PHYS 2401
Physics for future presidents

Lecture 2: Energy and Power, continued.

Last class we were talking about this table:

Table 1.1 Energy per Gram

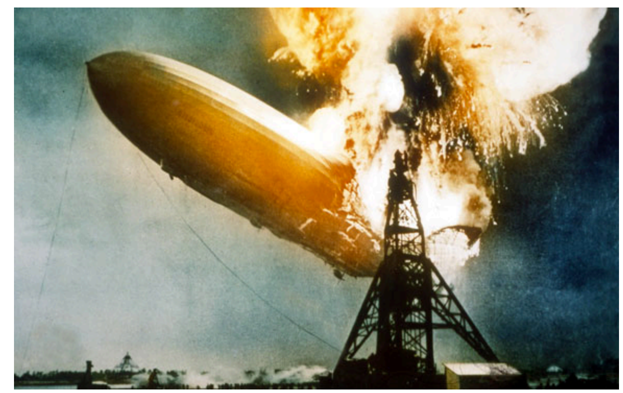
Object	Calories (or watt-hours)	Joules	Compare to TNT
Bullet (at sound speed, 1000 ft/s)	0.01	40	0.015
Battery (auto)	0.03	125	0.05
Battery (rechargeable computer)	0.1	400	0.15
Flywheel (at 1 km/s)	0.125	500	0.2
Battery (alkaline flashlight)	0.15	600	0.23
TNT (the explosive trinitrotoluene)	0.65	2700	1
Modern high explosive (PETN)	1	4200	1.6
Chocolate chip cookies	5	21,000	8
Coal	6	27,000	10
Butter	7	29,000	11
Alcohol (ethanol)	6	27,000	10
Gasoline	10	42,000	15
Natural gas (methane, CH_4)	13	54,000	20
Hydrogen gas or liquid (H_2)	26	110,000	40
Asteroid or meteor (30 km/s)	100	450,000	165
Uranium-235	20 million	82 billion	30 million

Note: Many numbers in this table have been rounded off.

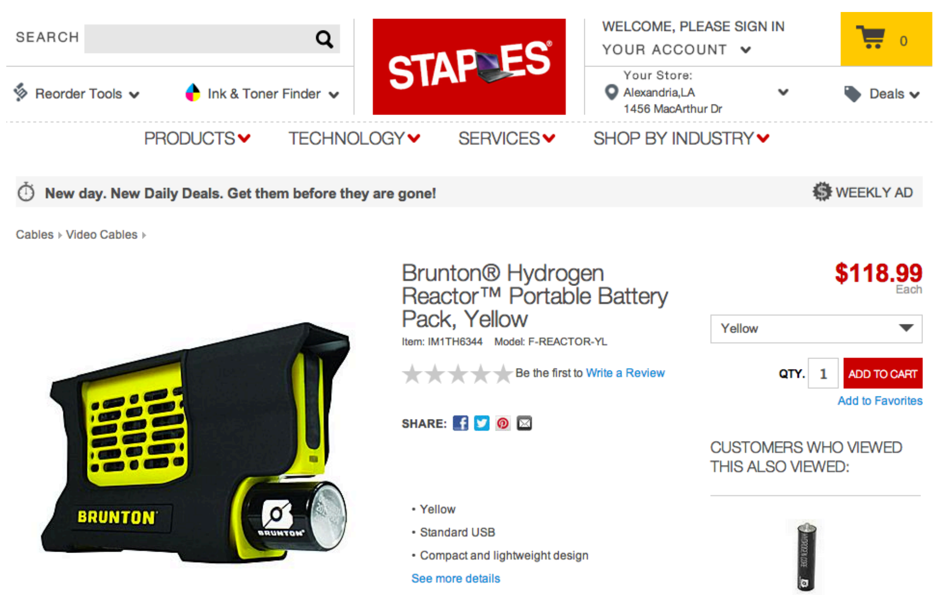
Hydrogen has over 2.5 times the energy content per unit weight than gasoline. Could it be used as a fuel? A president of the US seems to have thought so. Unfortunately, it did not quite pan out. Here we will examine why.

