Introduction to Uncertainty Analysis and Experimentation
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Module - 01
Outline, Introduction
Lecture - 02
Experimentation processes and applications overview

This is the 2nd lecture of the 1st module; on the course Introduction to Uncertainty Analysis and Experimentation. Today we will pick up where we left last time and look at a little more in detail about Experimentation processes and also applications both of experimentation and uncertainty analysis.

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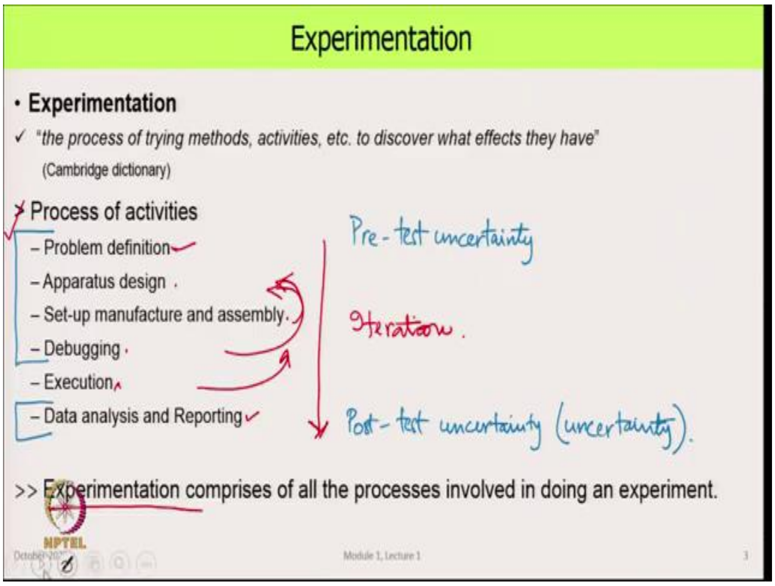

Experimentation, as we have defined yesterday; is the process of trying methods, activities, and others; experimentation is the process of trying methods, activities, etcetera, to discover what effects they have. So, this includes a whole variety of processes and these are listed here, and these are listed in the second item here.

So, what we are saying is that experimentation is everything from thinking about wanting to do something; to making a setup, taking measurements, collecting the data, analyzing it, drawing conclusions, and finally presenting those conclusions. So, here we have the first activity here, we are listed problem definition.

We have to define very precisely what is it that we are looking for that is the first step, having done that we decide what are the various ways in which we can make an experimental setup and realize it.

So, there is no one given design, there could be many possibilities, and we have to go through one of to select in one of them. After selecting that one we go to a complete detailed design, manufacture and assembly. So, this includes making the rig, buying instruments, putting electronics together, connecting it to a data logger or a laptop all of that comes here.

After doing that our next step is debugging, which is a set of activities that we do with the setup to quantify that it is doing what we want it to do in terms of quality, reliability, repeatability, and many other such things. Once we have done debugging or also called qualification testing, we are confident that we have a setup that will do what is it that we have wanted to do in the first place.

Now, we are ready to take data and this is what we call the execution. We run the experiment again and again for different parameters collect the data, after all that plan of what how much data we have to take is done, our data taking is complete; we now go to the last phase which is data analysis and reporting.

Reporting could be a report, could be a presentation, could be a short summary, could be a paper, could be a thesis any of those. So, all these activities usually go in a single direction, but there are times when for various reasons of manufacture, we need to go back and change the design.

Debugging says; well you need to take a different instrument, execution says that well change the data acquisition software slightly. So, this is in general in this direction, but within steps there is iteration, and all of this is what we call experimentation. We will come back to it in much more detail in week 3, now we will just give some examples also to illustrate that how these abstract ideas actually get translated into a real thing.

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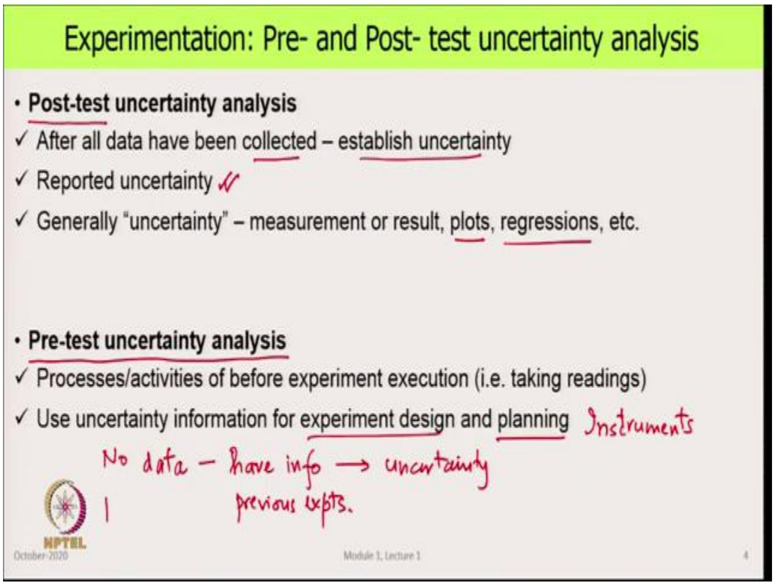

Now, in that sequence where does uncertainty analysis come in? And there are two stages in which uncertainty analysis comes in. First, is what we generally know as post-test uncertainty analysis, which means that all the data have been collected and now we establish the uncertainty.

So, this is what we report when we finally present the result, is your reported uncertainty, which in general terms we always refer to as uncertainty, uncertainty of a measurement or uncertainty of a result. And we also show that when we make plots, we present regressions, there also we show what the uncertainty in various constants is.

So, by and large it is post-test uncertainty analysis that we have generally come to know as uncertainty. But there is another phase which is before we even make the setup or during this assembly of the setup that uncertainty analysis is very helpful and that is called pre-test uncertainty analysis.

So, this is the stage where we have not yet designed the setup, we are in the process of selecting parameters, we are in the process of selecting instruments and we are also deciding how many readings to take, how to take, in what sequence to take, all of that is still fluid and we need to take a decision on that.

And, one of the criteria by which we make those decisions is to do an uncertainty analysis and that helps us a lot in experiment design, planning and also selection of instruments. This is very valuable because especially when it comes to instruments, this means usually a lot of investment is involved and it is very important that we wisely use our funds to select the right instrument that will do our job and that is where uncertainty analysis helps us.

The difference between pre- and post-test uncertainty analysis is that in this case we do not have any data. But we have information about the setup, about its behavior, about instruments and with that information we work out the uncertainty. So, this is no data from our experiment, but there could be previous data which would be here. So, there are two very different ways in which we use uncertainty analysis in those stages that we just saw.

So, what we are saying is that in these stages, so this is where the execution is, before the execution we have pre-test uncertainty. And after the execution in data analysis and reporting this is post-test uncertainty or what we generally know as when we report a result we just call it uncertainty. So, that is an important thing to know about both experimentation and how uncertainty analysis comes into play.

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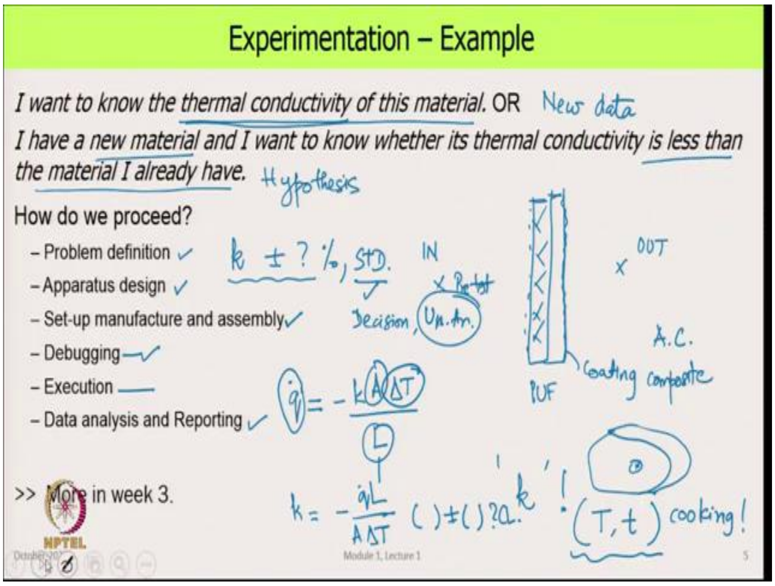

Now, we will take some examples and I will ,also show some pictures of what is this experimentation and the example I have taken here is say I want to know the thermal conductivity of a material or I could say I have a new material and I want to know whether its thermal conductivity is less than the material I already have.

So, in this case we are asking for new data which will be used later on in some other design process and here we have a hypothesis which we want to test. There are many many examples of materials whose thermal conductivity is needed.

For example, if you see buildings which have got colorful panels stuck on the outside those are composite multi layered panels, where outside there is a base sheet of aluminum, on that there is a very thin coating of different color which is what we see, it could even be printed.

Behind that is a layer of polyurethane foam and this panel we have put some glue on it, and it is stuck to the exterior of a building. And that is how you get the exterior facade of buildings that you see around you. One requirement is that (of) this thing has to withstand many conditions. We need to know what is its strength, we need to know whether it how it will behave in a fire, we need to know whether the glue will come off, we also need to know how much heat transfer takes place between the outside of the building and inside of the building.

So, this is your outside this is the inside of the building and we need to know this calculation, because from this calculation we get an important number that goes into designing the air conditioning of the building. So, we need to measure the thermal conductivity, in this case it is not a single material, but a composite.

This is one example; in food processing we could ask a very simple thing what is the thermal conductivity of a vegetable say a potato, I say well why do I need it; I would be boiling it or I would be deep frying it. And, the temperature and how long it stays at any point inside the potato, this will decide how well the cooking has taken place.

And that will decide whether it is raw, is not fully cooked, what flavor it has got, is it overcooked, all of that requires information about this thing. And one of the things to predict what is the temperature inside this, we put an instrument and measure it that is one way. The second is we measure its thermal conductivity and go to solve some equations and find out (what are) what to expect.

So, this is again you need a thermal conductivity and it is a very tricky issue in this case, because as the temperature changes with time the property of the material itself changes. So, it is a little tricky measurement out here. But what do we do, suppose we follow the same steps that we have looked at in what experimentation is.

First, we define the problem; see I have, look this is the material I want (I want) this thermal conductivity within plus minus so much percent or we can say I want thermal conductivity of this material as per this particular standard. Once we have said that, we say well what is the apparatus that I need to have? Either I can make it from scratch or if it is the standard it may tell us a broad principle of how to design this apparatus, then we have to follow this.

So, if we take that and now we have lot of options before us, because neither this case where we have to make the setup ourselves from scratch, or this case where we have to make it from a standard, they do not tell us what the size of the sample should be, what the temperature measurement technique should be, how do you measure the length; they give very broad guidelines especially in standards of what to do and what not to do.

After that we have lot of flexibility in deciding what we want. So, that is a decision to be made and that is where uncertainty analysis comes in. And this is your pre-test uncertainty analysis. With that we design the full geometrical features of the setup, we set up the manufacture we make the engineering design, buy the instruments, make the various parts, assemble them together, and now we are ready to say that look I can operate it.

Once it is ready for operation, our next step is debugging, where we run the test many times and check that it does everything right. Once we are satisfied with that, we go ahead collect data. After data is collected, we analyze it and report it. So, these are the general steps that we said what experimentation is and this is how we will be doing this.

We will come back to this example in more detail in week 3 and there is also a very extensive discussion on this particular problem given in the notes. I have picked up this topic in part because this is something everybody has learnt in science courses in school, in many engineering branches this is one of the experiments that they do. And so here is something that students, faculty, researchers from various fields have at least had as an exposure and you can appreciate what it is.

Plus, it is also a very simple thing in that we have only one formula that is coming from the heat equation which is based on Fourier’s law, that heat transfer rate is minus k A delta T upon L.

$$\dot{q}_x = -kA\frac{\Delta T}{L}$$

How do we measure? This has to be measured, this has to be measured, this has to be measured, and so here we have instruments to be used; how to measure it, establish its uncertainty, and this has to be measured.

After that we use the formula of k is equal to minus q dot L upon A delta T and calculate k:

$$k = -\dot{q}_x \frac{L}{A\,\Delta T}$$

And its uncertainty which we have to represent as some value plus minus some value at some confidence level. So, we will come back to this in more detail when we look at experimentation right.

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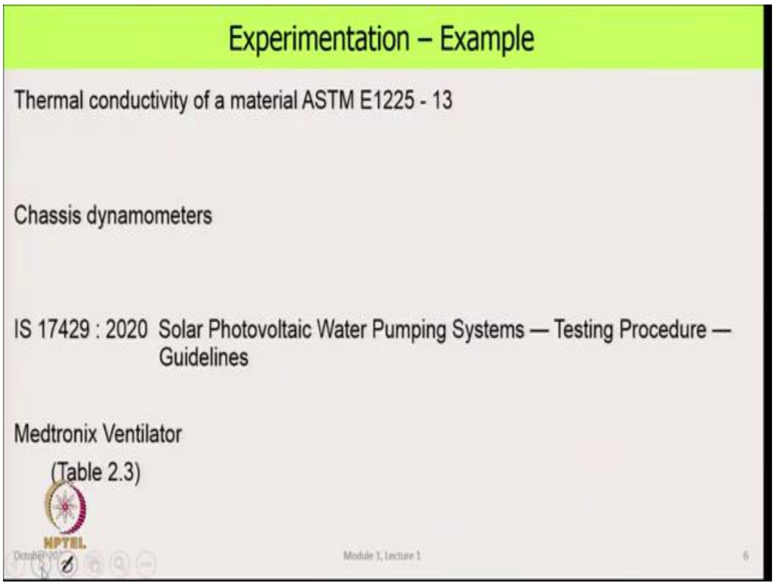

Now, I will give you quickly some examples of standards and facilities that people would use in experimentation.

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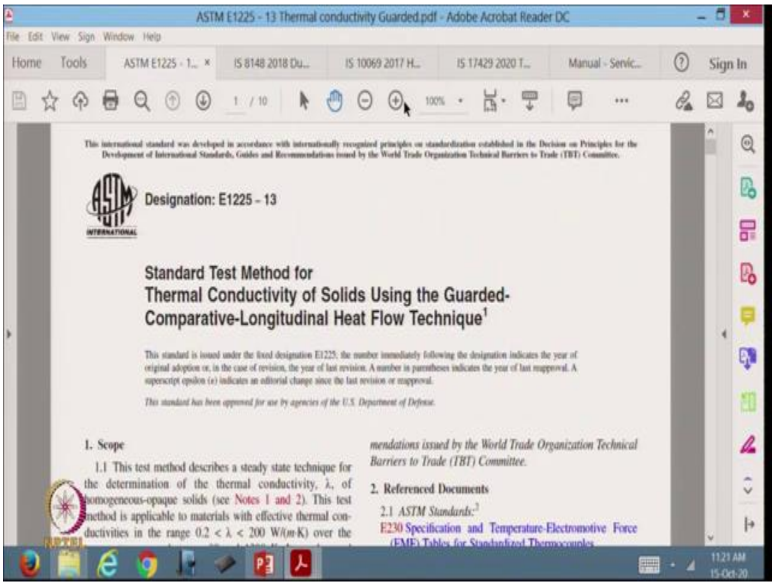

Here is an example which is the standard from ASTM American Society for Testing and Materials, the standard designation is given here at the top and this is E1225, this is ASTM standard E1225 which is the standard test method for thermal conductivity of solids using the guarded comparative-longitudinal heat flow technique.

