

University of Pisa

Department of Engineering

Final Report

IARC, Fermilab

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1 IARC

During my summer internship at Fermilab I worked at the Illinois Accelerator Research Centre (IARC). At IARC, scientists and engineers from Fermilab and Illinois universities work side by side with industrial partners to research and develop breakthroughs in accelerator science and translate them into applications.



Figure 1: IARC from outside.

In fact the IARC mission is transferring the knowledge acquired with research to technologies suitable for industries. Moreover another point is decreasing the time to market of the new industrial solution. IARC constantly search new partners, especially industries, for the new accelerator-based technologies.

The HAB, Heavy Assembly Building, is the application development area of IARC. Inside there are many projects, for example A2D2 and Mu2e.

They are developing a compact, superconducting accelerator that we believe will have impact on the nation's security, health and wealth. Along with development of the accelerator they are developing new applications that the compact accelerator would enable. To do applications development they are commissioning a repurposed industrial linac¹ called A2D2 (Application Development and Demonstration Accelerator).

They are integrating multiple new technologies to create a compact, portable and high power electron beam accelerator. The liquid helium is

¹Linear electron accelerator.



Figure 2: HAB inside.

removed so that is no more possible to increase the flow rate in order to have more refrigeration. Having conduction cooling, there is a fixed amount of heat that can be extract from the vessel.

2 COMSOL

On the first month I studied the basics of a, new for me, software called COMSOL Multiphysics, which is a cross-platform finite element analysis, solver and multiphysics simulation software. It allows conventional physics-based user interfaces and coupled systems of partial differential equations. COMSOL is useful for electrical, mechanical, fluid, and chemical applications.

I attended two web trainings and read a lot of materials online. After this first moment, I tried to set up some models.

2.1 Water temperature

My first task was determining the temperature in a glass of water which interact with an electron beam. I assume that the electron beam produce 1500 W of heat power concentrated in a small cylinder (1 cm radius, 5.5 cm height). The volume of water is contained in the glass in Figure 3.



Figure 3: Glass of water used in the experiments.

Under the glass there is a block of concrete and all around air at ambient pressure and temperature.

For the COMSOL simulation I assume that the heat transfer coefficient of air in contact with glass is $2 \frac{W}{m^2K}$. I also use this value for the interface with the concrete. Instead, I have used $50 \frac{W}{m^2K}$ for the boundary condition of water.

In Figure 4 is represented the whole model; instead in Figure 5 and Figure 6 there is a detailed view of the temperature distribution at different times.

In Figure 7 is shown a representative picture of the velocity field, which is composed by the convection motions.

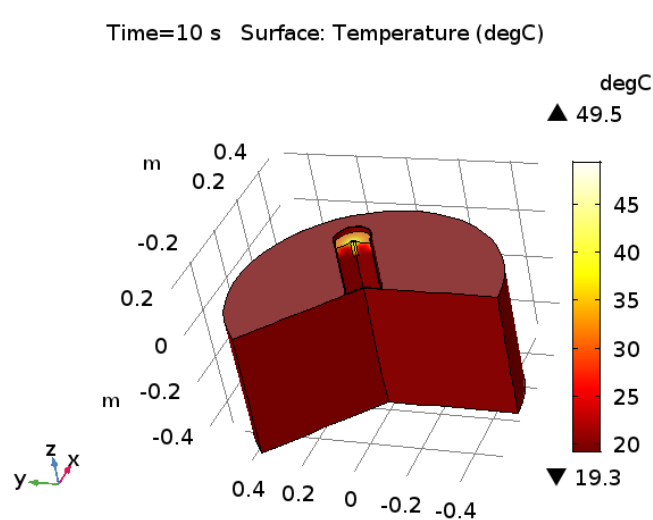


Figure 4: Representation of the model.

2.1.1 Problems

Electron beam It is almost impossible to model the interaction between the electron beam and the sample. So that I have assumed that the heat source is uniform distributed in a small volume; better approximation could be done looking at the distribution of the electron beam in space.

High temperature I found some problems in modelling the situation when water reaches the boiling temperature. COMSOL does not respond according to physical expectation at high temperature. It is also difficult to model the convection motions.

Boundary condition The boundary condition have been chosen through an accurate search but including air in the model could be a good idea for a more complete understanding.