The chemical reaction in which hydrogen releases its energy is by mixing with oxygen and producing H20, water. So it appears to be super-clean as well.

Since the amounts of energy released can be important, and can be released quickly, it requires certain ingenuity to "burn hydrogen" safely.



The devices used to burn hydrogen safely are known as "fuel cells".



To understand how fuel cells work we need to discuss electrolysis. The interesting thing is that you can run the process in reverse and produce electricity. That is how a fuel cell operates.

That is the science of it. However, in technology the devil can be in the details. The main technical problem with hydrogen is that it is not very dense. Yes, you can pack a lot of energy per unit weight, but for practical applications one is also concerned about energy per unit volume. Even when liquefied at high pressures that are manageable practically it has a density of 0.071 grams per cubic centimeter. A factor larger than 10 less than gasoline. So hydrogen loses to gasoline in what matters by a factor of almost five.

Hydrogen burns more efficiently than gasoline, so the real factor is about 3.

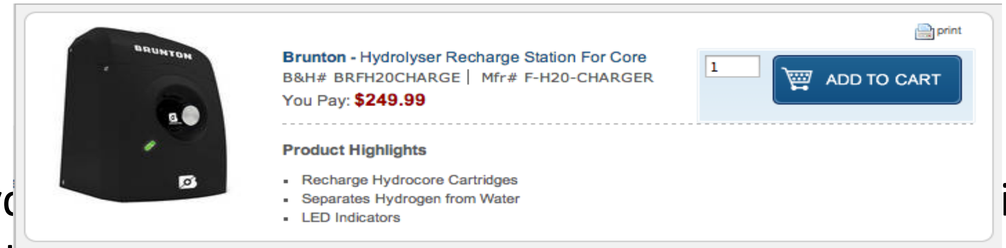
But the devil in the details continues: as most gases, if you compress it a lot it liquefies. But it turns out that as a liquid, it expands a lot witch changes in temperature. Making storage a problem. So you are better off storing it as a highly compressed, but not liquefied, gas. But then you lose further in energy density. And you need sturdy tanks to withstand the high pressures safely. All in all you end up with a factor of 6 with respect to gasoline.

All this suggests that hydrogen may offer more promise in large vehicles like buses and trucks, where there is more space available.

Another area of promise is in aircraft, which can be large as long as they are light (and hydrogen is). Hydrogen was actually used in the Apollo program.

Something that has to be understood about hydrogen is: you cannot mine it! There is a lot of hydrogen in the universe, but it is combined with other elements, like in H20.

You have to make it. For instance, via electrolysis. But that requires energy.



In a sense, hyd ing energy) than gasoline (a source of energy).

Creating the hydrogen always generates pollution in one way or another.

Advocates claim that one can use hydrogen to move the pollution away from highly populated areas like cities. Again the devil is in the details. Some cities suffer enormously from atmospheric pollution due to local geographic details (Los Angeles, Salt Lake City, Santiago de Chile, Beijing). Others do not.
The power plants that generate hydrogen can be made more efficient than a car engine (economies of scale) and have more elaborate pollution controls that cannot fit on a car.
In summary: the devil is in the details and more work is needed to make hydrogen more competitive.

An advantage of hydrogen over electricity: it is easier to store in massive volumes. This makes it particularly attractive when coupled with wind produced electricity. The latter is intermittent and therefore requires the ability to store the energy it produces.

There are a couple of “hydrogen cities” that are currently in operation. They produce electricity with wind, use the electricity to produce hydrogen.

Aberdeen, Scotland, uses the hydrogen to power city buses.

Pico Truncado in Argentina’s Patagonia, mixes the hydrogen with compressed natural gas (CNG) to power cars. CNG cars are common in Argentina and some other countries.

Gasoline vs TNT

In Hollywood movies, frequently one sees cars that explode when they collide. But in reality cars do not explode. Unless mixed with exactly the right amount of air (like in the fuel injector or carburetor of a car engine) gasoline burns but does not explode.

In the 1970s Ford produced a model, the Pinto, which had the gas tank way in the back and mounted in such a way that in a rear end collision it was prone to rupture and spill fuel. Bumper stickers appeared that read "bomb on board". But this is what a Pinto collision fire looked like. As you see there is no explosion.