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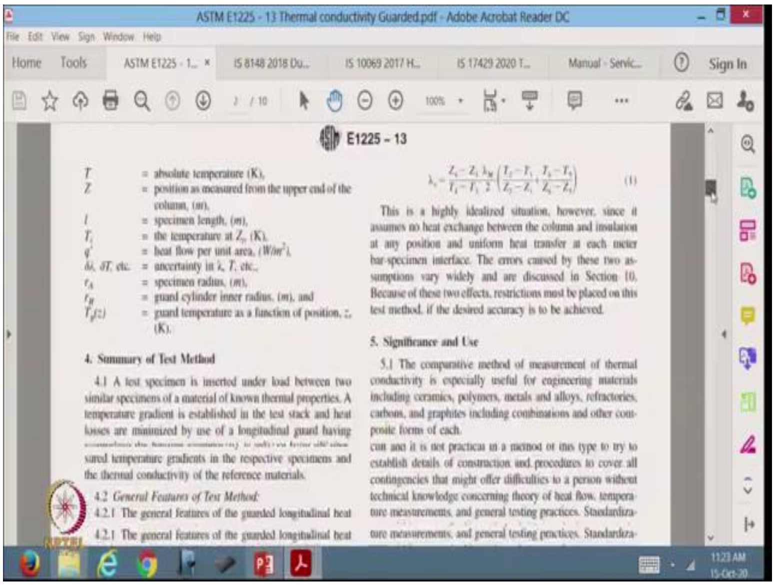

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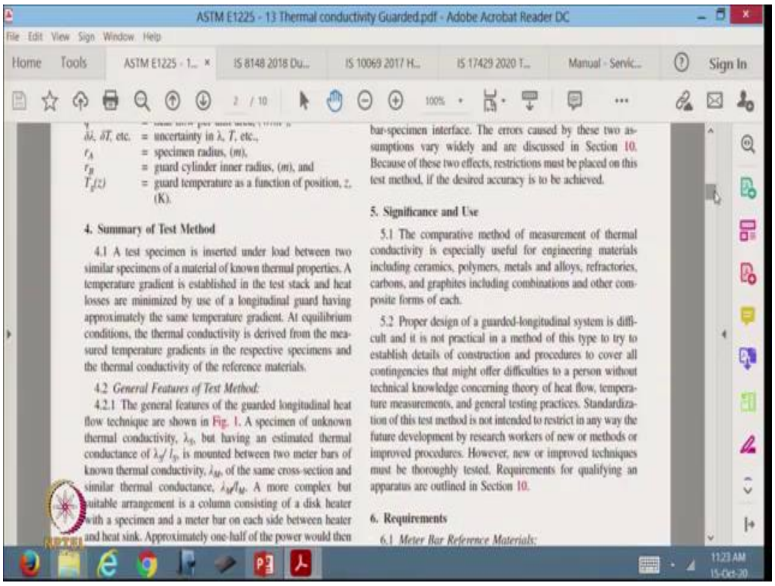

And if we look at this it gives the terminology, the symbols, and here is summary of the test method how to do it, its significance, and use and requirements.

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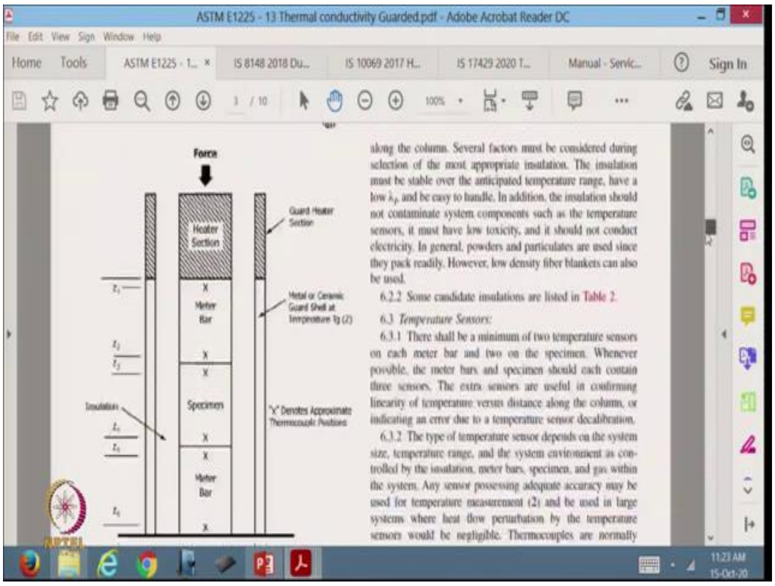

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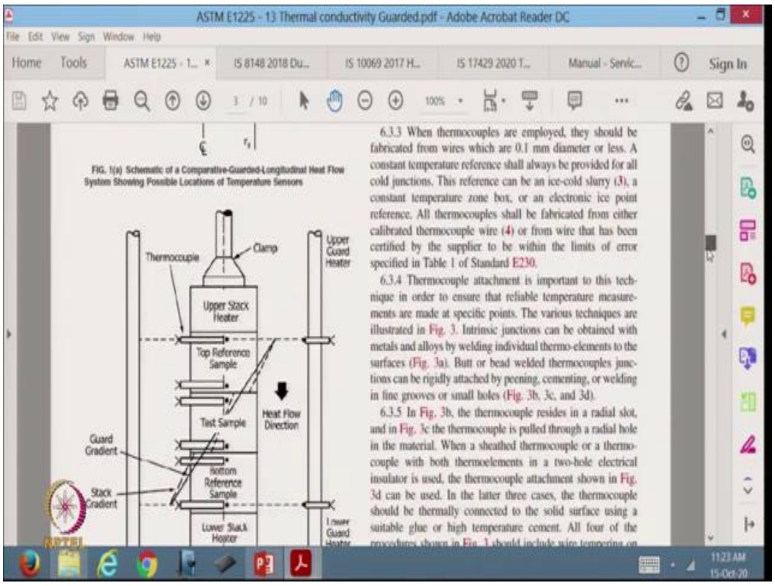

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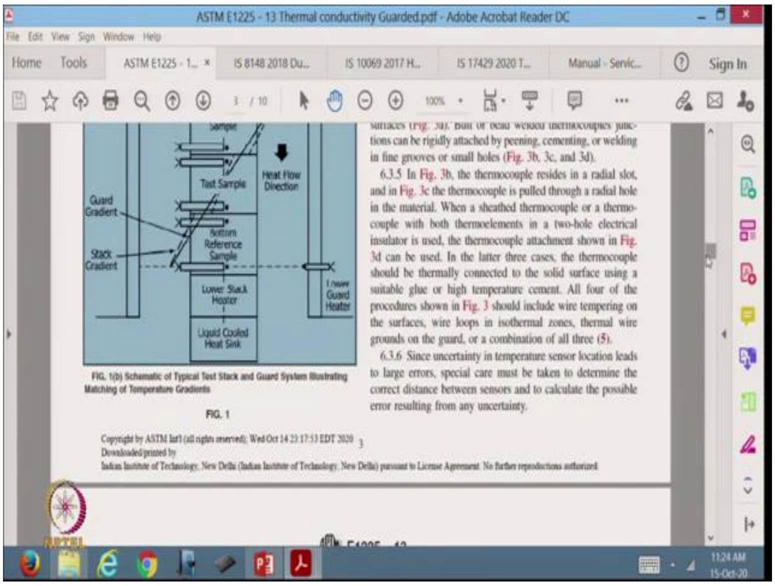

So, it gives us a sketch of what the general arrangement of the system should be. So, there they have said that there is a bar specimen, a meter bar, heater section, guard heater section, and how much distances they should have, and also where we should put the temperature sensors. So, these are all the temperature sensors that are coming here, this one, this one, this one, like that.

And it is also telling you what is the heat flow direction, where is the heater in this, here it is (up upper heat) upper stack heater, and at the lower end there is a lower stack heater, or a liquid cooled sink. And so, we establish in this case a one-dimensional heat transfer from the top to the bottom.

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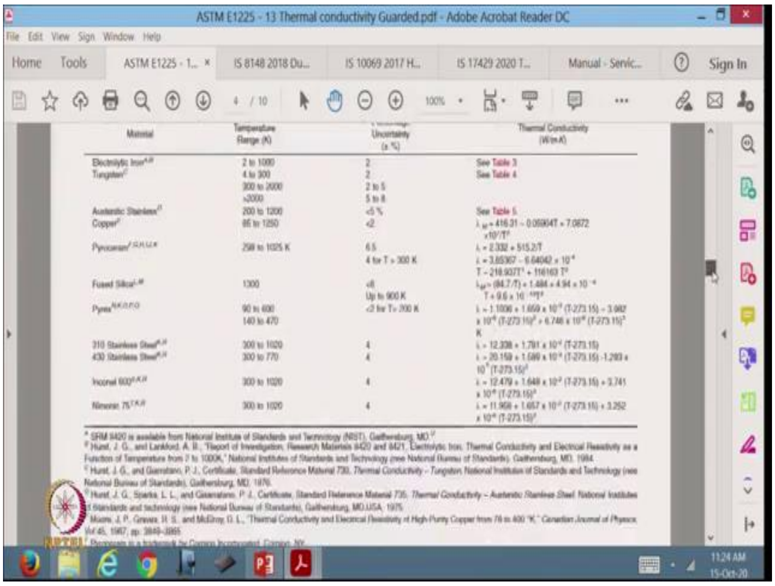

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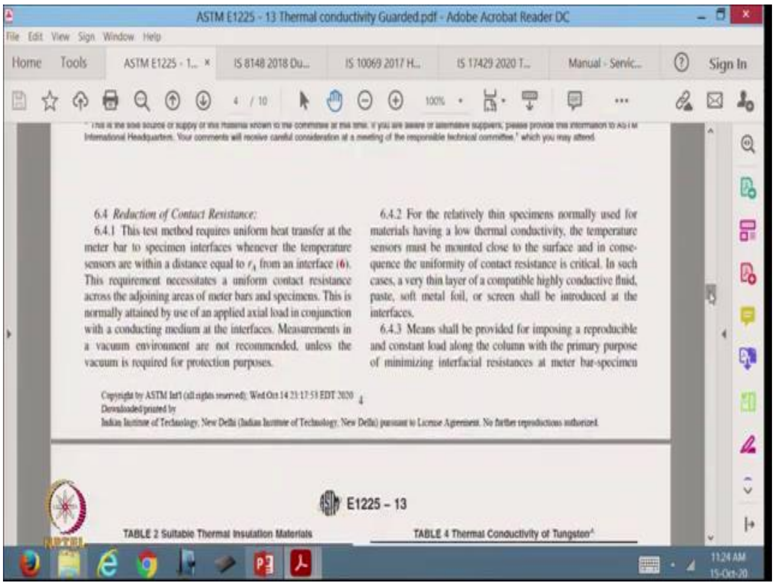

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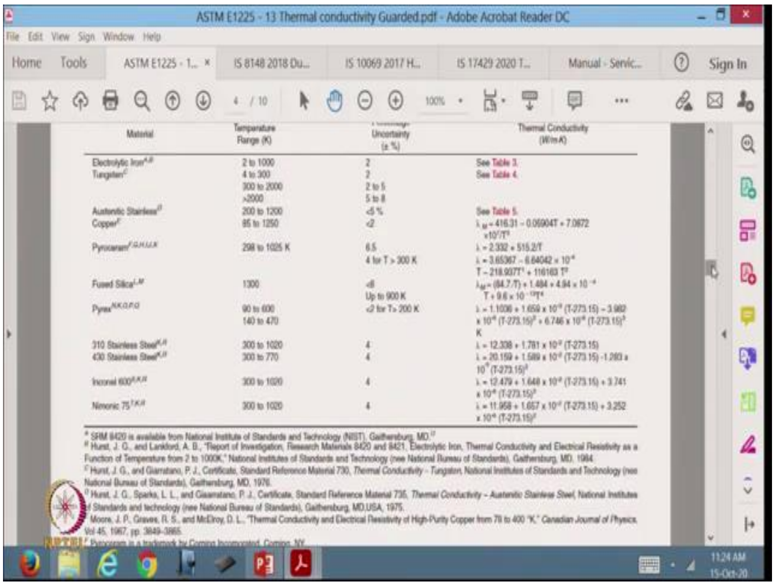

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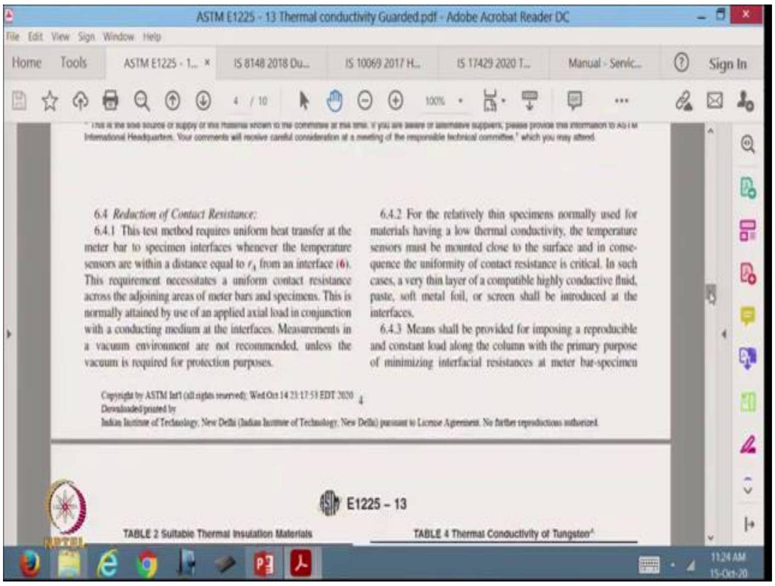

That tells us what is the heat transfer rate, and from then we have the geometrical parameters from which we calculate the thermal conductivity.