2.2 Aluminium

To find a solution to the water's problems, we thought about a solid with high conductivity, the aluminium. A useful parameter to see the differences between these two materials in the experiment is the thermal diffusivity, which is the thermal conductivity divided by density and specific heat capacity at constant pressure. It measures the rate of transfer of heat of a ma-

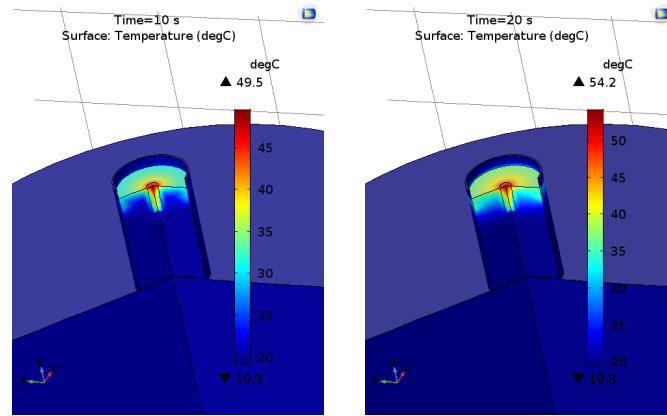


Figure 5: Temperature distribution after 10 and 20 seconds.

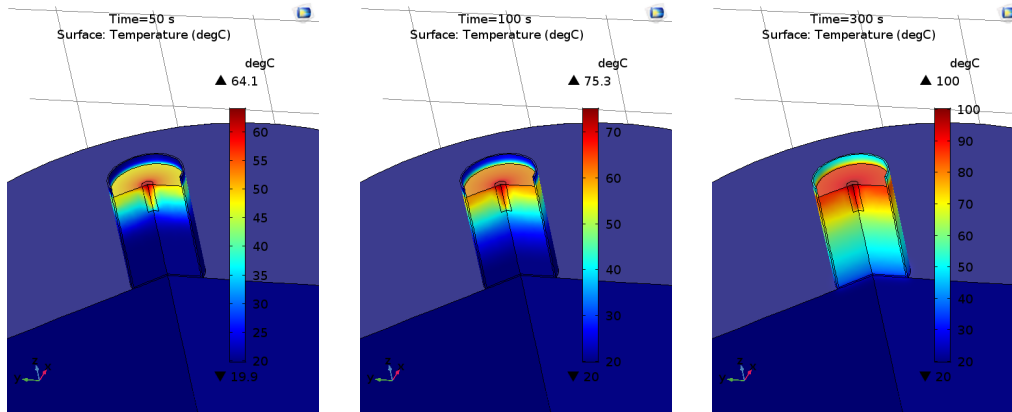


Figure 6: Temperature distribution after 50, 100 and 300 seconds.

terial from the hot side to the cold side. Aluminium's value is $970 \cdot 10^{-7} m^2/s$, instead for water is $1.43 \cdot 10^{-7} m^2/s$.

Aluminium is a very good material for this experiment in fact the temperature rise, all other things being equal, is bigger. This is helpful for the experiment because it is simpler to measure the temperature difference. The high thermal conductivity implies that the heat generation is rapidly distributed, see Figure 8.

Moreover aluminium allow us to complete different experiments together. In fact we can measure both the temperature rise and the voltage so that we have two results at the same time.

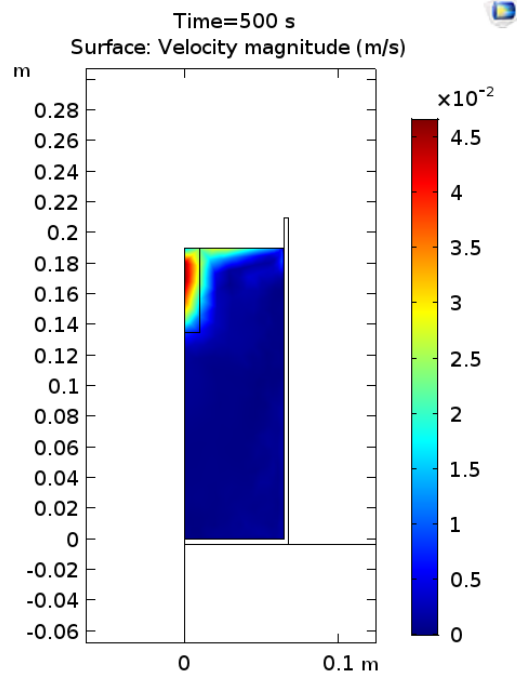


Figure 7: Distribution of velocity.