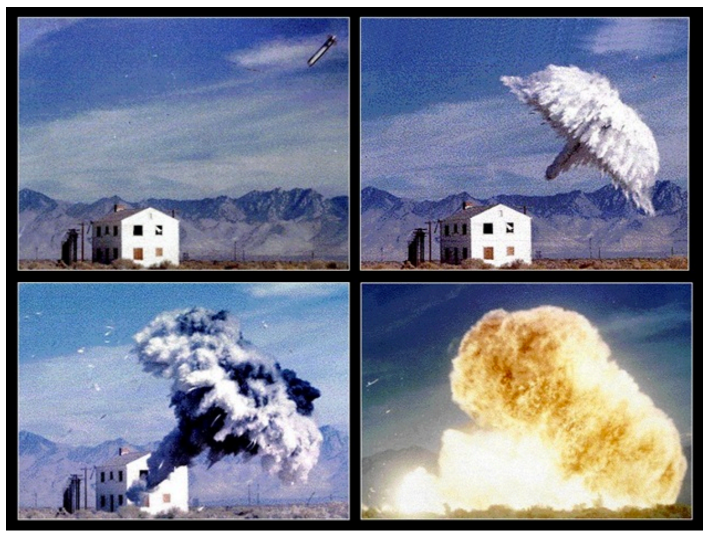
For risky applications (like fuel tanks in military aircraft or race v
is not explosion but fuel spillage. The technology used is the sel
layers of metal and rubber and other materials that "self seal" even after punctured, say, by a bullet. Anti aircraft guns resort to explosive shells to defeat this.

You may have heard of "Molotov cocktails", bottles filled with gasoline or other fuels with a rag protruding through the neck. The rag is set on fire and the cocktail thrown. The bottle breaks and the burning fuel spreads, potentially being able to disable even certain armored vehicles. The fuel burns, but does not explode.

Fuel-air explosive bombs

Some of you may have heard of thermobaric weapons. They contain some form of fuel (not necessarily gasoline) and use an explosive charge to disperse the gasoline over a wide area and then a second charge makes the gasoline mist explode. So the first explosion has the role of mixing the right amount of gasoline and air to make it explosive. Given the energy density ratio with respect to TNT these types of bombs can create significant damages with relatively low weights.

They are particularly effective against "soft targets" because among other things, the combustion takes away the oxygen. The Russians call them "vacuum bombs".



Uranium: 1,000,000.

Coal is dirt cheap

Suppose you want to buy a calorie to warm up your house. What is the cheapest way to do it? Let us ignore all other variables. It is not easy to compare. Gasoline is about $3.50 a gallon, electricity is 10c a Watt-hour, natural gas is $3 per thousand cubic feet, coal is $40 a ton.

Table 1.2 Cost of Energy

Fuel	Market cost	Cost per kWh (1000 Cal)	Cost if converted to electricity
Coal	$40 per ton	0.4¢	1.2¢
Natural gas	$3 per thousand cubic feet	0.9¢	2.7¢
Gasoline	$2.50 per gallon	7¢	21¢
Electricity	$0.10 per kWh	10¢	10¢
Car battery	$50 to buy battery	21¢	21¢
Computer battery	$100 to buy battery	$4.00	$4.00
AAA battery	$1.50 per battery	$1000.00	$1000.00

In a free market economy, shouldn't all forms of energy cost the same? Why do we willingly pay more for some of them?

In some cases it is convenience: we are eager to pay considerably more for energy from a AAA battery because they are very portable. Think about disposable batteries vs. rechargeable ones.

In other cases the market is not really free. Huge investments are needed to adopt a certain type of technology. For instance, our cars and road infrastructure were designed when gasoline was very cheap. In countries where gas has been historically more expensive, other solutions have been found: more public transportation, CNG use in personal vehicles.

Many sectors and some entire US cities were premised on cheap gas and that transportation would be by private automobile, leading to low population density (suburbia). Low population density areas cannot be effectively serviced by public transportation.

When we get to talk about climate change we will see that coal is one of the most pollutant forms of energy generation. But it is the cheapest, and alternative energy sources find the cost battle to be a real challenge.