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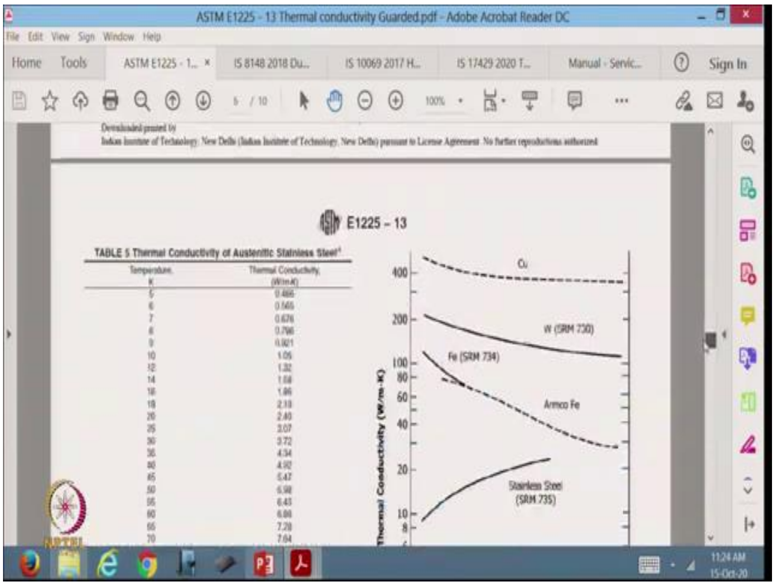

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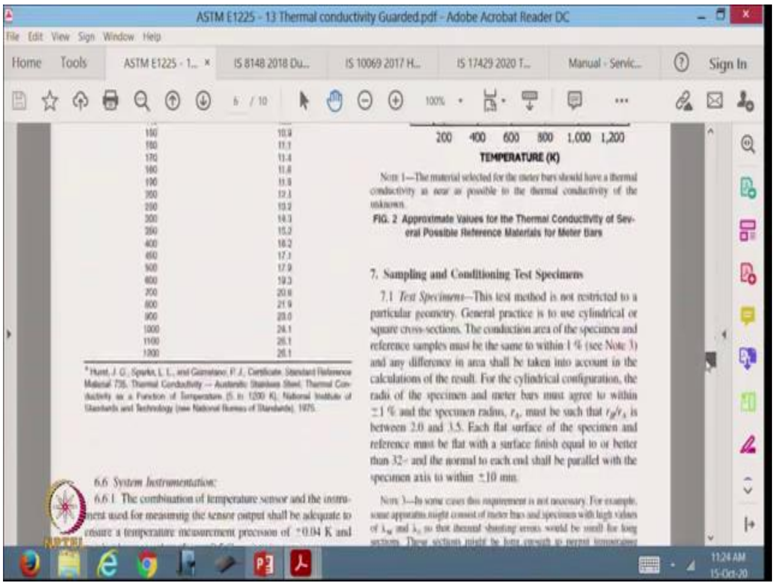

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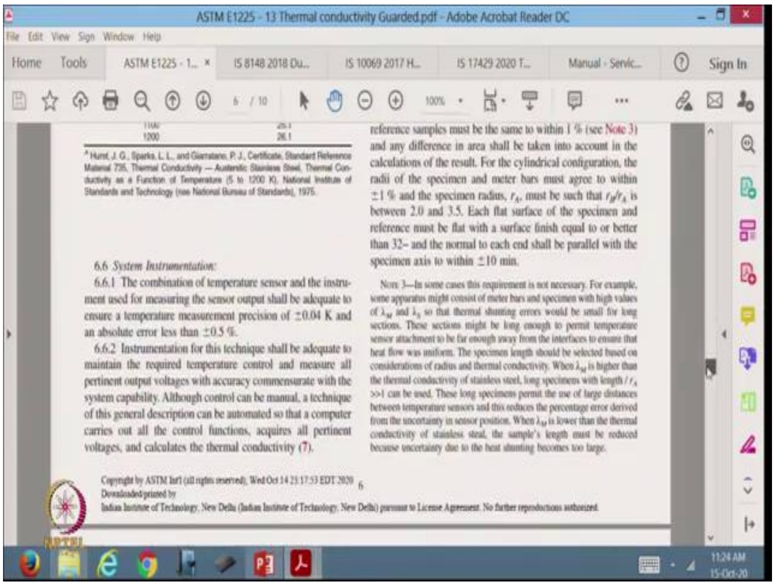

You can have a look at this yourself, but the thing is where is uncertainty coming in. And this is where that it has given some information and it says; the conduction area of the specimen and reference samples must be the same to within 1 percent. The radii of specimen and meter bars must agree to within plus minus 1 percent. Like this there are several things given, and finally in the end it tells us how to compute the errors.

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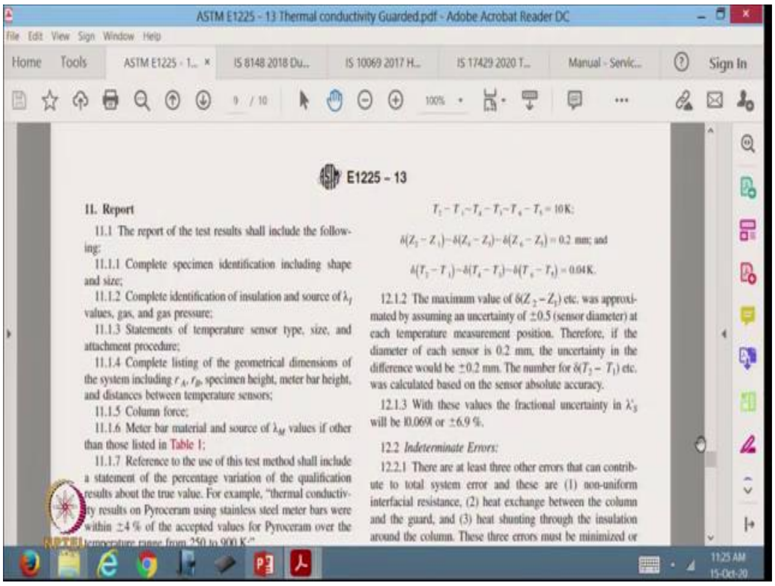

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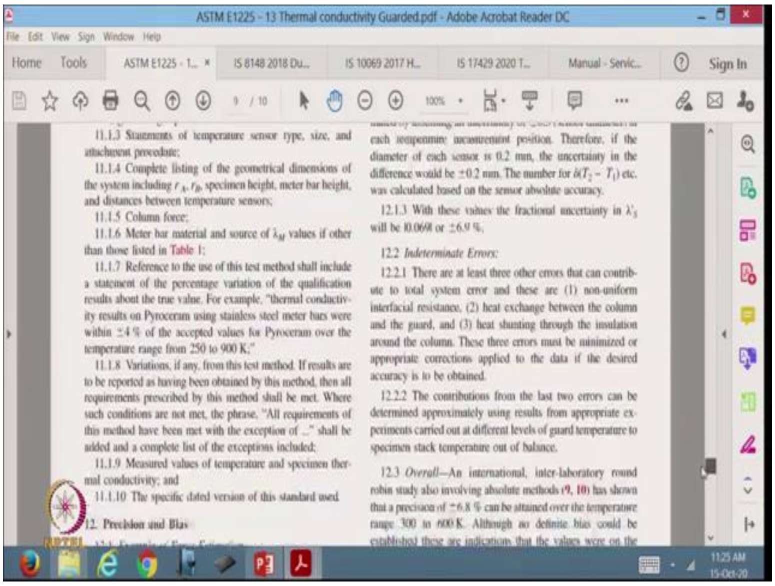

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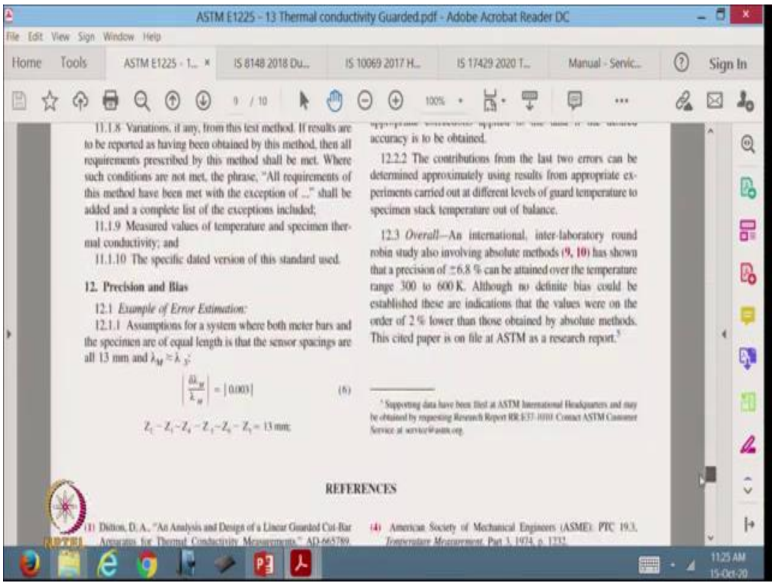

So, here it is, (report) how to make the report and finally, in the next section it says precision and bias. This is a slightly different terminology from what we will be using. Examples of error estimation, they have given the procedure of how to do it and then it says the maximum value of this by assuming an uncertainty of plus minus 0.5 and the number for the temperature difference was calculated on the basis of sensor absolute accuracy.

And then it says here in this section, with these values the fractional uncertainty in lambda which is the thermal conductivity will be this much or plus minus 6.9 percent. So, it is very explicitly telling us that if these were your dimensions this is how you had measured it, you would expect an uncertainty of this order of magnitude. So, that one example of why uncertainty analysis is so critical.

They also given something else here which says indeterminate errors and it says there are at least 3 other errors that can contribute to total system error, and these are non-uniform interfacial resistance, heat exchange between column, and the guard heat shunting through the insulation around the column.

So, it says that indeterminate means we know there is an error, but we do not have enough knowledge of how to quantify it. The only way we could do that is possibly do a numerical simulation of the whole system and establish the uncertainty from there. And, finally, it says after doing all of this what is the overall uncertainty and this is where this last para comes in and it tells you that the uncertainty is plus minus 6.8 percent in the range 300 to 600 K. OK; so this is one example.

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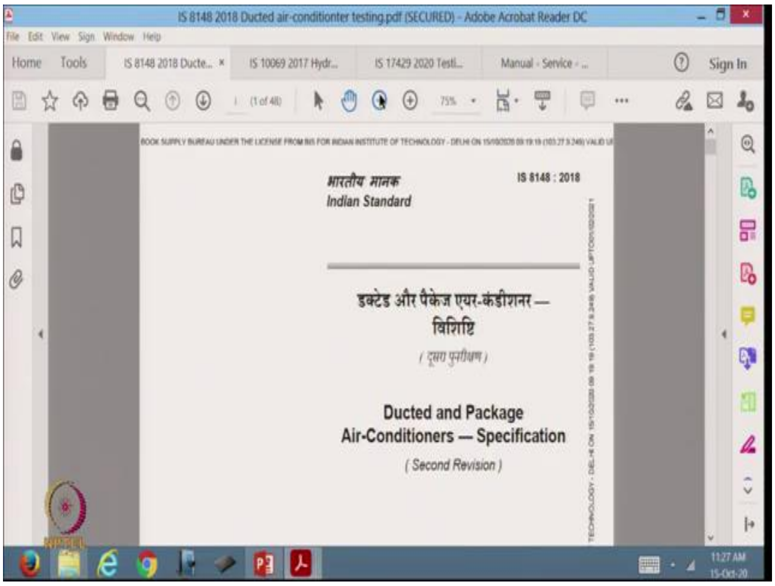

The second example is an Indian Standard IS 8148 – 2018 ducted and packaged air conditioners specification. All Indian standards are now freely available, and I encourage everyone to read these. So, let us see what this is? It is a fairly extensive document, and it tells you how to test an air conditioner.

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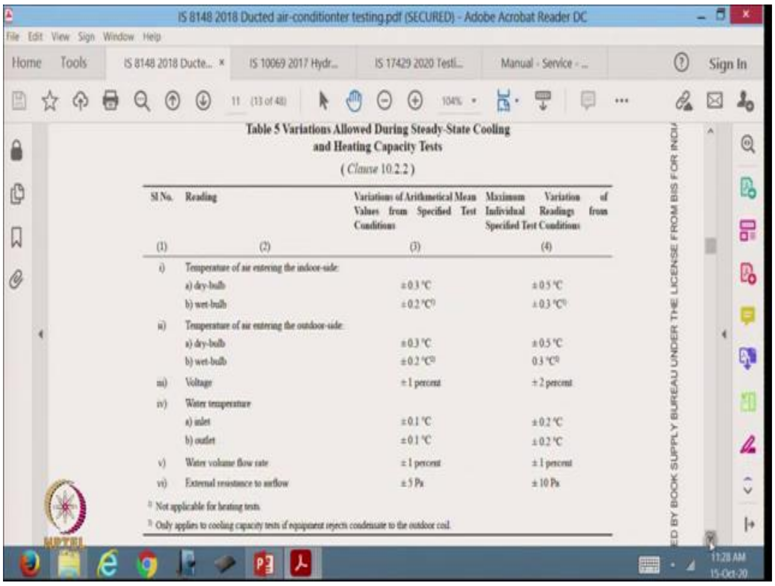

Table 5 Variations Allowed During Steady-State Cooling and Heating Capacity Tests

(*Clause* 10.2.2)

Sl No.	Reading	Variations of Arithmetical Mean Values from Specified Test Conditions	Maximum Variation of Individual Readings from Specified Test Conditions
(1)	(2)	(3)	(4)
i)	Temperature of air entering the indoor-side:		
	a) dry-bulb	±0.3 °C	±0.5 °C
	b) wet-bulb	±0.2 °C[1]	±0.3 °C[1]
ii)	Temperature of air entering the outdoor-side:		
	a) dry-bulb	±0.3 °C	±0.5 °C
	b) wet-bulb	±0.2 °C[2]	0.3 °C[2]
iii)	Voltage	±1 percent	±2 percent
iv)	Water temperature		
	a) inlet	±0.1 °C	±0.2 °C
	b) outlet	±0.1 °C	±0.2 °C
v)	Water volume flow rate	±1 percent	±1 percent
vi)	External resistance to airflow	±5 Pa	±10 Pa

[1] Not applicable for heating tests.

[2] Only applies to cooling capacity tests if equipment rejects condensate to the outdoor coil.

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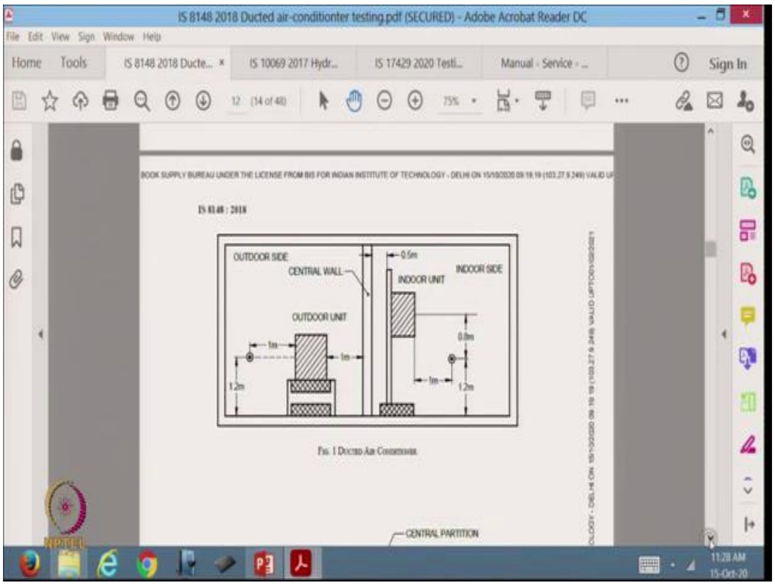

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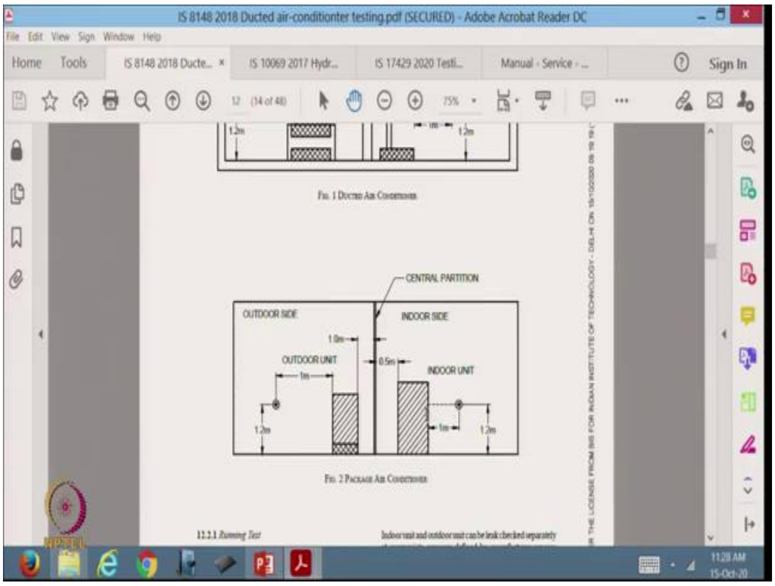

There are figures and then so that is one of the ways of putting (it) the system. So, there is a sketch which is given, some dimensions were given, where the instrument has to be placed. So, we do not have too much flexibility on that part.

But this is the table that we should be concerned about. And says during the experiment what are the variations allowed during steady state cooling and heating capacity test. So, temperature of air entering the indoor side the dry bulb temperature must be within plus minus 0.3 degree Celsius.