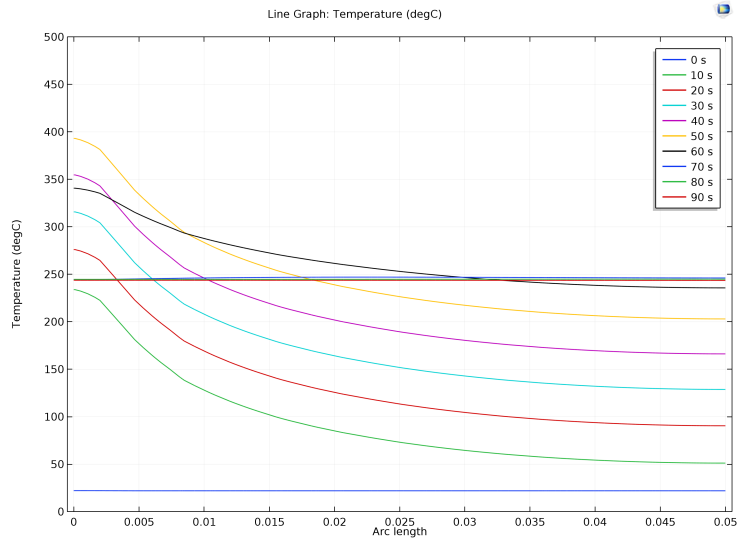


Figure 8: Temperature distribution in aluminium (the length is the distance from the center).

3 A2D2



Figure 9: A2D2 cave.

The melting point of aluminium is $660.37\text{ }^{\circ}\text{C}$, the boiling point $2467\text{ }^{\circ}\text{C}$. I have considered a block of aluminum with these sides measures: 50 mm , 37 mm , 25 mm . The external surface is 0.00805 m^3 . If P is the heat power, A the surface area and h is the overall heat transfer coefficient, it is possible to calculate the average difference of temperature between the surfaces and the air with the following equation:

$$\Delta T = \frac{P}{h \cdot A} \quad (1)$$

For example if $P = 1000\text{ W}$ and $h = 50\frac{\text{W}}{\text{K}\cdot\text{m}^2}$, the temperature difference is $2484\text{ }^{\circ}\text{C}$.

3.1 Python

I wrote a simple python code in order to easily calculate the power of the electron beam.

Listing 1: Simple Python code

```
import math
l1=0.109
l2=0.063
l3=0.025
```

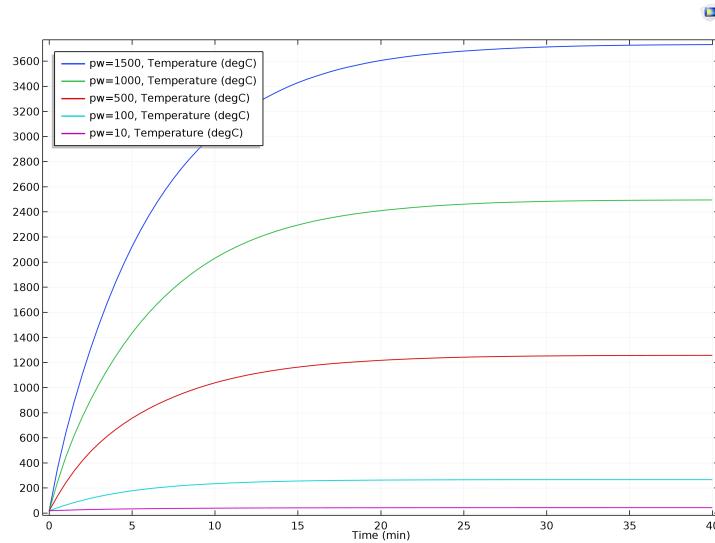


Figure 10: Average temperature of one side of aluminium.

```

#we have a hole
d=0.021
V=(11*12-math.pi*d*d/4)*13
print 'The_volume_is', V
sp=900
rho=2700
mass=rho*V
print 'The_mass_is', mass

temperaturai = input('Insert_the_initial_temperature:_')
tempi=float(temperaturai)
print 'The_initial_temperature_is', tempi

temperaturaf = input('Insert_the_final_temperature:_')
tempf=float(temperaturaf)
print 'The_final_temperature_is', tempf

time = input('Insert_the_experiment_duration_in_minutes:_')
tim=float(time)
print 'The_duration_is', tim
ts=tim*60

P=mass*sp*(tempf-tempi)/ts
print '\n_The_power_is', P, '\n'

```

3.2 Lock Removed

On Wednesday 6th of September a member of the company Acceletronics came to IARC and removed the lock in the accelerator. In fact the machine was predisposed to be a medical device so that the power was too low.