An Enfield sidecar outfit converted to coal-gas by W. Elce and Co., of Bishopsgate.

Forms of energy

We have talked of several forms of energy: food energy, chemical energy, the energy of a flying asteroid (kinetic), a compressed spring (potential energy), nuclear energy, gravitational energy.

The word “energy” is used in popular language in many ways. For instance, musicians speak of the “energy” of a crowd of spectators. It is fine for people to talk like this, but we should be precise when we are talking in physics terms.

In physics Power is defined as the rate at which energy is used or delivered. Power=Energy/time. In popular language sometimes these words are used interchangeably. But speaking precisely, we can say that TNT has less energy per unit weight than chocolate chip cookies, it has more power since it can deliver the energy faster. But it does so for a shorter time because it has less energy!

The unit of power is the Watt, after James Watt, the developer of the steam engine in the 19th century. It is defined as a Joule per second. A kilowatt would therefore be 1000 Joules per second. Quirks of language: kilowatt, kW, kilojoule, kJ.

Energy is conserved

If one fires a bullet, the chemical energy in the gunpowder gets first converted to thermal energy in the air, which expands due to the heat and pushes the bullet out of the gun. Roughly speaking the energy in all three phases is the same: it just gets converted from chemical to thermal to kinetic. This is what is meant by "energy is conserved".

This is an extremely useful law of nature. So much so that it gets a rather pompous name "the first law of thermodynamics". Thermodynamics studies heat, we will talk more about that later.

So if energy is naturally conserved, why are we constantly being admonished to "conserve energy"?

It turns out not all forms of energy are equally useful nor equally transferable. For instance, it is usually easy to convert chemical energy to heat, it is very difficult if not impossible to convert heat to chemical energy. The most useful forms of energy are potential energy. Among the least useful is heat, since it is difficult to convert to other forms.

Measuring energy

The easiest way to measure energy is to convert it to heat and see how much it heats up water. The Calorie is defined as the energy needed to raise the temperature of a kilogram of water by a degree Celsius (1.8F). There are 4200 Joules in a Calorie. A kilowatt-hour is the amount of energy delivered by 1000 Joules per second for an hour (3600 seconds). That is 3.6 million Joules. So 860 Calories. That is why we say that a Watt-hour is approximately a Calorie.

Unfortunately there is another unit that sometimes gets used, usually in HVAC contexts, the British Thermal Unit (BTU), which is about ¼ of a Calorie.

Power

The rate at which energy is transferred. A rate of a quantity is the amount of the quantity divided by the time involved. So the rate at which one travels is measured in miles per hour. So when 1 gram of TNT releases 0.651 Calories in 0.000001 second, the power is 651,000 Calories per second.

More common units for power are Joules per second and horsepower.

The funny name of horsepower (hp) comes from James Watt, who determined that a horse tied to a rope could pull up 330 pounds of weight a distance of 100 feet in one minute. He called that rate of work to be one horsepower. This turns out to be 746W, so approximately one can say that 1hp is equivalent to 1 kW.

To give some ballpark figures, a car engine typically delivers between 70-400 hp.
BMW Z4 240-355hp. Toyota Prius 134hp. Ford Escape 168-231hp. Bugatti Veyron 1,200hp.

Mega and giga and tera Watt are commonly used when talking about power generation.

Since energy is conserved the whole power industry consists in converting one form of energy into another, although in popular talk one uses the word “power generation”.

A typical large “power generating” plant, be it coal/oil fueled or nuclear, typically generates 1 gigaWatt of power. A relatively modest home consumes about 1kW (10 light bulbs).
So a large power plant can provide one million homes. Local utilities may have smaller power plants 50-100MW, so those could provide 50-100,000 homes.

Summary:

- Hydrogen: devil is in the details.
- It is hard to make gasoline explode.
- Coal is dirt cheap.
- Energy is conserved.
- Energy is measured in Calories, Joules or Watt hour.
- Power is rate of energy, measured in Joules/s Watts or hp.
- Powerplant rate: 1GW.
- 1kW~1hp, 1Calorie~1W hour.