Wet bulb plus minus 0.2 degree Celsius, voltage plus minus 1 percent, and there is another maximum variation is given here which for a short period could be tolerated. Water temperature should be within plus minus 0.1 degree Celsius; outlet water temperature should be measured within plus minus 0.1 degree Celsius, water volume flow rate plus minus 1 percent, and external resistance to air flow plus minus 5 Pascal.

So, what we are seeing is these limits have been specified in how the experiment has to be done and what the numbers (may) themselves may not immediately strike to you as something very significant. Some of these numbers are very very stiff, they require very very careful measurement design of the experiment, only then you can achieve say what temperature measurement within plus minus 0.1 degree Celsius or what volume flow rate measurement within plus minus 1 percent.

These are very stringent requirements and require very high quality measurement, experiment setup design and experimental procedures all of which requires the understanding of uncertainty analysis. So, this was a second example I wanted to share with you.

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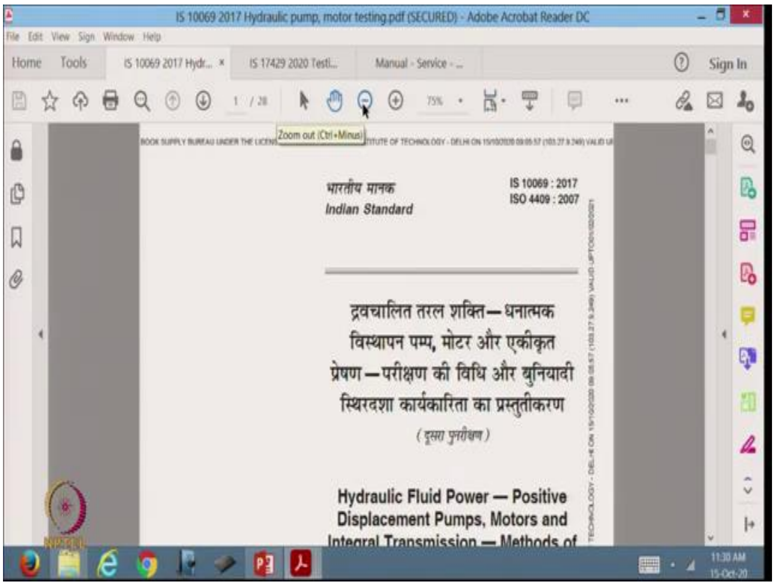

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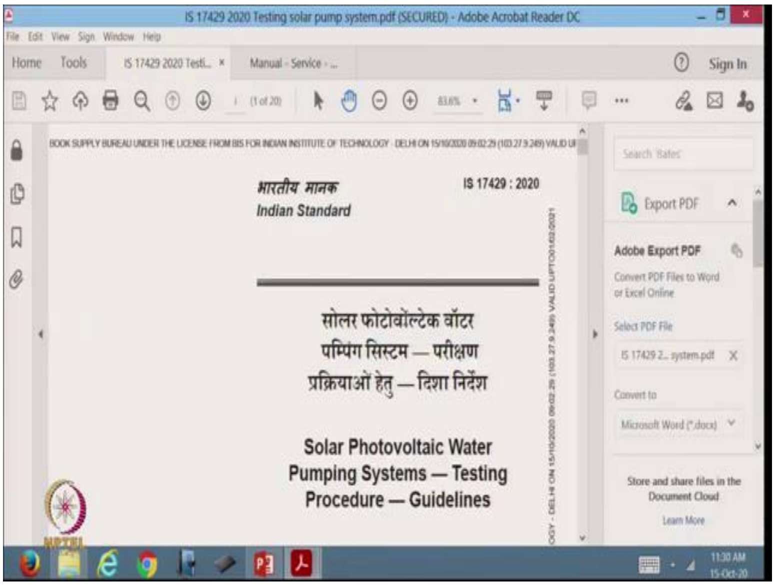

Third example, this one we will skip, I will not worry about this one yeah. There is a lot of talk and you would have seen in many places about solar operated pumps. So, this is Solar Photovoltaic Water Pumping Systems testing procedure and guidelines.

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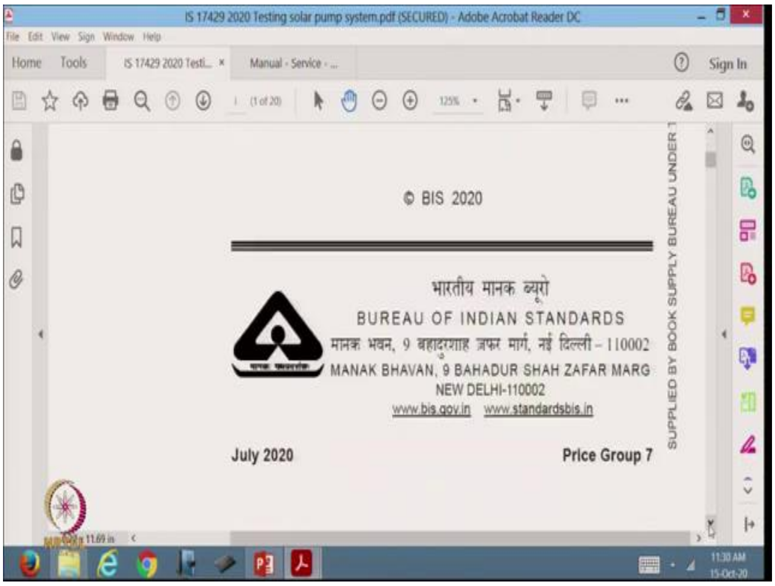

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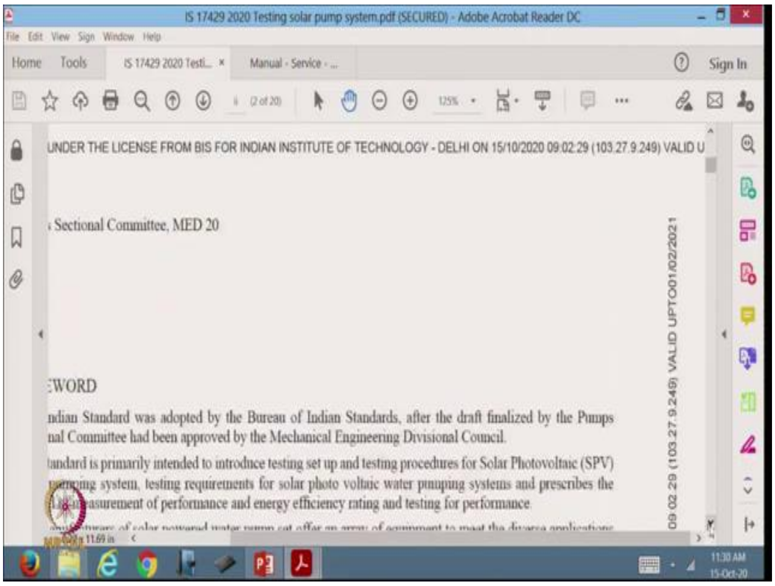

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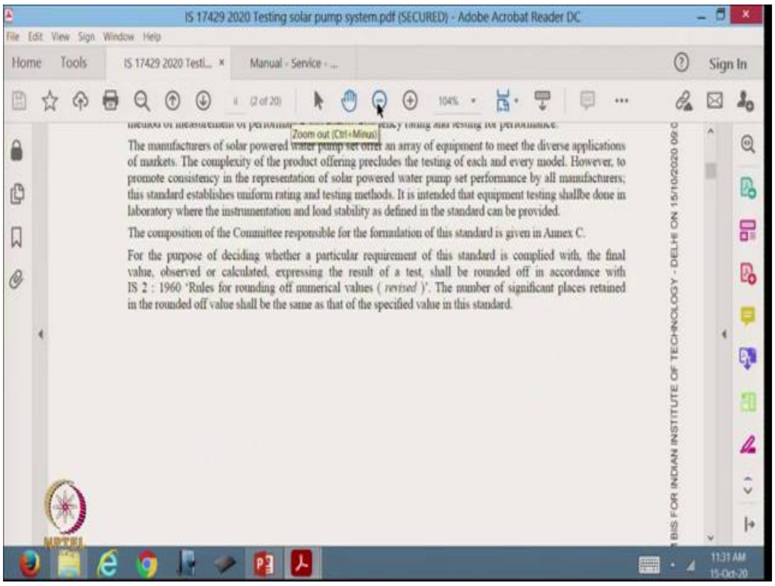

So, this has been made by the bureau of Indian Standards and this is; IS 17429 2020, very very recent actually current standard and it tells you how to test a solar powered water pump.

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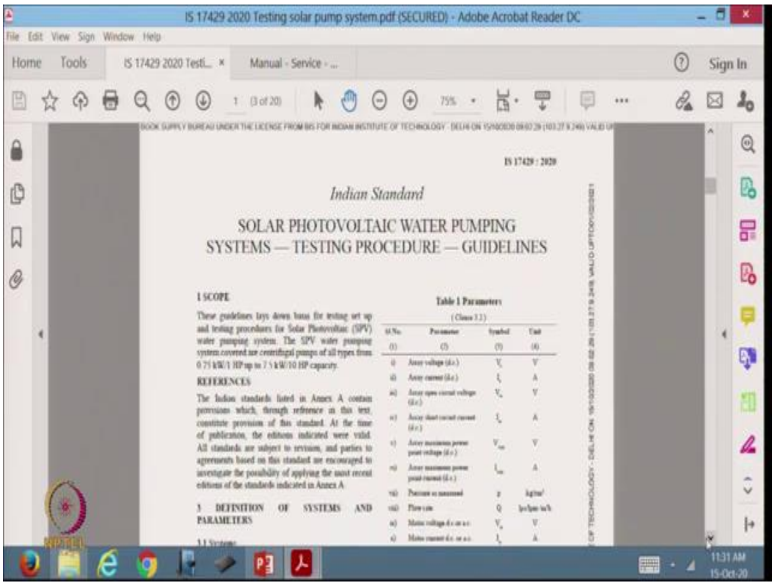

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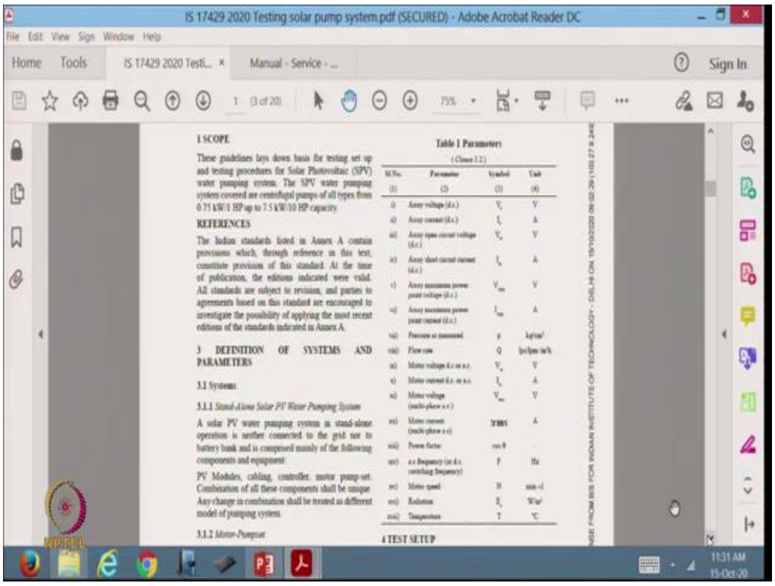

So, there is background information given about what we are doing. You can see here in this case they are saying what are the various parameters in the experiment some of these are measured some of these are calculated and see there are lots of them.

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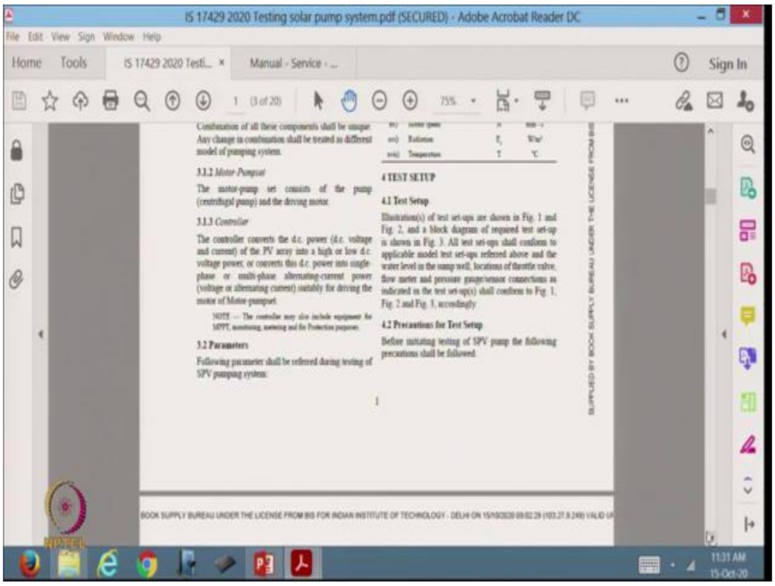

And then what type of a test setup should be there.

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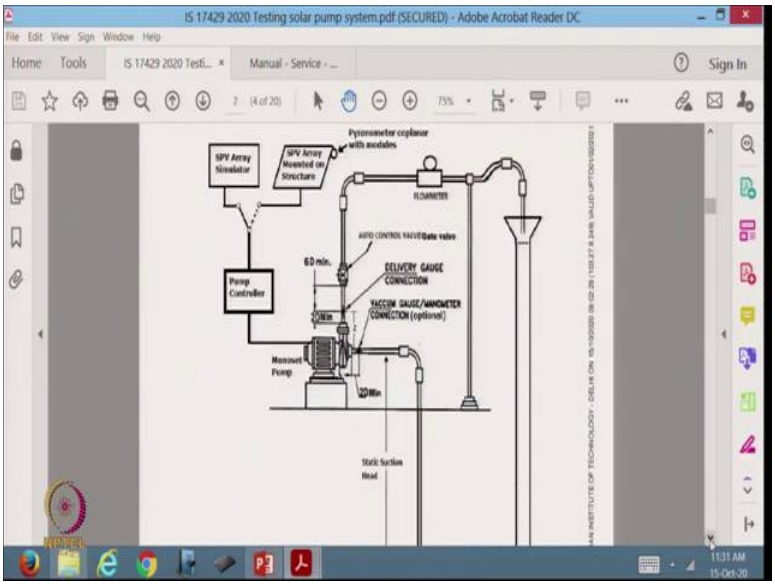

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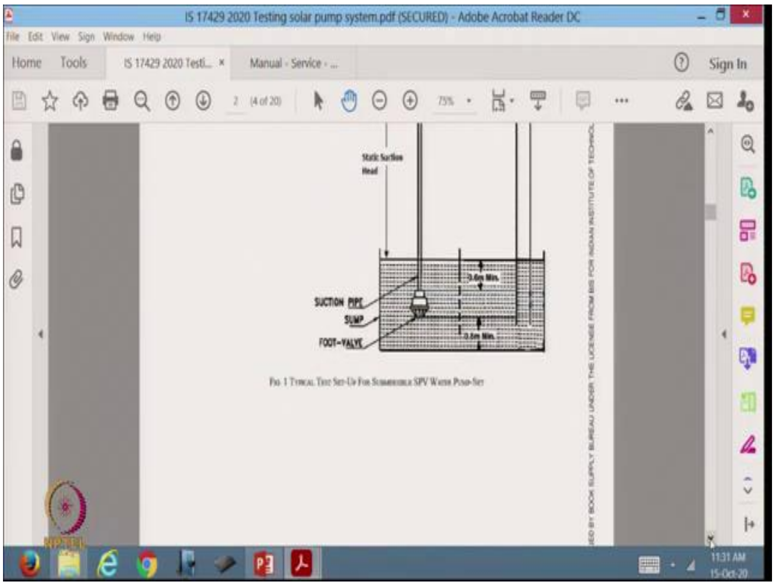

This is the general guidelines for putting it up. There is a sketch which says that right here in the middle we have the pump, the pump controller, solar photovoltaic array, the structure and here it picks up water from a tank below the pump, pumps it through some instrument, there is the flow meter and dumps it into back into the tank.

