Introduction to Uncertainty Analysis and Experimentation
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Module - 01
Outline, Introduction
Lecture - 03
Developments in uncertainty analysis. Approach

Welcome to this course, we are now in the third lecture of the first module which is Outline and Introduction. In this lecture, we will look at developments in uncertainty analysis and the Approach that we will follow in this course and how the two are connected.

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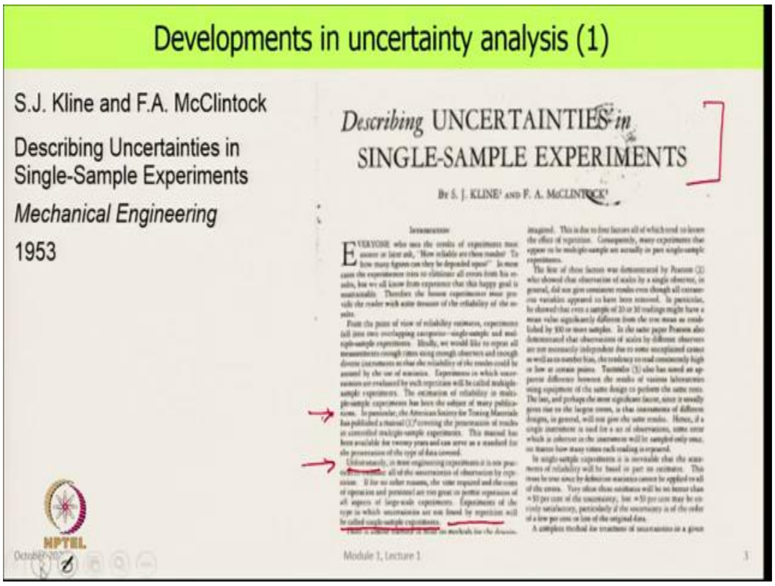

The history of errors and uncertainties goes back about 100 years, but those were isolated cases where experimenters and researchers tried to find out what is the error and made their own theory to report that error.

It was in 1953, that one of the seminal papers on uncertainty analysis was put out and this is what the title was "Describing uncertainties in single sample experiments". The authors of this paper were professors S. J. Kline and F. A McClintock and this was published in the journal Mechanical Engineering way back in 1953. This paper became a sort of a major starting point for scientists and engineers to seriously look at uncertainty.

And since then, there have been a lot of improvements, changes, modifications and now we have reached a point where we have a reasonably stable methodology for doing uncertainty analysis; which is uniform across the world and everybody interprets a result in the same way.

I will read out one paragraph from this, and this is here this article is freely available on the net. And it says, here in particular, the American Society for Testing Materials has published a (material a) manual covering the presentation of results in controlled multiple sample experiments. This manual has been available for 20 years and can serve as the standard for the presentation of the type of data covered.

Unfortunately, in most engineering experiments, it is not the practice to calculate all the uncertainties of observations by repetition. If for no other reason, the time required and the costs of operation and personnel are too great to permit repetition of all the aspects of large-scale experiments, experiments of the type in which uncertainties are not formed by repetition will be called single sample experiments. So, this gave a definition of single sample experiments and also established the methodology to do the calculation.

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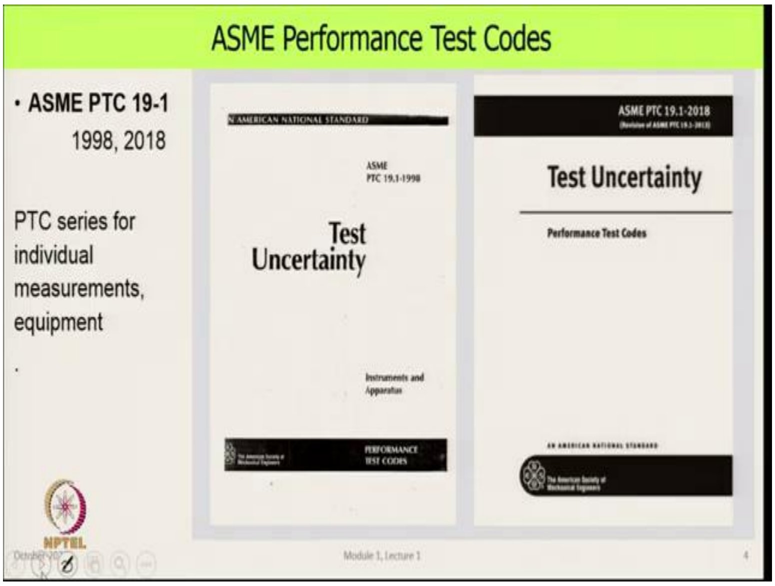