With this modification we are able to reach more than one kilowatt of power.

3.3 Experiment

3.3.1 Radiation indicators

After the lock was removed, we did many experiment in order to understand the new output of the machine.

Because of the gas chromatic film was too sensitive, we tried with radiation indicators, which change color from yellow to red at 3 kGy of dose.

Firstly we run the electron beam for 0.15 minutes at 600 mu/min but the dots were all red. Then we tried with one sixth of the previous dose rate and the result is shown in Figure 11.

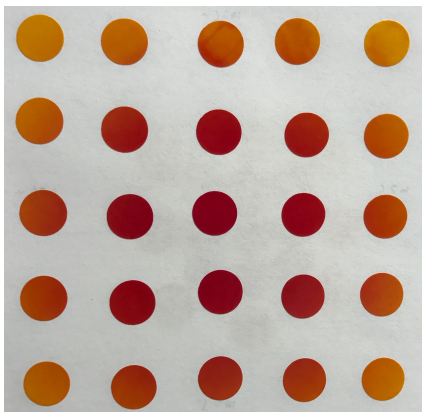


Figure 11: Electron beam section at the bottom (100cm).

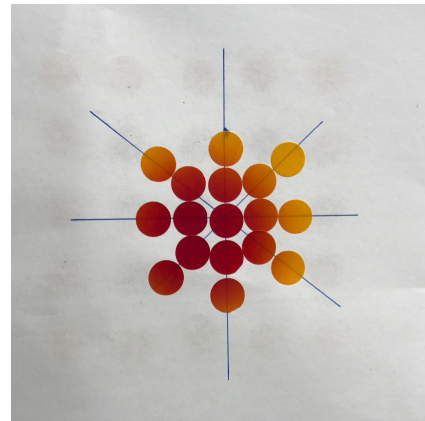


Figure 12: Electron beam section at the top (60cm).

Afterwards we place a new sheet in an upper position in order to see the enlargement of the electron beam due to scattering. As shown in Figure 12, is easy to understand that the electron beam is more concentrated at the top and more distributed at the bottom.

We concluded that it is not a perfect electron beam but it looks like.

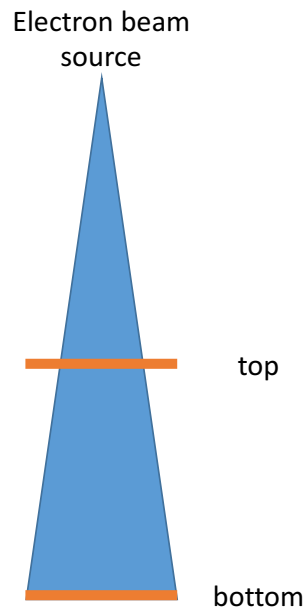


Figure 13: Air scattering of electron beam.

3.3.2 Water

We did some experiments with the beaker of water. Probably the main result was that the penetration depth of the electron beam in water is, as we know from literature 5.5 cm. On September 22nd, we irradiated a 1 liter beaker of water that was on a stir plate (at the maximum power). Starting with an initial temperature of 23°C, after 2.5 minutes run the temperature was 45°C. After 105 seconds of pause and another run of 2.5 minutes, we reached 68°C.

This temperature increase does not match with 1 kW of power because the beaker was located more than 100 cm far away from the electron beam source. So that the water does not intercept all the beam; in fact the stir plate, which was bigger, broke.

3.3.3 Voltage measurement

One way to understand the power of the electron beam is measuring the voltage of the aluminium. In fact every electron is stopped by the block and changes the voltage of $1.6 \cdot 10^{-19} \text{ C}^2$. If the block is linked to a resistor, is

²In physics, the electronvolt (symbol eV) is a unit of energy equal to approximately $1.6 \cdot 10^{-19}$ joules (symbol J). By definition, it is the amount of energy gained (or lost) by the charge of a single electron moving across an electric potential difference of one volt.