So, it has given (~~a~~) some broad guidelines that this distance should be 0.6 meters, this should be 0.5 meters, and what should be the size of the pipe, some of those are given there, the rest we have to decide. But that is a general idea of how to make the setup. And one of the reasons for showing this is to appreciate that when you design an experimental setup, a single apparatus or a involved system.

What you are seeing here is a relatively simple system, we make a nice picture a sketch, we start from there. So, this sketch is like a concept design of an experiment slightly more than that because some piece information is given here like what it should be this is diameter, what is this distance, what is this distance here like that.

And it is from here that we do the detailed engineering and say what is the length of this pipe that I should buy, what is the type of threaded connection I should have, how do I make this leak proof, what is the type of mounting that I need, all of that is the detail engineering design of the setup.

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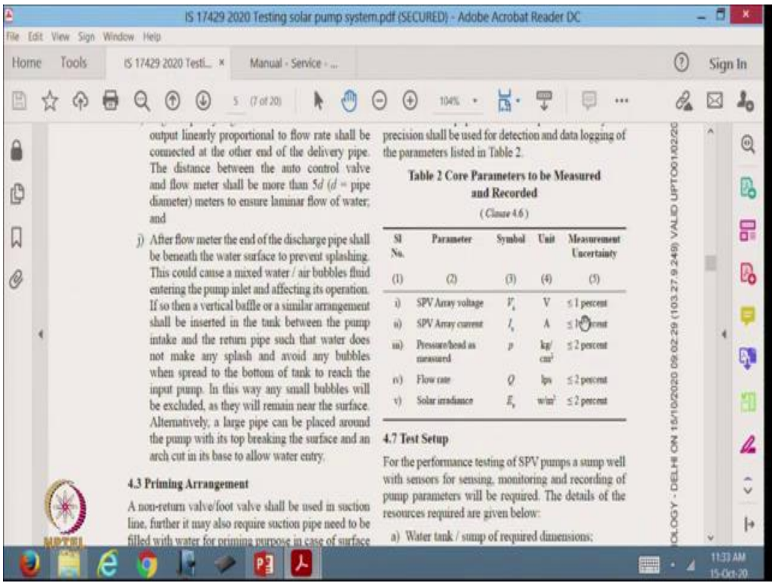

output linearly proportional to flow rate shall be connected at the other end of the delivery pipe. The distance between the auto control valve and flow meter shall be more than 5*d* (*d* = pipe diameter) meters to ensure laminar flow of water; and

j) After flow meter the end of the discharge pipe shall be beneath the water surface to prevent splashing. This could cause a mixed water / air bubbles fluid entering the pump inlet and affecting its operation. If so then a vertical baffle or a similar arrangement shall be inserted in the tank between the pump intake and the return pipe such that water does not make any splash and avoid any bubbles when spread to the bottom of tank to reach the input pump. In this way any small bubbles will be excluded, as they will remain near the surface. Alternatively, a large pipe can be placed around the pump with its top breaking the surface and an arch cut in its base to allow water entry.

4.3 Priming Arrangement

A non-return valve/foot valve shall be used in suction line, further it may also require suction pipe need to be filled with water for priming purpose in case of surface

precision shall be used for detection and data logging of the parameters listed in Table 2.

Table 2 Core Parameters to be Measured and Recorded

(*Clause* 4.6)

Sl No.	Parameter	Symbol	Unit	Measurement Uncertainty
(1)	(2)	(3)	(4)	(5)
i)	SPV Array voltage	V_s	V	≤ 1 percent
ii)	SPV Array current	I_s	A	≤ 1 percent
iii)	Pressure/head as measured	p	kg/cm²	≤ 2 percent
iv)	Flow rate	Q	lps	≤ 2 percent
v)	Solar irradiance	E_s	w/m²	≤ 2 percent

4.7 Test Setup

For the performance testing of SPV pumps a sump well with sensors for sensing, monitoring and recording of pump parameters will be required. The details of the resources required are given below:

a) Water tank / sump of required dimensions;

But this is something which is common to all experiments. Then here is the next thing that is (be) relevant to us. Table 2, core parameters to be measured and recorded. So, what does it tell us? SPV array voltage should have a measurement uncertainty less than or equal to 1 percent, SPV array current less than 1 percent pressure head as measured in kg per square centimeter. So, this is not SI unit but we should use bar or kilo Pascal.

This is plus minus less than plus minus 2 percent flow rate in litres per second, to be less than 2 percent. And solar irradiation this should be measured within plus minus 2 percent. So, here it is that this standard for solar powered water pump tells you that you have to measure these parameters from instruments and, finally, you have to have an uncertainty which is less than what is specified here.

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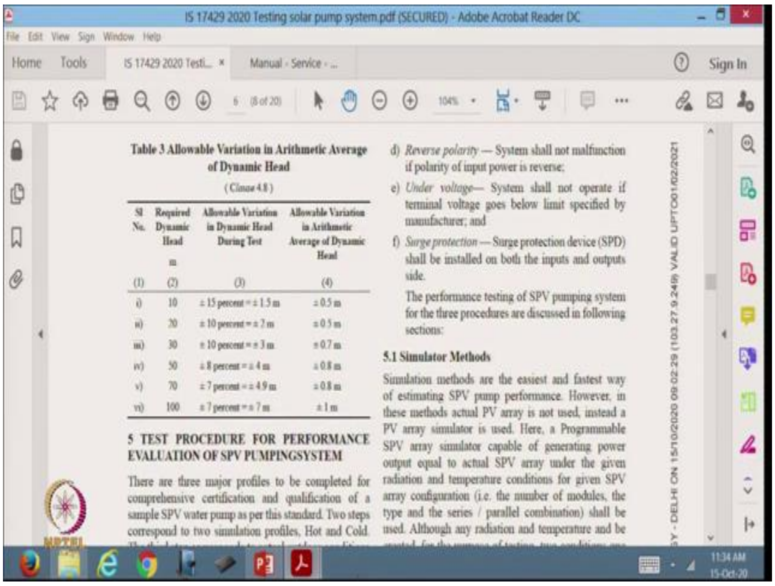

Table 3 Allowable Variation in Arithmetic Average of Dynamic Head

(Clause 4.8)

Sl No.	Required Dynamic Head m	Allowable Variation in Dynamic Head During Test	Allowable Variation in Arithmetic Average of Dynamic Head
(1)	(2)	(3)	(4)
i)	10	± 15 percent = ± 1.5 m	± 0.5 m
ii)	20	± 10 percent = ± 2 m	± 0.5 m
iii)	30	± 10 percent = ± 3 m	± 0.7 m
iv)	50	± 8 percent = ± 4 m	± 0.8 m
v)	70	± 7 percent = ± 4.9 m	± 0.8 m
vi)	100	± 7 percent = ± 7 m	± 1 m

5 TEST PROCEDURE FOR PERFORMANCE EVALUATION OF SPV PUMPINGSYSTEM

There are three major profiles to be completed for comprehensive certification and qualification of a sample SPV water pump as per this standard. Two steps correspond to two simulation profiles, Hot and Cold.

d) *Reverse polarity* — System shall not malfunction if polarity of input power is reverse;

e) *Under voltage*— System shall not operate if terminal voltage goes below limit specified by manufacturer; and

f) *Surge protection* — Surge protection device (SPD) shall be installed on both the inputs and outputs side.

The performance testing of SPV pumping system for the three procedures are discussed in following sections:

5.1 Simulator Methods

Simulation methods are the easiest and fastest way of estimating SPV pump performance. However, in these methods actual PV array is not used, instead a PV array simulator is used. Here, a Programmable SPV array simulator capable of generating power output equal to actual SPV array under the given radiation and temperature conditions for given SPV array configuration (i.e. the number of modules, the type and the series / parallel combination) shall be used. Although any radiation and temperature and be

Only then the result that you report for testing the pump that you have will be acceptable and will be meaningful. There is another table here which says allowable variation in arithmetic average of dynamic head that when you are setting up the apparatus how much variation is allowed.

So, it is a plus minus 15 percent, plus minus 7 percent, plus minus 8 percent, like that it is telling us. That means when you are designing the setup you have to have certain parameters within these limits as well.

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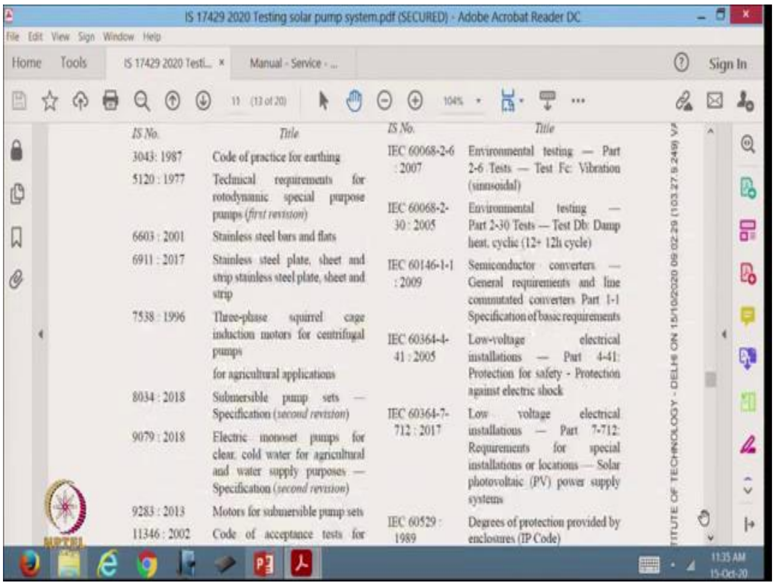

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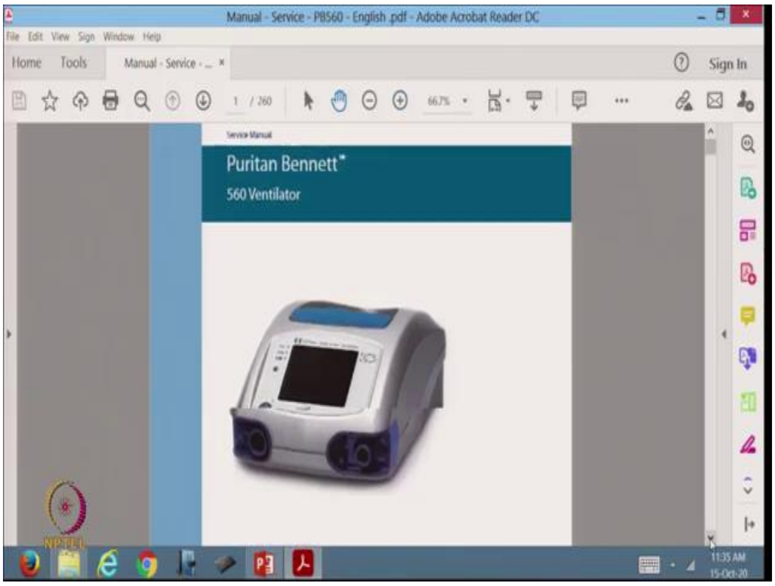

So, that is the third example, and finally we will close with one more example which is very hot topic for the last 6 months particularly since the beginning of (say) March or April. When the Covid 19 pandemic hit, our first concern was of course for ventilators and we thought that we would be needing very large number of ventilators based on experience in various other countries.

Looking at this as a humanitarian crisis, one of these companies in this case this is Medtronics, they made the complete design of one of their ventilators fully public, each and everything about this ventilator is public you can freely download it from the web and says if you want to make it, make it. And this is an excellent example of what an engineered product is it has got mechanical aspects, biomechanics is coming into it, instrumentation, measurement, electronics, reliability, all types of things are coming in.

It (is a) looks like a very simple device what you are seeing here is no bigger than say a toaster, but it is a very sophisticated instrument, and we have seen in the last few months how difficult it has been to make a reliable ventilator. But, if you go and look at the specifications of this ventilator, and of course there are many other companies whose ventilators compete in the market for similar purposes, (when we come down) and we say well (let us see) whatever has been given.

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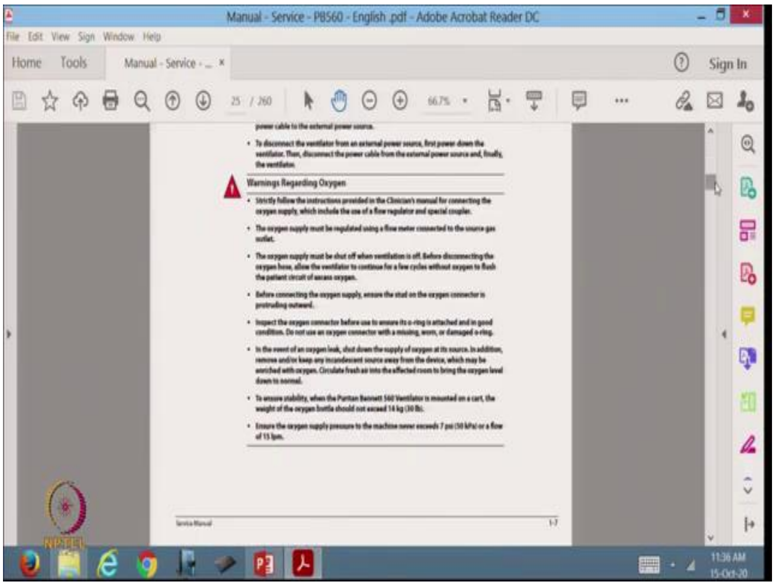

So there is a huge amount of information given and this is just one document I have picked up which is the service manual, and you can see here that this has got 260 pages. So, all of this has been written and with so many things like warnings regarding oxygen, will not worry about all of that.