After many advances on uncertainty research the American Society of Mechanical Engineers came out in 1998; with the standard called PTC 19.1 which is the Performance Test Codes. ASME already had several test codes for equipment like boilers, turbines, feed water heaters, condensers pumps, heat exchangers.

But until then uncertainty was not as tightly coupled into the testing process or the measurement process or the design process. This standard the front page of which I have displayed here this came out in 1998, this one and it gave both type of instruments and method methodology for doing uncertainty analysis.

This got updated and there is a very recent version of this PTC 19.1 2018 which says test uncertainty performance test codes. Now 19.1 between 1998 and 2018, in these 20 years, lot of changes took place and finally, diverging opinions in different parts of the world by researchers and academicians converge to a fairly uniform approach.

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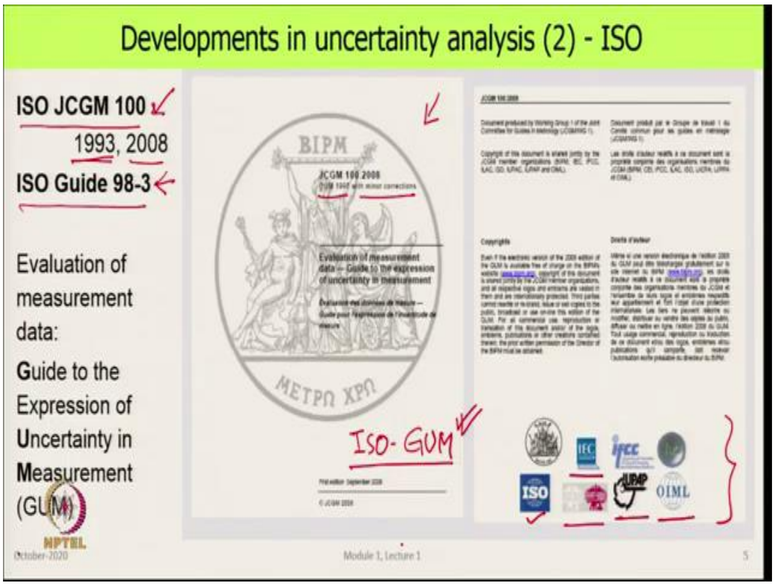

One of the approaches that was different from the ASTM, ASME approach was happening with the ISO the International Standards Organization. They approached the issue of uncertainty in a slightly different way and finally, in 1993 they came up with a document called JCGM 100 whose front page is shown over here. This is the revision which were there in 2008 and it says it is GUM 1995 with minor corrections.

The title of this is “Evaluation of Measurement Data: Guide to the Expression of Uncertainty in Measurement” and so, it is very popularly and frequently referred to as GUM in the notes and in the lectures we will repeatedly refer to this as ISO GUM. So, this standard is much more extensive, expansive, it goes into the statistical basis in a more rigorous way and tells us how to express uncertainty in a measurement. Nevertheless, there is a slight difference between PTC 19.1 and JCGM 100.

We will come to that when we look at the lectures on uncertainty, these differences were large until about 1993 and subsequently ISO, ASME and other experimenters across the world got together and said let us have one uniform system and let us harmonize our standards. JCGM 100 is freely downloadable from the web you can get it; it is also published as ISO Guide 98 dash 3. The (document is) two documents are exactly identical you can read either of them.

In literature there are some places where they refer to JCGM 100 many others where they refer to it as ISO Guide 98 dash 3, both are the same. The difference of ISO was that it brought together many different professional organizations across many disciplines; because uncertainty analysis is not one discipline specific like we may think that ASME was for mechanical engineering, but it is universal and no field no experimentation is exempt from uncertainty. So, they brought together in an umbrella a bunch of organizations which are listed over here, this is the second and third page of this document.