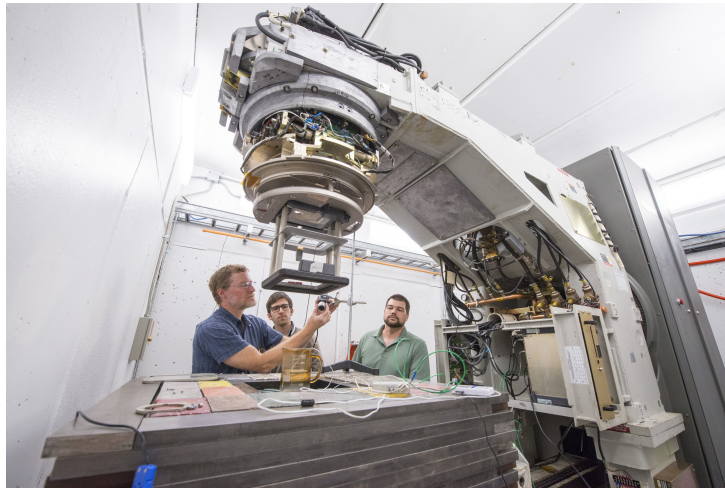


Figure 14: Set up of the experiment.

possible to calculate the current. Multiplying the current by the energy of electrons, in eV, is obtained the power.

In this way, the measured power is going to vary quickly because the electron beam is pulsating at 360 Hz. In order to have a constant voltage, it is possible to add a capacitor in parallel to the resistor. If the time constant of the RC circuit is high than $1/360=0.00278$ seconds, the current can be considered constant. In Figure 15 is displayed the configuration of the experiment. The electron beam is assumed to be a current generator.

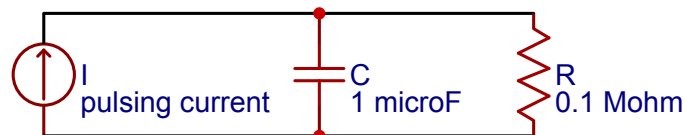


Figure 15: Schematic circuit of the experiment.

We chose a capacitor of $1 \mu\text{F}$. The time constant with a $0.1 \text{ M}\Omega$ resistor is 0.1 seconds and is ten times bigger with $1 \text{ M}\Omega$.

The running time was 0.5 minutes per every measurement.

Thus it is 1 volt (1 joule per coulomb, 1 J/C) multiplied by the elementary charge (e , or $1.602 \cdot 10^{-19} \text{ C}$).

Measure n°	Position	resistance	Dose	Voltage
1	bottom	.1	300	1.7
2	bottom	.1	400	2.3
3	bottom	.1	600	3.46
4	bottom	.1	600	3.55
5	bottom	.1	600	3.68
6	bottom	.1	600	3.8
7	top	.1	600	3.78
8	top*	.1	600	12.26
9	top*	1	600	124

Table 1: Voltage measurement of aluminium block.

The line marked with * are the experiment where we put another aluminium plate over the first block in order to increase the area which intercepts the electron beam.

3.4 Next steps

Next few weeks there are other steps that can be done. Firstly is important to understand the precise power distribution along the radius and also the penetration depth of the electron beam in various materials.

Moreover for future applications there is the requirement of figuring out how to treat the whole sample with the same dose.

4 Radiation

The task of this section is to calculate how much H_2 is generated from 1 $M Gy$ dose on 2 L of water. Assuming that the density of water is 1000 kg/m^3 , there is 2 kg of water. 1 $M Gy$ correspond to 1 $M J/kg$, so that in this experiment the energy provided is $2 \cdot 10^6 \text{ J}$.

G factor is defined in units of molecules formed or dissociated per 100 eV of energy absorbed. Because of $1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ J}$. Calling N the Avogadro's number and knowing the ideal gas law (1 mole = 22.4 L), 1 J of energy generates:

$$\begin{aligned} \frac{G/100}{1.602 \cdot 10^{-19}} \text{molecules}(H_2) &= \frac{G/100}{1.602 \cdot 10^{-19} \cdot N} \text{moles} \\ &= \frac{22.4 \cdot G/100}{1.602 \cdot 10^{-19} \cdot N} L \end{aligned} \quad (2)$$

As calculated, there are $2 \cdot 10^6 \text{ J}$

$$\frac{2 \cdot 10^6 \cdot 22.4 \cdot G/100}{1.602 \cdot 10^{-19} \cdot N} L = 4.64 \cdot G L \quad (3)$$

Having a G value for beta ray of $0.06 \text{ } \mu\text{mol/J}$, which correspond to 0.5788 molecule/100eV, the liters of H_2 generated are 2.69.