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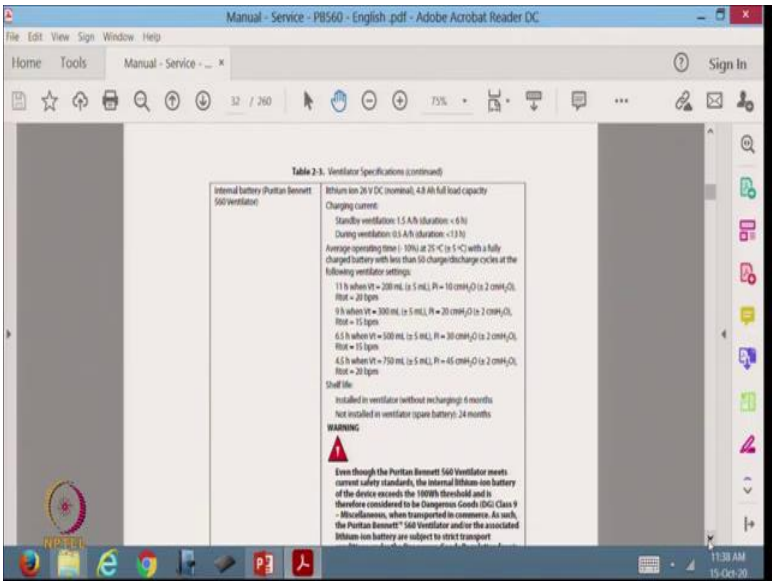

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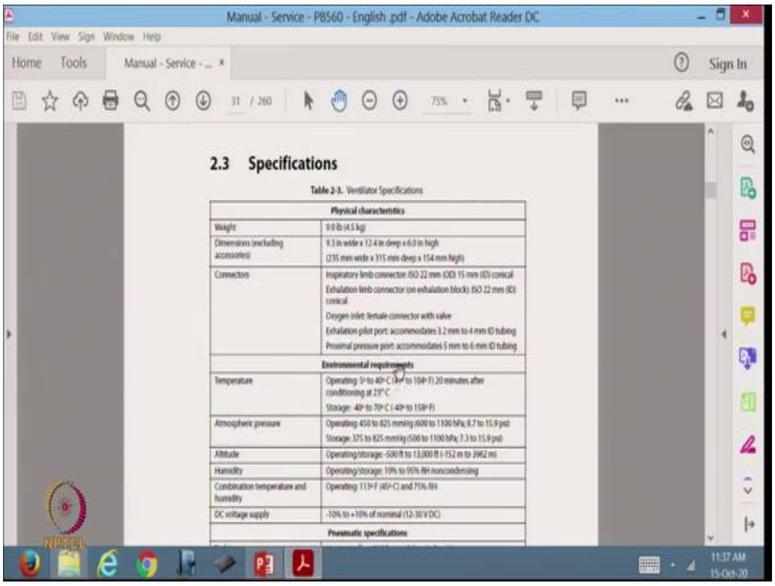

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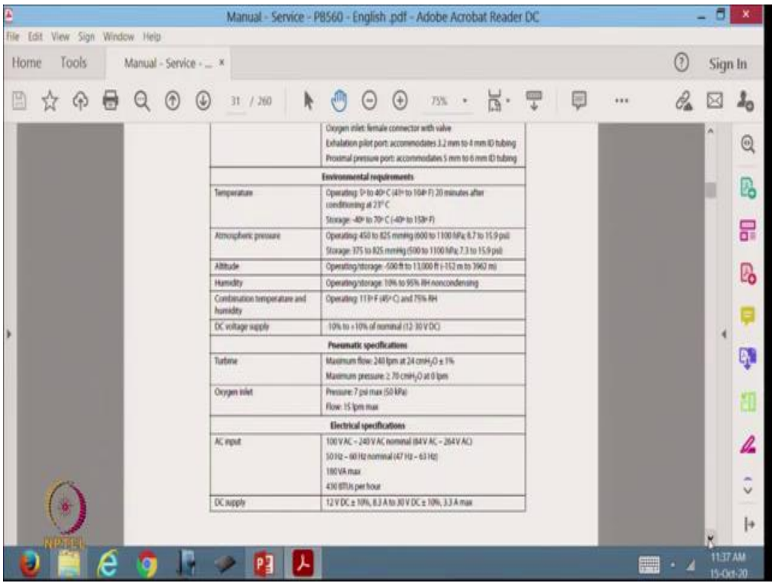

	Oxygen inlet: female connector with valve Exhalation pilot port: accommodates 3.2 mm to 4 mm ID tubing Proximal pressure port: accommodates 5 mm to 6 mm ID tubing
Environmental requirements	
Temperature	Operating: 5° to 40° C (41° to 104° F) 20 minutes after conditioning at 21° C Storage: -40° to 70° C (-40° to 158° F)
Atmospheric pressure	Operating: 450 to 825 mmHg (600 to 1100 hPa; 8.7 to 15.9 psi) Storage: 375 to 825 mmHg (500 to 1100 hPa; 7.3 to 15.9 psi)
Altitude	Operating/storage: -500 ft to 13,000 ft (-152 m to 3962 m)
Humidity	Operating/storage: 10% to 95% RH noncondensing
Combination temperature and humidity	Operating: 113° F (45° C) and 75% RH
DC voltage supply	-10% to +10% of nominal (12-30 V DC)
Pneumatic specifications	
Turbine	Maximum flow: 240 lpm at 24 cmH_2O ± 1% Maximum pressure: ≥ 70 cmH_2O at 0 lpm
Oxygen inlet	Pressure: 7 psi max (50 kPa) Flow: 15 lpm max
Electrical specifications	
AC input	100 V AC – 240 V AC nominal (84 V AC – 264 V AC) 50 Hz – 60 Hz nominal (47 Hz – 63 Hz) 180 VA max 430 BTUs per hour
DC supply	12 V DC ± 10%, 8.3 A to 30 V DC ± 10%, 3.3 A max

But we will come here, and this table gives us the specifications of the ventilator. This is all weight, dimensions, etcetera, environmental requirements, that is under what conditions it will work. And now pneumatic specifications that its got a turbine whose maximum flow rate is 240 lpm, litres per minute, at 24 centimeters of water column pressure plus minus 1 percent.

Maximum pressure is more than 70 centimeters of water at 0 litres per minute. So, when you have shut it off completely this is the pressure it gives. DC supply 12 volt DC plus minus 10 percent, 8.3 amperes to 30 volt DC plus minus 10 percent. So, it is (tell is) telling us how much power it will consume.

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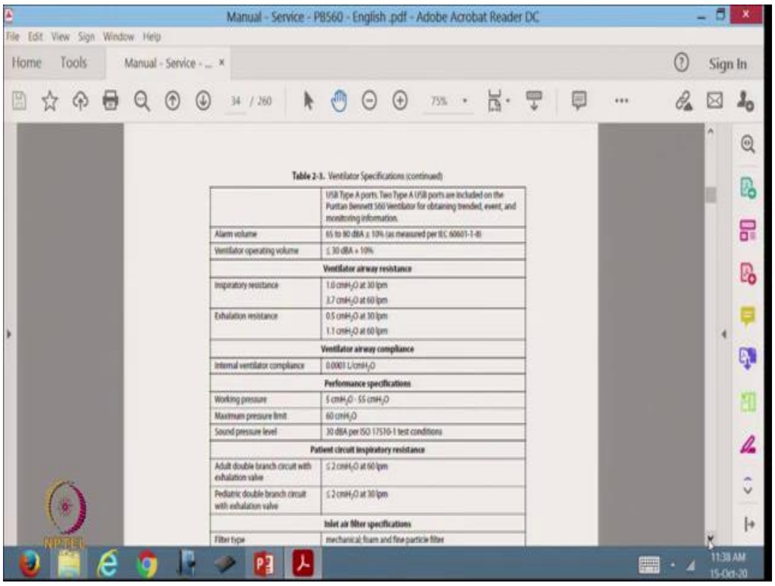

Then there are specifications on the internal battery of how many hours it will work and then there is specifications about what it does, it has to supply air or a mixture of air and oxygen and this is what it says. It gives out an alarm under some circumstances and it is 65 to 80 dBA plus minus 10 percent as per IEC 60601 dash 1 dash 8 standard.

So, it is not only telling you how (much the) loud the alarm is, but as per which standard that alarm is made, ventilator operating volume 30 dBA plus minus 10 percent. So, you do not want a ventilator that makes a lot of noise in an ICU, inspiratory resistance is this much, the range is given on this.

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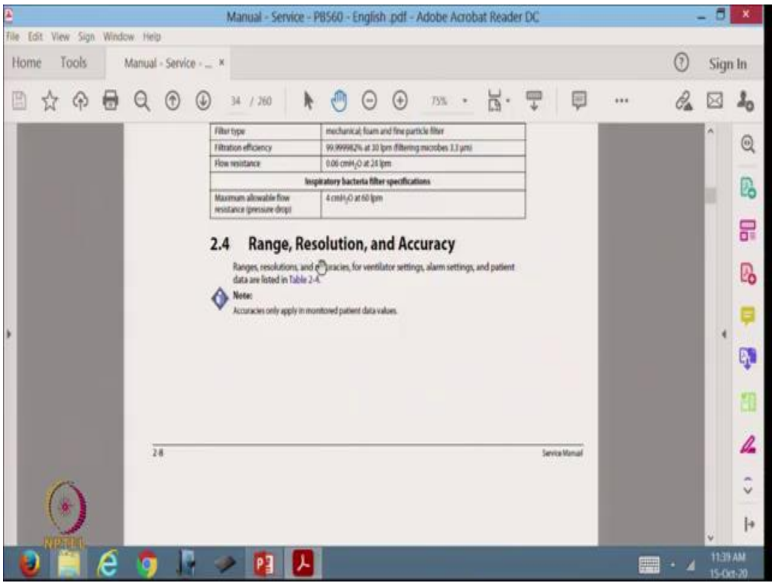

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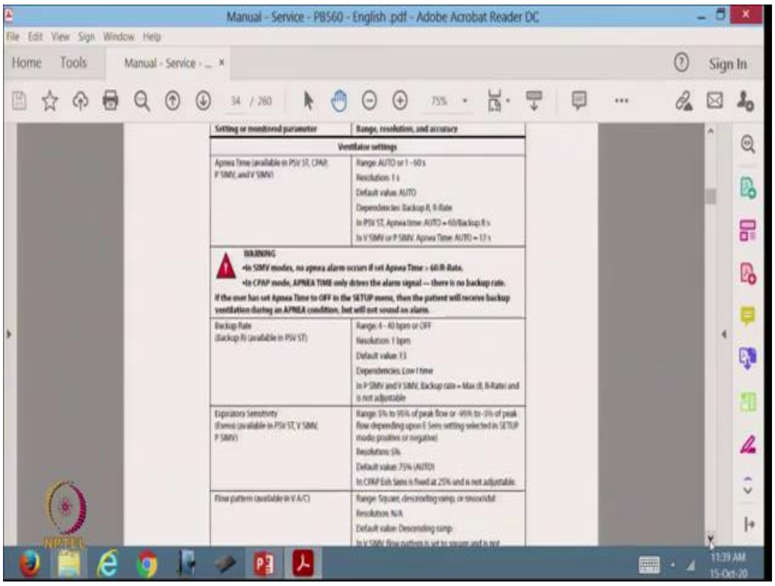

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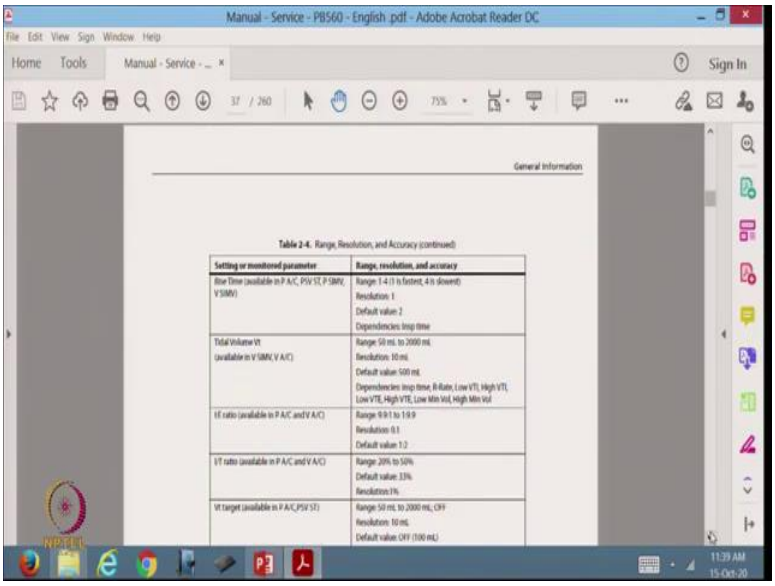

Then a whole section on range, resolution and accuracy so let us see what this is. These are various terms that are there in the use of ventilators. We look at a few of them say the second one, tidal volume VT which is the total amount of volume that the ventilator will push in one breath; it says 50 millilitres to 2000 millilitres we can set it with a resolution of 10 millilitres default value is 500 millilitres. So, here now we are coming across two parameters: range and resolution.

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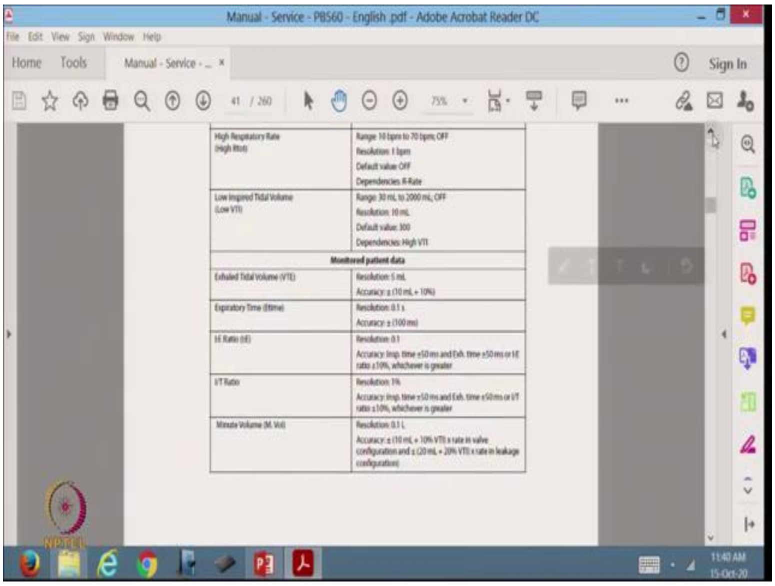

Then there are various things of how much time it takes for inspiration and expiration all of that is given there and then here is monitored patient data, exhale tidal volume resolution is 5 millilitres accuracy plus minus 10 millilitres plus 10 percent. Now what does this mean?

So, we will come to this later on when we look at instruments and how to characterize them. Expiration time; that is how much time the patient is expiring air expelling air the resolution is 0.1 second accuracy plus minus 100 milliseconds. The ratio of these two times resolution is 0.1 accuracy, inspiration time plus minus 50 milliseconds, expiration time plus minus 50 milliseconds, the ratio plus minus 10 percent or whichever is greater.

So, you can see that everything that they have said, what the ventilator can do and the treatment doctor can adjust or the nurse can adjust, they have given the range within which it can be adjusted what is its resolution and what is its accuracy.

This is very very important in the treatment because if your resolution is not good or your accuracy is very low, then when you are trying to set it for some value it will actually set it over a much larger range which actually you do not want it may endanger the health of the person.

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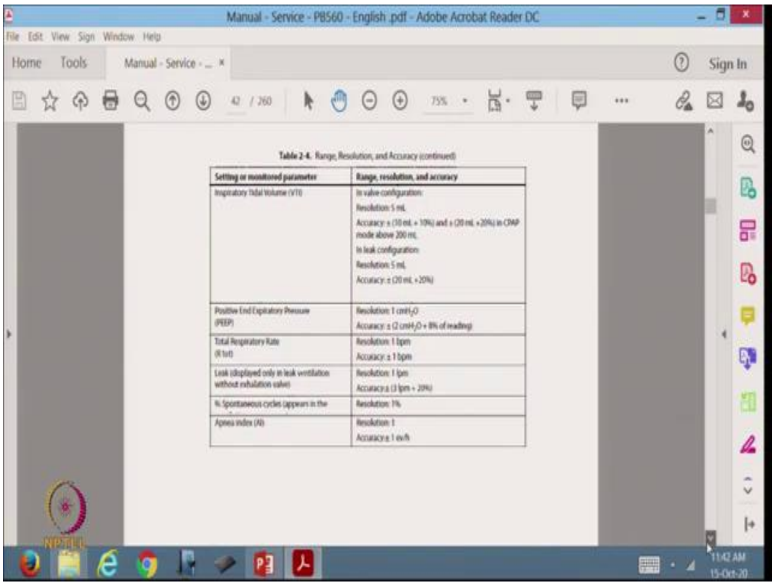

Table 2-4. Range, Resolution, and Accuracy (continued)

Setting or monitored parameter	Range, resolution, and accuracy
Inspiratory Tidal Volume (VTI)	In valve configuration: Resolution: 5 mL Accuracy: ± (10 mL + 10%) and ± (20 mL +20%) in CPAP mode above 200 mL In leak configuration: Resolution: 5 mL Accuracy: ± (20 mL +20%)
Positive End Expiratory Pressure (PEEP)	Resolution: 1 cmH_2O Accuracy: ± (2 cmH_2O + 8% of reading)
Total Respiratory Rate (R tot)	Resolution: 1 bpm Accuracy: ± 1 bpm
Leak (displayed only in leak ventilation without exhalation valve)	Resolution: 1 lpm Accuracy: ± (3 lpm + 20%)
% Spontaneous cycles (appears in the	Resolution: 1%
Apnea index (AI)	Resolution: 1 Accuracy: ± 1 ev/h

So, that here it is continuing on range, resolution and accuracy, you have positive end expiratory pressure, it says resolution 1 centimeter water accuracy plus minus 2 centimeter water plus 8 percent of reading. So, it is telling you what (is the how to get what) is the accuracy in that particular measurement.