And this ISO, its own offices were there, who were coordinating it that is this ISO here, but they got together another very large major standards organization called IEC which is the International Electro Technical Commission. This IEC puts out standards related to any aspect of electrical, electronics, communication engineering, whether it is a power supply, whether it is your Bluetooth, or whether it is your USB, they are all as per some IEC standard.

This is again a fairly established 50 year old standards body and the whole world of electrical electronics is governed by their standards. Then they brought in IFCC, ILA, IUPAP which is International Union of Pure and Applied Physics, IUPAC which is International Union of Pure and Applied Chemistry, and a very large organization called OIML which is International Organization for Legal Metrology.

So, all of them came together they all agreed on some things and the document that came out was this – is the ISO GUM. In more than one way this became the established norm for all international practice and gradually ASME PTC 19.1 got harmonized with it and today PTC 19.1 and JCGM 100 or ISO GUM they are practically identical.

So, we now have a consistent methodology for doing uncertainty analysis. This was not the case 30, 40, 50 years back and if you look up the literature you will find somebody is reporting the uncertainty in some way somebody is reporting the uncertainty in some other way, their interpretations were off and so, there were a lot of things going on between them.

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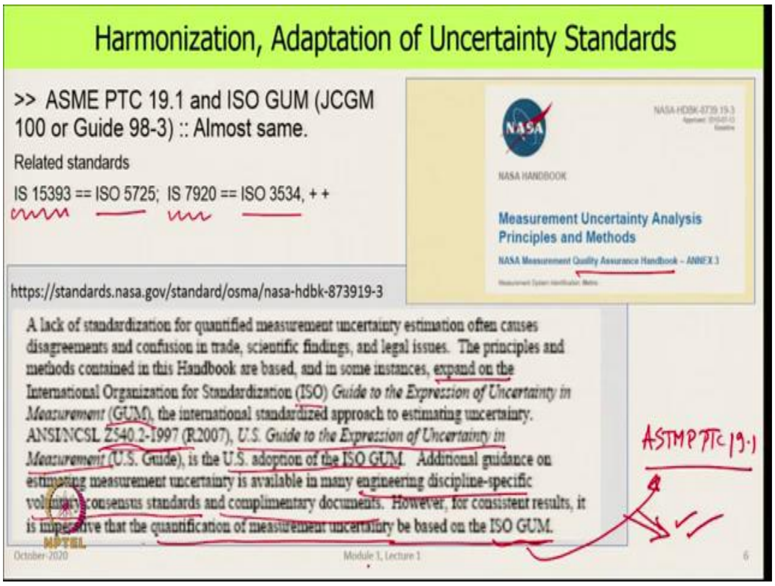

So, this is where we are now. Once ISO GUM became established as the international standard, lot of organizations started upgrading adopting it, changing their standards and wherever they had their own standard they harmonized it with ISO GUM.

One of the major changes that happened, I am putting here, this is a document from NASA and they have come out with a series of volumes where they upgraded their complete quality assurance test and this is their measurement quality assurance handbook. This is again freely available on the web I encourage you to read it and I picked out a little paragraph from the preface to the standard.

It says “A lack of standardization for quantified measurement uncertainty estimation often causes disagreements and confusion in trade, scientific findings and legal issues. The principles and methods contained in this handbook are based and in some instances expand on the International Organization for Standardization ISO Guide to the Expression of Uncertainty in Measurement GUM.

The international standardized approach to estimating uncertainty another standard which they have said here ANSI American National Standard Institute this particular standard 2007 which is the US Guide to the Expression of Uncertainty in Measurement is the US adoption of ISO GUM.

Additional guidance on estimating measurement uncertainty is available in many engineering specific, voluntary consensus standards and complementary documents. However, for consistent results it is imperative that the quantification of measurement uncertainty be based on the ISO GUM. So, this in a nutshell very crisply captures the spirit of ISO GUM and how everyone has undergone a change and finally, adopted it.

This is the case with India also, that ISO GUM has been adopted by as Indian Standards there are related standards which I have cited here ISO 5725 and ISO 3534, these are available as Indian Standard 15393 and this has Indian Standard 7920; they give various aspects of GUM and it is practically the same as the JCGM 100 ISO GUM.

