm5uSH4

and

https://www.youtube.com/watch?v=I9jd1Ew_YGU

During a chemical reaction, atoms are rearranged, and bonds are broken within reactant molecules as new bonds are formed to produce product molecules. This involves breaking of chemical bonds between atoms of reactant molecules and forming new chemical bonds between atoms of product molecules. Bond energy is defined as the amount of energy that it takes to break one mole (6.02×10^{23}) of bonds in the gas phase. Energy always has to be added to break a chemical bond. Making a bond always releases energy. If more energy is released during bond forming (of the products) than bond breaking (of the reactants), then the overall reaction is exothermic. This can be represented by the energy-level diagram in this figure.



(see http://www.bbc.co.uk/schools/gcsebitesize/science/triple_ocr_21c/further_chemistry/energy_changes_chemistry/revision/3/)

"Activtation energy" in the figure is defined as the minimum amount of energy needed to activate atoms or molecules to a condition in which they can undergo chemical transformation. It is sometimes much less than the bond energy of reactants, and can even be zero for some reactions.

Energy is required to break bonds; but energy is released when bonds are formed. The numerical value of the bond energy is the same whether it is being broken or formed. But, the change in energy is positive (+) when bonds are broken and negative (-) when bonds are being formed. The minus sign is important to show, as this signifies heat energy is released when bonds are formed. The total energy change of the reaction (or "enthalpy" of the reaction") is the energy it takes to break the bonds of reactants plus the energy that it takes to make new product bonds. It is generally indicated as ΔH. This is the same as subtracting the total amount of energy produced as bonds are formed from the energy used to break the bonds of the reactant molecules.

A covalent bond, also called a molecular bond, is a chemical bond that involves the sharing of electron pairs between atoms. In a covalent bond, atoms with the same electronegativity share electrons because neither atom preferentially attracts or repels the shared electrons. The best examples of covalent bonds are the diatomic elements like H_2, N_2, O_2, and F_2 ,etc. Water (H_2O) is another example, as it is formed by sharing electrons between hydrogen and oxygen. The reaction to form water from hydrogen and oxygen can be represented in the following equation. Activation energy is provided by heat from a flame contacting the gas.

$$2\ H_2 + O_2 \xrightarrow[\text{(flame)}]{} 2\ H_2O \qquad \Delta H = -\ 481\ \text{kJ.}$$

The H-H bond in hydrogen gas has an energy of 436 kilojoules per mole (kJ/mol). The O-O bond in oxygen gas has an energy of 499 kJ/mol. Therefore, the energy needed to break the bonds of two moles hydrogen and one mole of oxygen is (2 x 436) + 499 = +1371 kJ. The O-H bond in water has an energy of 463 kJ/mole and a molecule of water has two O-H bonds. The energy needed to form both bonds in two moles of water molecule is 2 x 2 ×463 = -1852 kJ. The energy produced during this chemical reaction is then +1352 + (-1852) = -481 kJ.

A watt of power is defined as one joule of energy per second (1 Watt = 1 J/sec). One kilowatt (kW) is 1 kJ/sec (1000 J/sec). Thus, by burning two moles of hydrogen and one mole of oxygen each second, 481 kW (481 kJ/sec) of power can be produced. By comparison, a house requires about 4-5 kW of power for heating, lighting, etc.

Nuclear Reactions

Nuclear reactions are quite different in that they involve interactions with the very small, internal nucleus within atoms. Atomic bonds are not involved. The nuclei within atoms consist of neutrons and protons, and are positively charged due to protons that they contain. Nuclear reactions also involve nuclear particles (e.g., alpha particles, beta particles, neutrons) produced from these internal nuclei.

The web provides a lot of information on how nuclear reactions work. See, for example:

https://www.youtube.com/watch?v=lUhJL7o6_cA

and

https://www.youtube.com/watch?v=xrk7Mt2fx6Y

The probability of an effective nuclear interaction depends upon the size (cross section) of the interacting particles and the velocity (or kinetic energy) with which the particles interact. Due to their small size, it is a statistical process. The interacting nuclei or particles have to be on nearly exact, but opposite, trajectories so that they will collide; or, one of the particles may be stationary. A positively charged particle, such as a proton or an alpha particle, can only interact effectively with a positive nucleus in an atom if its velocity is also sufficient to overcome the height of the coulomb barrier produced by its proton(s) and the protons in the nucleus. In fusion, two positively charged nuclei can interact and combine if their velocities are sufficient to overcome the height of the coulomb barrier produced by their protons. The height of the coulomb barrier represents an effective “threshold energy” for nuclear reactions involving charged particles. A neutron does not contain a positive charge, and can more easily interact with nuclei in atoms.