Then total respiratory rate resolution 1 breath per minute accuracy plus minus 1 breath per minute. So, what is the rate at which it is able to measure how many times we breathe in and breathe out in a minute. Leak from the ventilator, resolution 1 litre per minute accuracy plus minus 3 litres per minute plus 20 percent.

So, (like) this is a very extensive document, do have a look at it will give you a good flavor for what engineering is all about and it tells you in the context of this course. Why this uncertainty accuracy resolution this is so very very important and that is what (in) this course we will learn, how to look at these things.

So, we come back, so those were some examples that I had given and now we come back, (to our) we have some more examples here.

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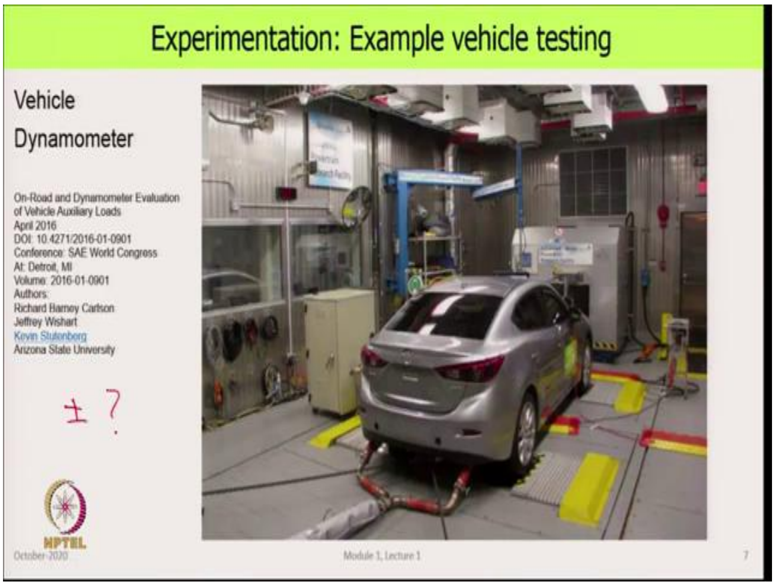

This is the example of a vehicle dynamometer, many students are fascinated by automobiles, but the way the automobile is actually tested is in a facility which you see in this picture this is taken from a website.

This is a very extensive facility and what you are measuring is, you run the vehicle (~~at a~~) in a particular way and measure its emissions you measure the fuel it consumes all of that. But in doing that everything on this facility is controlled very very tightly and within plus minus something.

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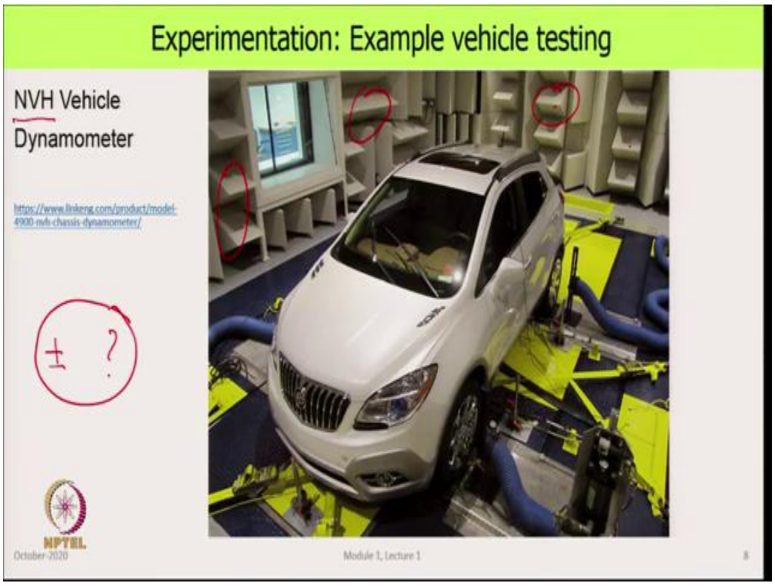

And that is how the testing of a vehicle is, something that by and large we cannot do unless we go to such a facility. The cost of putting up such a facility is like 10's of cores, to operate it costs a lot and if you want to get a testing done that will cost you a few lakh rupees.

So, that is what actually testing of an engine or a testing of a vehicle is all about, and what we do typically in a college experiment is a very crude way of trying to do it, the experiment test that actually means very little for certification purpose, for actually deciding how well your vehicle is performing manufacturers will go for this testing only and nothing else.

A slightly different type of a vehicle testing facility is the NVH dynamometer; here NVH stands for Noise, Vibration and Harshness. So, how much noise does the vehicle make, where does the noise of the vehicle come from, how can we minimize it; all of that. And what you see here is this vehicle along with a whole bunch of things on which it has been tied below, that it is sitting on drums which is like simulating the road condition there is road resistance then the aerodynamic resistance being created.

And what you see at the back are all these funny looking things here these are devices that absorb sound and so you can measure with instruments only the sound generated by the vehicle and not the reflected sound coming from the walls. This is an even more expensive facility, but then certification of a vehicle before it can come on the road requires it to be tested with all these type of things.

The reason for showing these two pictures is that this type of testing, if there is a facility here, what we are talking of an experiment it, is a very elaborate experiment setup, very intricate, very expensive, very sophisticated which normally an average person cannot use. But you can go take a vehicle get it tested and get the result out of it.

In all the result data that they give they will always tell you what is the plus minus uncertainty in that, and we should be able to interpret the meaning of that and whether we are happy with it or not.

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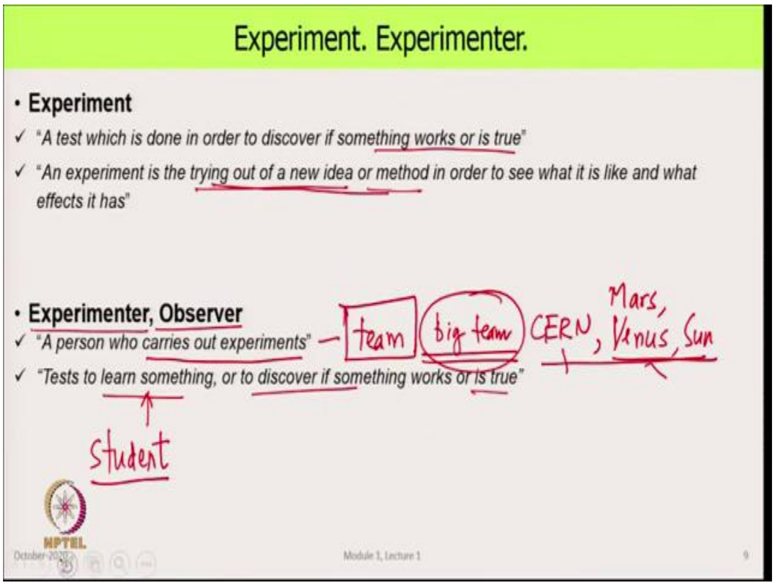

Now, we come to another few more definitions. First the definition of what is an experiment and we say an experiment is a test which is done in order who discover if something works or is true or just to collect data. That means, you are actually doing something with an idea that I want to know something about a particular thing. Another definition of the experiment is that experiment is the trying out of a new idea or a method in order to see what it is like and what effect it has.

So, this is a very broad definition and they are applicable to any field, it is not just that it is an engineering or mechanical engineering or civil engineering. This idea that trying out of a new idea could be anything, it could be health related, it could be medicine related it could be economics related anything is possible. So, the experiment in general these are the definitions.

In our case we will also look at what, who is an experimenter or an observer. So, an experimenter is a person who carries out the experiment very simple as that or an experiment is a person who tests something to learn something or to discover if something works or that something is true. So, learn something brings in the idea that we could be a student.

The second thing is although we say that the person who carries out an experiment if you only look at this part as to who carries out an experiment, it need not be only one person, it could usually be a team and in some cases it could be a very big team.

And a good example of a very big team is the nuclear research facility at CERN in Switzerland where there are literally thousands of physicists working together along with engineers computer scientists and everybody else to try to understand the basic composition of matter.

Another good very big complex experiment is or your space probes. So, there is a probe which has gone which is the probe that is gone to Venus which is orbiting Venus right now, there is a probe which is orbiting the sun they have very sophisticated instruments on that which are sending data; somebody designed those put them together. The data is coming back and now it is being made available to everybody that they can interpret and figure out and learn something more about these planets.

There is also a probe which is right now going around Mars and sending us to very lot of very interesting information. So, these are experiments, the vehicle testing I showed that is an experiment, it is not done by one individual by a done by a team, the vehicle dynamometer could have a team of 8 to 10 people, this has got a few 100 people who have to work together, this could be a few 100 to few 1000 people working together.

All of them have their own job to do and they do it and communicate with each other to make the experiment a success. So, a very important thing about whether you are a student, or a researcher is that to understand that experimentation and experiment usually involves working in teams. Teamwork is central to the process of experimentation. So, now we ask the question; why should I do an experiment?

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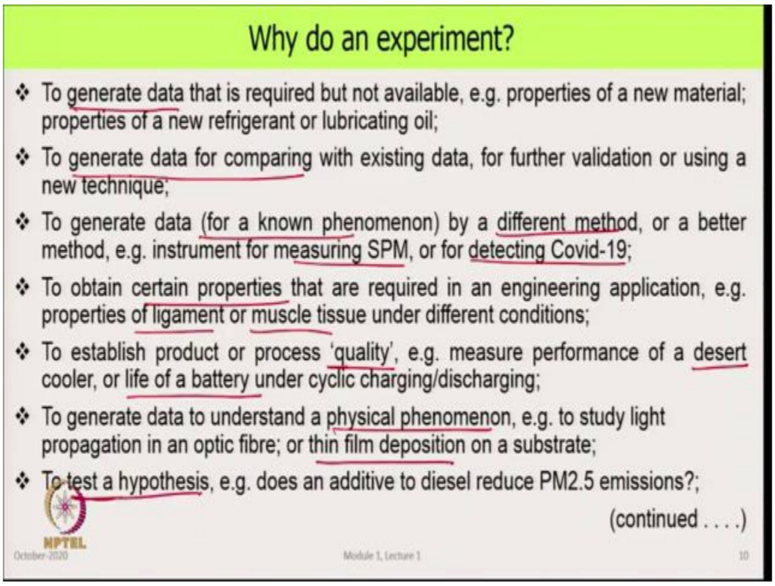

And here are some reasons that I have listed. We will quickly go through these. And first one it says I want to generate data which is a required but not available. For example, properties of a new material properties of a new refrigerant or a lubricating oil. Or I want to generate data for comparing with existing data or I want to generate data for a known phenomena by a different method.

For example, I want to develop a new technique for detecting Covid 19, or for measuring particulate matter in air or I want to obtain certain properties that are required in an engineering application. For example, properties of a ligament or muscle tissue under different conditions.

Or I want to establish the product or process quality. Say I want to quantify how good is a desert cooler or I want to design an experiment to tell me what is the life of a battery under different charging-discharging cycles. This is very important these days when you are talking of electric vehicles and lot of other things.

Or, I want to understand a physical phenomena. For example, I want to study light propagation in an optic fiber, or I want to study thin film deposition on a substrate or I want to test a hypothesis. For example, if I put an additive to the fuel, or if I make a biodiesel will it reduce emissions from a diesel engine? So, that is a question we are posing that we have a base case right now and we have a modified case, and we want to know relative to the base case do I have a better system or a worse system.

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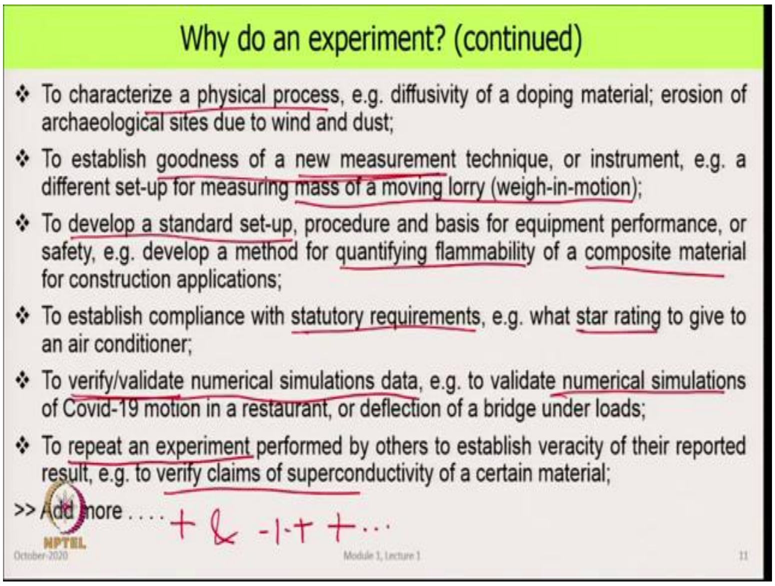

Other reasons for doing an experiment, we would like to characterize a physical process. For example, diffusivity of a doping material or I would like to know what is erosion of an archaeological site due to wind and dust, or we may like to establish the goodness of a new instrument measurement technique.

For example, we want to set up a device that will measure the mass of a lorry or the weight of a truck on the road without stopping the truck. Because we all know that on Indian road many of the trucks are overloaded and they cause a lot of accidents. So, can I make an instrument that will measure the truck as it is moving, a new instrument has to be designed and we need to establish whether how accurate the reading is compared to stationary mass of the truck.

Another reason for doing an experiment is that we want to develop a standard. For example, we have a composite material and we want to measure its flame resistance or fire resistance. So, I need to quantify the flammability of that material for use over there, or we may want to do an experiment to meet a certain statutory requirement.

For example, if you have an air conditioner or a refrigerator question is how many star rating should it be given and that can be done by doing an experiment. Another very important thing that we do frequently is to verify and validate numerical simulations data, this is particularly true of engineering and in many sciences also.

So for example, recently we have been looking at articles coming in which says that in (when) well ventilated places Covid 19 is less infectious, in close spaces Covid 19 is more infectious; well how do we verify that? Well somebody there are two ways to do it: one is we do a numerical simulation, which means that you solve the governing equations of that physical domain and figure out where the Covid 19 is going and where it stays ineffective.

And then make some measurements and say whether that is the case or not. So, that is where you do a verification and validation of a numerical simulation. And, finally there is one more reason that I have put is that if you have done an experiment which is very novel and reporting something for the first time, the community at large in the world will accept it only after they are able to repeat it and confirm your result.

So, that is another reason for repeating or doing an experiment, that you want to repeat it exactly as somebody else did whom you do not know, we want to do it again and to see whether that persons result and your result match. Then we can have more confidence in the conclusions that we get.

An example of that, what the claims of superconductivity of a certain material. And you can, to this you can all, add many more things, this is just a small representative list of why we do an experiment.