And as this says this particular standard Z542 0 standard this is also pretty much similar to ASME PTC 19.1 which has been harmonized with ISO GUM. So, this is the process that we will follow in this course and learn how to do uncertainty analysis.

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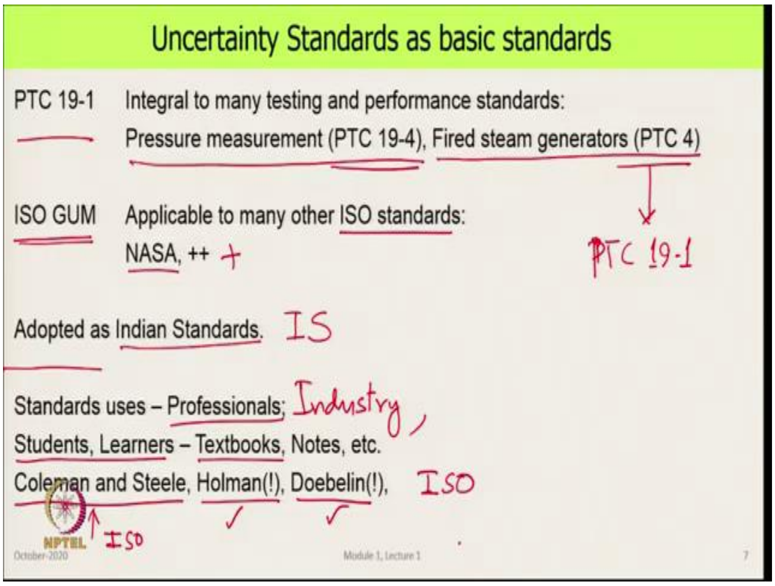

What has happened is that these standards PTC 19.1 or the ANSI standard there, or the ISO GUM, they have become like mother standards for a whole lot of other engineering scientific activity. For example, PTC 19.1 which deals only with test uncertainty and how to do uncertainty calculations has many other sister standards for example, for pressure measurement there is the standard PTC 19 dash 4.

So, if you are teaching somebody how to measure pressure this is the place to go. There are a series of other standards in ASME for example, there is fired steam generators PTC 4 which is basically boilers. Similarly, there are about 25 standards in the PTC family and what has happened is, each one of these finally, incorporates in it PTC 19.1 and says how to do the experiment, how to report the uncertainty only then your testing is acceptable and it is meaningful.

Same thing with ISO GUM. I gave the example of NASA in the previous slide, there are many more things including almost all ISO standards which deal with several things all of them say that wherever there is the measurement done, wherever there is an uncertainty where is the interpretation of a measurement you shall follow ISO GUM.

India is a member of ISO and we have adopted many of these as Indian Standards which are designated as IS. So, sometimes in our notes I have referred to as IS somewhere ISO GUM somewhere PTC 19.1 the specific things which are slightly just I am referring to but at the base of it all of these are the same. What these standards have done and why we have to do that in this course is that, these standards are used by professionals, by industry and in today's world no matter what you make what you design there are lot of standards that govern it.

And so, you have to be aware of that and see that wherever there is a quality issue, a measurement issue, uncertainty issue this is where you have to start. So, to be able to use it, both in industry, engineers and scientists (you) need to learn this uncertainty analysis. And this is also the case for students who if you want to be immediately employable and be able to work with industry, you have to learn these standards.

The difficulty is, so far has been that there have been very few text books for example, there is a chapter on uncertainty in these two books which are widely used. The latest edition of J. P. Holman or the measurement book by E. O. Doebelin, these have been standard text for many years in most engineering colleges; but they are old and they are not harmonized with the ISO's process that is a drawback of these books.

Among the more recent ones which has tried to bridge that gap is this book which has come out a few years back which is authored by Professors Coleman and Steele and this book is essentially telling you how to do uncertainty analysis with ISO OK. So, that is with the textbook by Coleman and Steele; the reason I have made these notes and this course is that there are certain aspects in Coleman and Steele which are easy to understand there are others which are a little tricky.

I have adopted ISO largely selectively from PTC 19.1 and presented the entire material in a slightly different format which is relatively easy to understand.