The probability of a nuclear reaction is described by the manner in which cross section changes as a function of kinetic energy of the interacting particles. Cross sections have previously been determined from laboratory measurements, and are in units that can be compared to a typical geometrical cross sectional area for a nucleus, which is about 10^{-24} cm^2 (this unit of measure is called a "barn"). The cross section for neutron induced reactions increases with decreasing velocity or kinetic energy because the likelihood that a neutron can be captured depends upon the amount of time it spends near a particular nucleus. The cross section for positively charged particles increases with increasing energy because of the presence of the coulomb barrier.

Cold Fusion Reactions

As indicated above, some in the scientific community believe that cold fusion (or LENR) is possible because they were able to determine that MeVs of energy (in the form of heat) was produced in their experiments. In addition, nuclear reaction products (alpha particles and neutrons) were detected in some experiments. From these observations, it has been assumed that energy from cold fusion can be produced by the same types of nuclear reactions (fusion, fission and transmutation) that have otherwise been observed for standard nuclear reactions. It has furthermore been assumed that the conditions/parameters for the reactions must be different to enable the cold fusion reactions to occur.

A p-d fusion reaction can be represented by the following equation:

$$p + d \rightarrow \text{He-3} + E\ (5.5\ \text{MeV})$$

Energy could be provided by a 5.5 MeV gamma ray from excited helium-3 (He-3) produced in the reaction.

Similarly, d-d fusion can be described to occur by three competing paths shown in the following equations:

$$d + d \rightarrow \text{He-3} + n + E\ (3.3\ \text{MeV})$$

d + d → T-3 + p + E (4.0 MeV)
d + d → He-4 + E (23.8 MeV)

These equations indicate the manner in which protons (p), neutrons (n), tritium (T-3), helium-3 (He-3), and helium-4 (He-4) and energy could be produced in the reactions.

In nuclear reactions, energy can be produced when some of the mass of reactants on the left side of the equations is converted to energy, along with the products on the right side of the equations. This is a major difference between nuclear reactions and chemical reactions, as little-to-no mass is converted to energy in chemical reactions. The amount of energy that can be produced is determined by the difference between the masses using Einstein's formula $\Delta E = \Delta M c^2$, where ΔM is the mass difference and c is the speed of light. If mass is given in atomic mass units (amu), then a mass difference of 1 amu can be converted to 931.5 MeV of energy (1 amu = 1.66054×10^{-27} kg).

The following table illustrates energy calculations for some fusion reactions.

Examples of Energy from Fusion Reactions

M_n = 1.008665 amu; M_p = 1.007828 amu; M_e = 0.00054858; 1 amu → 931.5 MeV.

Reactants(1)	Product(2)	Mass Difference (1-2)	Energy Estimate (maximum) Mass difference x 931 Mev
p + d → 1.007828 + 2.014102	He3 3.016029	0.005901	5.5 MeV
d + d → 2.014102 + 2.014102	He3 + n 3.01029 + 1.008665	0.00351	3.3 MeV
d + d → 2.014102 + 2.014102	T3 + p 3.016049 + 1.007828	0.004327	4.0 MeV
d + d → 2.014102 + 2.014102	He4 4.00206	0.025602	23.8 MeV
d + T3 → 2.014102 + 3.01605	He4 + n 4.002602 + 1.008665	0.018884	17.6 MeV

Heat could be produced by absorption of energies from helium-3 and neutrons (He-3 and n), from tritium and protons (T-3 and p), from helium-4 and neutrons (He-4 and n), and by gamma radiation from excited He-3 and He-4.

The following table illustrates energy calculations for some neutron produced transmutation reactions in nickel.

Examples of Energy from Transmutation Reactions

M_n = 1.008665 amu; M_p = 1.007828 amu; M_e = 0.00054858; 1 amu → 931.5 MeV.

Reactants(1)	**Product(2)**	**Mass Difference(1-2)**	**Energy (maximum)**
n + 58Ni → 59Ni → 1.008665 + 57.935346	e^+ + 59Co 0.00054858 + 58.933198	0.01026	9.6 MeV
n + 60Ni → 1.008665 + 59.930788	61Ni 60.931058	0.008395	7.8 MeV
n + 61Ni → 1.008665 + 60.931058	62Ni 61.928346	0.011377	10.6 MeV
n + 62Ni → 63Ni → 1.008665 + 61.928346	e^- + 63Cu 0.00054858 + 62.939598	-0.003135	None
n + 64Ni → 65Ni → 1.008665 + 63.927968	e^- + 65Cu 0.00054858 + 64.927793	0.00829	7.7 MeV

By inspecting data in these tables, it is possible to surmise that cold fusion reactions might, in general, be able to produce about 5 MeV of energy per reaction. Since 1 MeV of energy is equivalent to 1.6 x 10^{-13} joules, 5 MeV = 8.0 x 10^{-13} joules. Thus, in comparison to the above discussion on chemical reactions, in order to produce 480 kJ of energy would require about 6 x 10^{17} nuclear reactions. This number of cold fusion reactions would be required each second for 480 kW of power.