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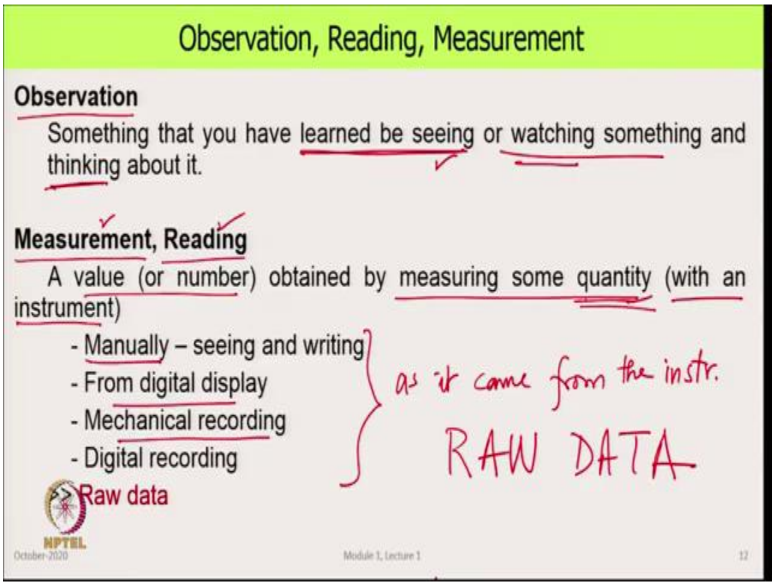

Now, every experiment we make a measurement and we have a reading, (we call) we define two things now, one is observation. That observation in general is not just that you have observed a reading and noted it down, but in general observation is something that you have learnt by seeing or watching something and thinking about it. And, this is the start of important things from which we learn lot of things.

A good example is the Plate Tectonic theory of the Earth's surface. A scientist, he observed various things of rock formations about seas about coast lines about mountains, and from there that is what he saw that is what he watched how it might have changed with time over thousands and millions of years. He thought about it and then said that the Earth's crust is made of a solidified surface which is moving all the time; that was seeing and watching.

Another good example is Professor S Chandrasekhar the Nobel laureate on going on a ship he saw stars and thought about it wondered about it and came up with a whole bunch of theory, so that is observation. So, it is not just about observing an instrument and recording the reading but observing anything.

What we are looking going to talk a lot about and use these words very frequently in the course is measurement and reading which is a very specific definition that measurement is a value or a number obtained by measuring some quantity usually and almost invariably with an instrument.

So, we have an instrument, we see it or we somehow record it and we get a number that represents a certain physical quantity. That is a measurement, or we call it the reading and in some cases we have call it an observation. So, but largely this is what it means a measured value all of these terms tell you that we have got a numerical value of a (some) quantity from an instrument.

How do we get that number? We could do it manually by looking at the instrument and noting it or digitally that the instrument displays a number in digital form, we record it or that it could be recorded in a mechanical way.

For example, if you see the ECG type of a chart it prints out something on a strip of paper and that is what you have these days of course, it is all electronic, or it could be digital recording that you make a reading it is recorded on a laptop, computer, cell phone somewhere then you open a file and see what numbers you got.

So, all of this is data as it came from the instrument, we did not do any manipulation to it, we did not do any calculations to it, it is just the way the instrument showed us what the value is and this is very very important for us in this course. This is what we call Raw Data. And in the experimentation process we will see the importance of this why it should be preserved. So, that you can later on come back and see what actually happened if something went wrong.

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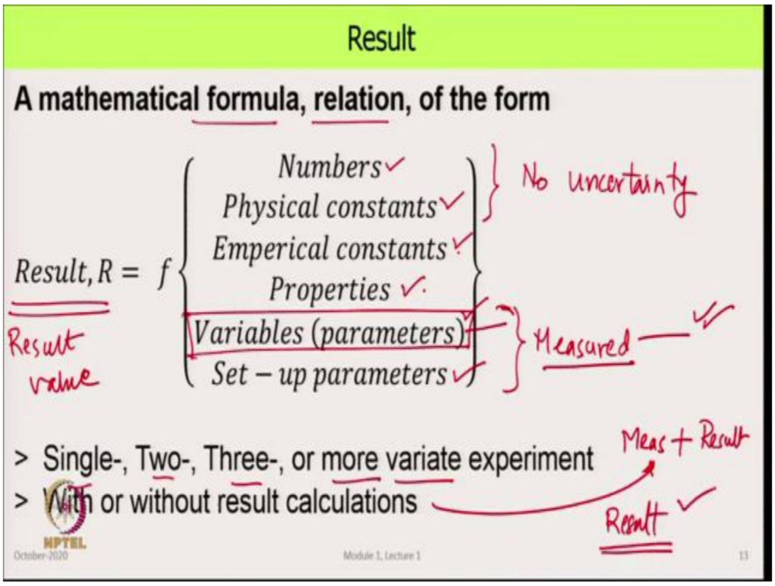

So, that is two definitions. A third definition is about we have talked yesterday about the result and the context of this course, a result is a mathematical formula or a mathematical relation which has got in its if the function of some numbers.

Physical constants, they do not change, (say) empirical constants which were obtained by some experiment and we put some numbers in it, some properties, properties of materials, and variables, this is what we measured.

So, this, what comes from the experiment setup parameters these are also measured, they are also coming from an experiment, but they do not change as frequently as these change.

So, both these are measurements, so they are coming, they (have) are coming with their own uncertainty. They may cause an uncertainty in this, maybe in this these two will generally say that there are there is no uncertainty and we will look at it little later in detail about these things.

So, we have this formula which has all these types of things we do a mathematical calculation. So, everything on the right side of the equation is known in the formula, the answer we get this is what we will call in this course the result, the result or the result value.

You could have an experiment where the number of variables could be single, two, three or more and these are single variate, two variate, bi variate, tri variate experiments and we could be using the data either directly as the measurement came which is these values. So, they are our reported data or it could be that we report measurements plus a result, and that is what this part is.

So, we could only report measurements, or we could report combination of measurements and results, or the third case we could only report the result(s). So, that is what we do with this type of an operation.

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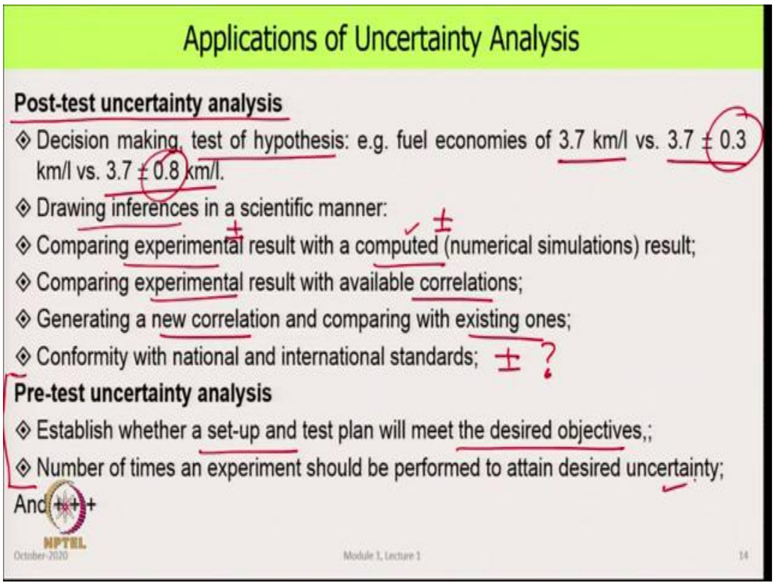

Now, we give some examples of application of uncertainty analysis beginning with post-test uncertainty analysis. So, in a decision making or test of hypothesis we get do an experiment and we get data that the fuel economy of a fleet is 3.7 kilometers per litre. But then the number does not make any sense because, we do not know the uncertainty and then somebody says I will tell you my uncertainty.

One person says it is 3.7 plus minus point 3 kilometers and the other says that I maintained the vehicle very well and then I did a similar test and I got a value of 3.7 plus minus 0.8 kilometers per litre. Now you begin to start seeing things, both of them would have reported 3.7, but now we have two things coming in here.

And the question is, is the second test superior to the first one? And that is where we got to start interpreting the plus minus numbers that are coming in. So, this is what we would call drawing inferences in a scientific manner, (we could all) we also need this uncertainty to compare experimental data with computed data, neither of them is exact that is the truth.

Even this data although it came from a computer calculation has plus minus uncertainty in it, experimental data as we are learning always (is) has got an uncertainty in it, it has always got errors. How do I compute two numbers both of which have different values of uncertainties?

We could also want to compare an experimental result with available correlations or we would like to generate a new correlation and comparing with existing ones or more, very important if we want a product to be certified according to a certain national or international standard, we will get a data plus minus something.

So, this is all post-test uncertainty; that means, we have done the experiment and now we are looking at how to interpret the data. What we have seen now is that there is also possibility of pre-test uncertainty, where we decide the by doing some quick elementary calculations whether the setup that we have will meet the desired objectives at all.

Or (where) whether you need to change an instrument and invest in some other type of an instrument. So, that is what is coming in over here.

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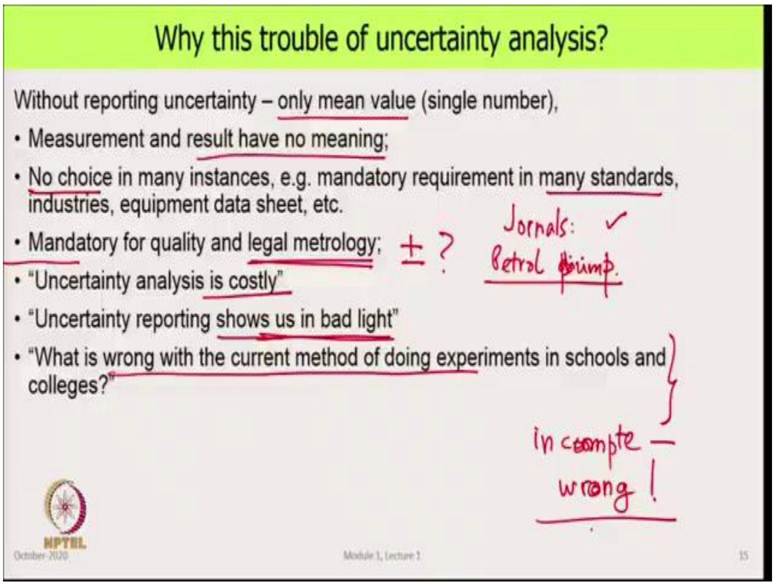

And, then many people ask why this nuisance of uncertainty analysis? Why are we taking this trouble of doing all this, what use is this? And, many arguments will be given for not doing an uncertainty analysis.

So, here are some of the arguments that we can look at, first and of course the most important thing from a scientific perspective is, if you do not report an uncertainty only a mean value, the measurement has no meaning, matter ends. Then in many instances like we saw standards just now, we do not have a choice – the standard says you must report the uncertainty. There are many instances where there are research journals which say that unless you report the uncertainty we will not publish your paper, there again it is mandatory.

In many applications it is a legal requirement, you have no choice; legal metrology, when you buy vegetables or any other material at a grocery store they have a weighing balance. That weighing balance is governed by the laws of India and if that balance does not confirm to those laws, the shopkeeper is likely to be prosecuted; that is legal metrology.

So, this is the requirement of that, there are standards which are notified further by laws, each one of these which tells that your measurement must be within plus minus so much percent; a very good example of the same thing is your petrol or diesel dispensing machine, pumps. When you fill petrol or diesel in your vehicle you think that you got 1 litre.

But the question is, it is not exactly 1 litre, how much is it? What does the law require that it is your right to get so much petrol? There is a limit on that.

Then there are three arguments that you would often hear uncertainty analysis is costly, we will see in this course that is not so, it is a little more of calculations and once you have appreciated what it is all about the benefits that come from it are very significant and the cost addition is not really that significant.

Another argument that comes is that if I show the uncertainty it shows us in bad light, there is no product or device is not very good, it is plus minus 10 percent. Well, that is reality we have to live with it and if somebody else product is plus minus 8 percent and yours are plus minus 10 percent, well that is the way it is.

It also tells you that when you improve your product and make it plus minus 7 percent. So, your product becomes better than the other product. So, it tells you it is not just that you look at it in a negative sense, but take it as a positive feedback as to where you should be going.

And this last question that I have put is in the context of education, schools and colleges, where in most cases we just report a number or plot points without showing the uncertainty bands. And this is how we have been teaching, we have been teaching it for so many years.

And so, some would say well what is wrong with the current method of doing experiments and teaching students? Well, the thing is that everything that we have been teaching here; if uncertainty analysis is not brought into the picture that education is grossly incomplete and in the practical context as we are learning it is practically wrong, something is badly missing. The idea of doing an experiment is not complete unless we appreciate the uncertainty associated with it.

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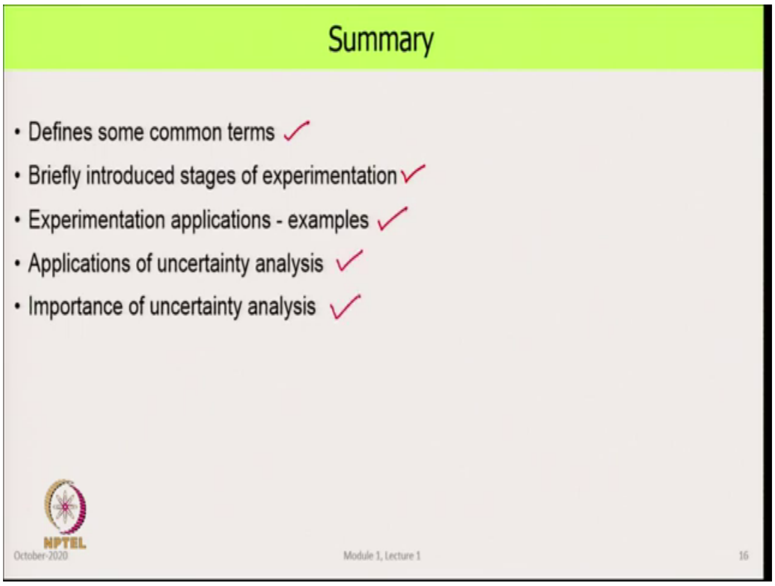

So, to conclude this lecture, what we have done today is we defined some common terms that we will be using throughout the course. We briefly introduced the stages of experimentation, few lectures later on we will come back to it in more detail.

We saw some examples of experimentation and we (look) appreciated something about the applications and importance of uncertainty analysis. So, this sets up the stage for our next part, where we will start looking at the systematic way of finding out the whole process of doing uncertainty analysis and reporting a result.

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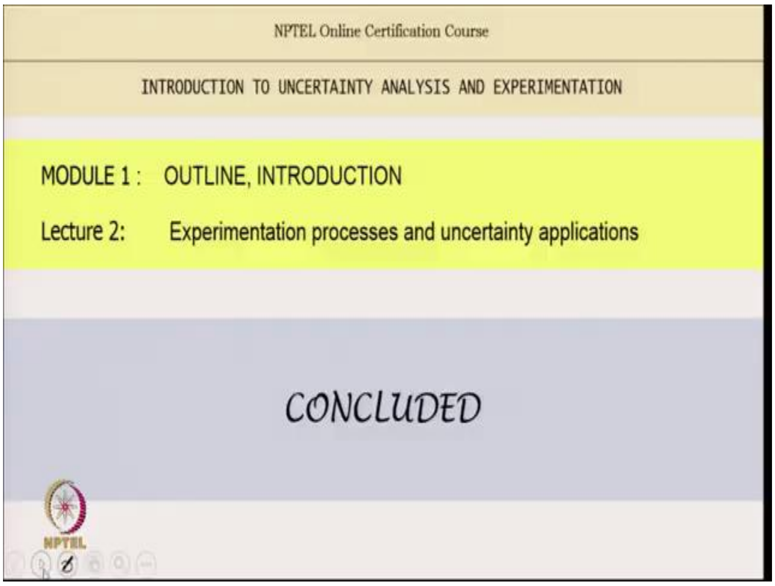

So, with that we conclude the second lecture of the first module which is on experimentation processes and uncertainty applications.

Thank you.