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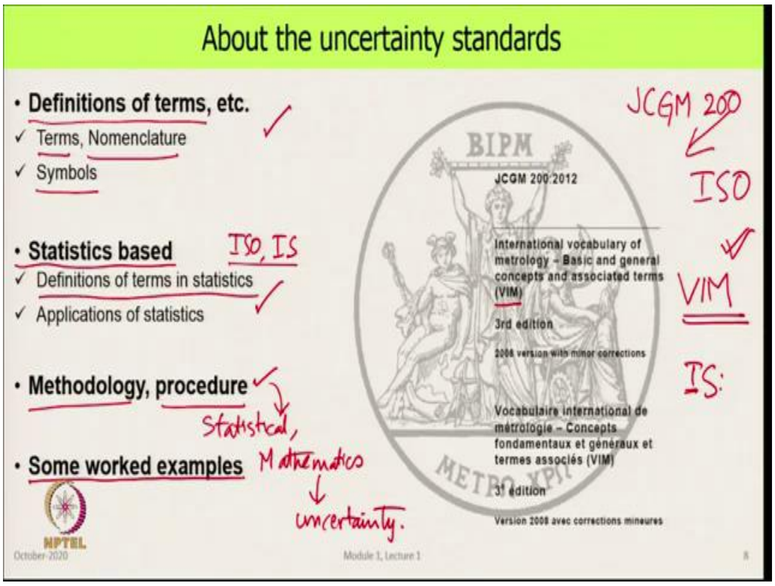

So, that is how we have come where we are. All these standards including any other standard that you look at has one fundamental aspect that it begins with the definition of terms, that words, that we use they have to be fairly precise.

So, they are terms or nomenclature, and even symbols, these are defined very precisely and the guiding document for that was put back few years ago and it is the front page of that I have displayed here this is your JCGM 200. Again this is an ISO document also available as a guide and the title of this is International Vocabulary of Metrology.

Now, metrology is, in general, all measurements and basic and general concepts and associated terms. So, this is your vocabulary of meteorology and this is referred to in many places as ISO VIM or just V I M; VIM. This document is also freely available it can be downloaded and all of that has also been made into an equivalent Indian Standard, this is freely available and we will use this.

What it does is that there are many terms that are used in experimental work and in measurements for example, what is accuracy, what is bias, what is the uncertainty, what is the hysteresis, what is error and many many more terms, and across the world different people have interpreted it slightly differently.

So, when you sit to talk with each other there is likely to be a mismatch. So, it is important that we stick to one common thing which is this document V I M which gives all the terms and this document has been adopted by various American Standards Indian Standards and everywhere else in the world.

So, this is our second guiding document from which we will pick up terms and in the notes, I have kept the terms as and when as they come into that particular chapter, but the definition is largely drawn from V I M. The second thing about these standards on uncertainty analysis is they are very heavily statistics based; which leads us to another set of issues. In statistics, as well, there are very many different ways by which people call terms or they interpret them as being different. So, there is another standard which gives the definition of terms in statistics.

There is an ISO standard and there is an equivalent IS standard the details I have given in the notes and we will follow that. So, that as you will see in this course you will soon see there are too many terms coming in and we will need to have one consistent clear approach as to what each term means whether it is in the measurement part or in statistics we will follow these standards.

The standards also give a broad methodology of how to measure, what to measure, and the statistical and mathematical basis which is the procedure by which you can calculate the uncertainty. In some of the references it is explained very clearly in some others you have to do a little more thinking and interpolation and all standards will have some worked examples to illustrate what they are saying. So, that is what we have we will get if you look up any of these uncertainty standards.