5 Wind Turbine

5.1 Current situation

The costs for a utility scale wind turbine range from about \$1.5 million to \$2 million per MW of nameplate capacity installed.

Nowadays there are many problems on the transportation of wind turbines as it is shown in Figure 16.



Figure 16: Wind turbine blade transportation.

5.2 Additive manufacturing

3D printing, or additive manufacturing, is the process of producing a three-dimensional, solid object from a digital file. A 3D printer layers semi-molten material into the computerized shape, a process that offers improved design flexibility, decreased energy consumption, and reduced time to market.

5.2.1 Electron Beam Additive Manufacturing

Electron-Beam Additive Manufacturing (EBAM) is a type of additive manufacturing, or 3D printing, for metal parts. Metal powder or wire is welded together using an electron beam as the heat source.

Although wind energy is among the fastest growing clean energy technologies, some obstacles are critical challenges in achieving our national clean energy goals.

A possible solution is utilizing large-scale additive manufacturing, ORNL (Oak Ridge National Laboratory) researchers were able to redesign the traditional mold, eliminating unnecessary parts and procedures. Creating unique opportunities in this traditionally time consuming process.

Considering the time for designing and manufacturing a wind turbine, in the traditional way is about 10 months (8 for plug fabrication and 2 for the mold), instead with the 3D printer is only 1 month for design, print and finishing. Moreover in the second case there is no need of plugs.

In the 3D printer is quite easy to incorporate air passages into design instead in the traditional manufacturing is hard.



Figure 17: Wind turbine blade with additive manufacturing.

Charlie Cooper and I figured out that there is a possibility to collaborate with ORNL. At the moment this lab is developing new application for additive manufacturing, so that a collaboration could bring to EBAM.

6 Conclusion

During this months I have the opportunity to learn a software, called COMSOL. My was a complete researcher experience in fact in the first moment I studied the principles in some books, then I developed some simulations on COMSOL and in the end I verify the results at the laboratory.

I spend the last week review the data collected during the two month and writing this final review.

The summer intership at Fermilab is a wonderful experience where I learned a lot of new things about the world of the particle accelerator. Moreover for the first time I had the chance to test the abilities learned at university.

A Monitor unit

A monitor unit (MU) is a measure of machine output from a clinical accelerator for radiation therapy such as a linear accelerator or an orthovoltage unit. Monitor units are measured by monitor chambers, which are ionization chambers that measure the dose delivered by a beam and built into the treatment head of radiotherapy linear accelerators.

The monitor chamber reads 100 MU when an absorbed dose of 1 gray (100 rads) is delivered to a point at the depth of maximum dose in a water-equivalent phantom whose surface is at the isocenter of the machine (i.e. usually at 100 cm from the source) with a field size at the surface of 10 cm by 10 cm.

B Conversion

B.1 Particle generation per energy

From molecule per 100 eV to μmol per J.

$$\begin{aligned}
 x \frac{\text{molecule of } H_2}{100 \text{ eV}} &= \frac{x \text{ mol of } H_2}{N \cdot 100 \text{ eV}} \\
 &= \frac{x \cdot 10^6 \mu\text{mol of } H_2}{N \cdot 100 \text{ eV}} \\
 &= \frac{x \cdot 10^6 \mu\text{mol of } H_2}{N \cdot 1.602 \cdot 10^{-19} \text{ J}} \\
 &= x \cdot 0.1037 \frac{\mu\text{mol of } H_2}{J}
 \end{aligned} \tag{4}$$

Likewise:

$$y \frac{\mu\text{mol of } H_2}{J} = y \cdot 9.6472 \frac{\text{molecule of } H_2}{100 \text{ eV}} \tag{5}$$

B.2 Temperature

Celsius	Fahrenheit	Kelvin
-273.15	-459.67	0
0	32	273.15
100	212	373.15
600	1112	873.15

Table 2: Conversion between Celsius, Fahrenheit and Kelvin degrees.

B.3 Length

Standard units	Metric units
1 inch	2.54 centimeters
1 foot	30.48 centimeters
1 yard	0.9144 meters
1 mile	1.60934 kilometers

Table 3: Conversion between standard units and Metric units..

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