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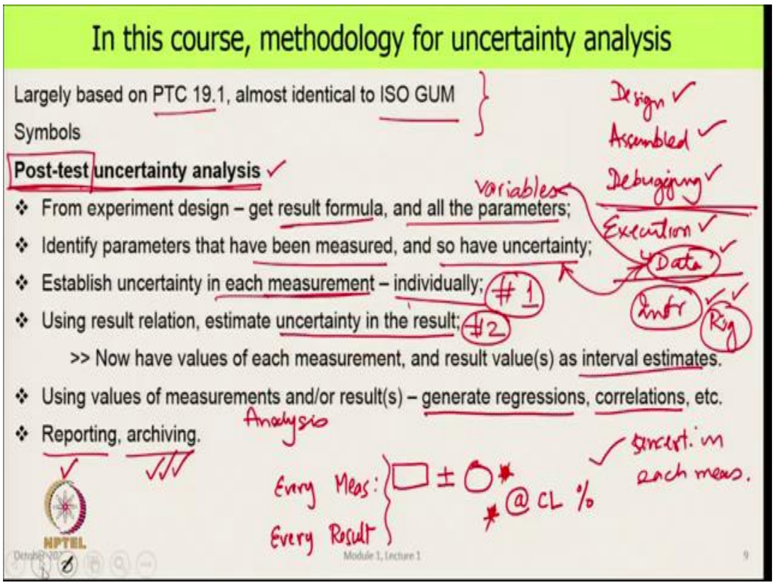

So, what we will do in this course? We will follow a methodology which is largely based on PTC 19.1 and ISO GUM which as I mentioned is largely the same. Where there are differences I have brought those out and I have also given an idea of how to resolve that difference. Those are very minor in nature we really do not have to worry about it whatever approach we see it will be good enough and it is completely consistent and harmonious with these, that is the first point.

Then the approach has two parts. The general approach of uncertainty analysis that you see anywhere in these standards is what we will call as post-test uncertainty analysis. What post-test means is that you have designed the setup, you have put it together, you have done the qualification test and debugging and you have executed the experiments which is when you take data.

So, you have reached that point where you have done all of these maybe you skipped some of these for example, if the setup was already ready then the first two may not are not required third may or may not be required only the data has to be taken. If it is an experiment in a school or a college, we largely do not do the first three we straight away tell the students we will take the data. So, you have data.

So, you have done the experiment, you know everything about the instruments you have all the data that you want all the data about instruments is available; all the data about the rig or the setup that you have that is available, and now you have everything that you need to do the uncertainty analysis.

So, that is what it is called post-test uncertainty analysis and when you report a result or write a paper or a thesis or a dissertation, it is this uncertainty that we actually use. So, this is the most visible, most frequently used, and most popular of all the uncertainty analysis reportings.

So, this is what we did which is that from the experiment design we get the result formula. So, that is the other thing we have; that means, what measurements we make and what calculations we do and we have all the parameters which are also the variables in the experiment.

The data pertains to the variables. So, what we do is, we identify the parameters that have been measured we list them out. And because they were measured, so, they have uncertainty and they were measured once twice many times and the data pertains to these parameters.

Then we will see the process by which we will establish uncertainty in each measurement individually. So, this is step number 1. We identify what has been measured what are the parameters what are the instruments used and with all our knowledge of the process we establish the uncertainty in each measurement.

So, you reach a point where you say I did all of this, now I know that these are all the measurements and I have all the uncertainty in each measurement. So, this is what we got. Then we get back to the result formula and there could be one two or many more, each one of those formulas has some constants and it takes data from some of these measurements. There is a mathematical relation we put things into it and from there we estimate the next thing, which is uncertainty in the result, this is the step number two.

If there are two computed results there will be two different formulae, there will be two different uncertainty analysis and so, we get uncertainty in the result. The next step. So, is that we establish this uncertainty as interval estimates. So, what do we have at this point? If it was a measurement, we say that this measurement had this mean value plus minus this much uncertainty, or this and this at a certain confidence level.

We will see what these two differences are and the same thing with every result. So, every measurement we have this with every result also we have the same form. Two numbers corresponding to some confidence value, or just two numbers which implicitly mean something else, we will see what that means. So, there are two things happening here one and this is two. Now we use these values for various interpretation and other things.

So, we can generate regressions, we can make correlations, we may be interested in only certain measurements that is our result we report that or we make a relation between two measurements, we may report that. That is what your next step was which is data analysis where we not just make a formula and do a calculation or make a plot but along with that in all of that we say what is the uncertainty.

Having completed that we go to the last step which is reporting and archiving and all the standards tell you the best practices for reporting data with uncertainty and finally, how you should store it, so that in future people who are not familiar with the apparatus or do not know the experimenter can read that report and fully understand what was done, how it was done, why it was done, and get the answer.

This is extremely important. So, this is the normal (~~test of~~) process of doing the uncertainty analysis; which as I said essentially corresponds to posttest uncertainty analysis. And this is something everyone has to do, but even if you did not design the setup you did not do pre-test uncertainty analysis you did execute the experiment and get all the data. So, you have to do this and report it as a result.

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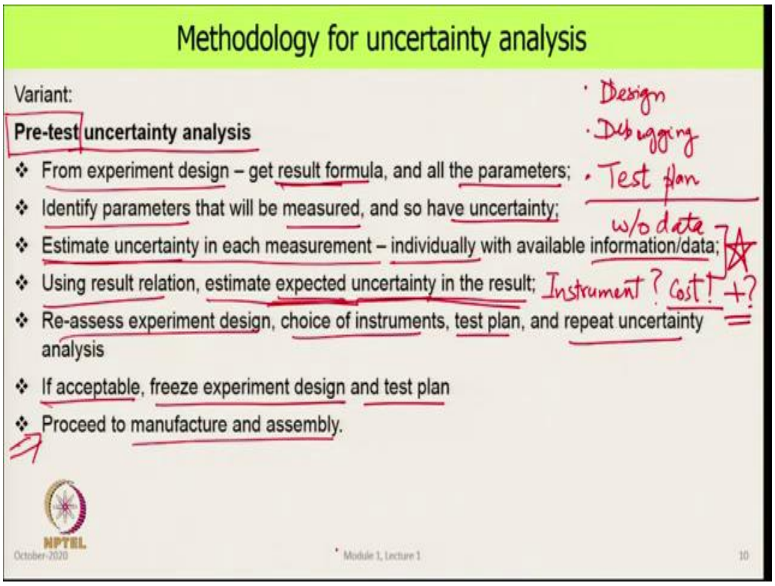

A subset of this is what is there in the next part which is pre-test uncertainty analysis. This method is a subset of post-test uncertainty analysis and some of the issues are treated slightly differently, but largely within the same framework as ISO GUM or PTC 19.1.

So, (what is) pre-test uncertainty analysis is what we saw in the earlier slide design assembly and debugging; when we do uncertainty analysis at these stages that is what we call pre-test uncertainty. So, in setup design of the experiment, debugging and in the making of the test plan or the test matrix. So, we have not reached the stage of doing the experiment which is why this is called pre-test.

In the design stage we can use uncertainty analysis to this be able to tell ourselves well before design or doing the experiment as to what is the uncertainty going to be if we design it in this particular way. So, there is a procedure for doing that and it begins like this.

We come up with an experimental design a concept that this is how I will do the setup and this is what I will measure and this is my result formula. So, you have a sketch you have an equation or a set of equations for each result that you want, and you know that to get the data in that result what are the parameters and under these parameters that you are going to measure later on.

Some of these are of course constant, some are measured. So, the next step is we identify parameters that will be measured and so, these are the parameters that will have uncertainty. Next step we do is, we estimate uncertainty in each measurement without data. So, this step we do not have data and you may wonder you know how can I estimate the uncertainty if I do not have data.

We will learn about that there are ways to establish this uncertainty and, in general, experience also counts in setting up the uncertainty. So, we will take all the knowledge the information and data that we have about every measurement individually by looking at say its specification sheet what we know from previous experience about using that instrument and as many things as we can know about it we tabulate those and estimate their uncertainty on some statistical basis that becomes an estimate of the uncertainty in each measurement.

So, this is the step where we are slightly different from what we do in post-test uncertainty analysis because here we are estimating it without date any data. And as the name suggests this is only an estimation which is helping us in design the experiment and it does not mean that we will not do the post-test on uncertainty that is number one.

Second, this value is a tentative value which is good for designing the experiment, it is definitely going to be different from the value that we get after we have done the experiment and then done the uncertainty analysis. Then here using the relation we estimate the expected uncertainty in the result this is expected it is not the actual uncertainty in the result.

And this is very valuable information; because it tells us before doing an experiment how good a value can I get if it is acceptable you are on the right path if it is not according to expectations well you have to change the instrument change the setup or maybe abandon the whole idea that you have started off with and start with a new idea.

So, this is extremely important, here we also decide, but do I need to change the instrument. And this has a lot of cost implications you may have started off assuming that I will buy a relatively inexpensive instrument whose uncertainty and accuracy and everything else is known and then you find that well it does not meet my expectations I need to get a better instrument that would invariably mean the cost goes up. So, you have lot of options in buying instruments and how do you decide on which instrument to buy, you get a valuable feedback from this pre-test uncertainty analysis.

So, that is what the next step that is listed here is, that based on this data we reassess the experiment design choice of instruments maybe redraw the test plan and then we again do this pre-test uncertainty analysis and finally, we if everything is OK, we freeze the experiment design and test plan. What this means is now proceed to manufacture, assembly, execution, everything else.

So, before even reaching this part, we have learnt a lot about what our apparatus can do and what it cannot do and so, when we actually go ahead invest time, money, and effort, in making the setup, we are reasonably confident that it will do what we want it to do. If we had not done this, chances are we make everything, make the setup make measurements and find that in the end the post-test uncertainty tells us well not good enough. The entire effort has gone waste we start all over again, and that is what is avoided by doing the pre-test uncertainty analysis.

So, in the course we will look in general at the post-test uncertainty analysis procedure then we will see which are the items which are not relevant to pre-test uncertainty analysis and which are the additional complexities that are coming in and how do we handle those. So, that will tell us the idea about pre-test uncertainty analysis.

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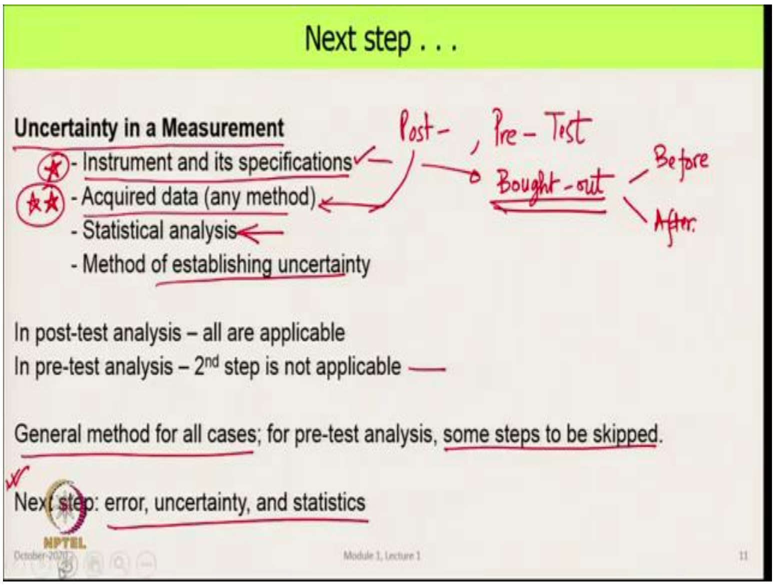

So, our next step what we will learn in the course is that first as we saw we need to establish uncertainty in a measurement; whether in the post-test scenario and then as a special case in the pre-test scenario.

For this we need inputs, there is acquired data if any, this is the case which will pertain to the post-test uncertainty analysis instrument and its specifications will be there always, we need to see where is the instrument specification, and we will also see in this course how to interpret what the manufacturer is telling us.

This part is important; because most instruments that we will use are bought out. We buy the instrument and so, we need to know before buying what is its specification how good it is and how to interpret it and after we buy it we should know how to put it together and then interpret the data that it gives.

So, we get two inputs in terms of information about the instrument that is one number and second about the acquired data which we use in formulas and perform statistical analysis on that and then we will learn how to establish the uncertainty in these measurements.

So, as we just saw, in the post-test analysis, all these are applicable in the pre-test uncertainty analysis, second step is this method is this part is not applicable. So, that is what we will learn a general method for all cases and figure out which steps to be skipped for pre-test uncertainty analysis.

So, in the next step what we have to do (get here) is we will start by two things. In one case we will look at instruments and their specifications and how to interpret them this is one thing. The second thing is this part which is an understanding of errors, uncertainty on the basis of statistics.

So, here I encourage you to look up websites in the first week's assignment there will be such type of questions where you go and discover what this is all about; what are manufacturers telling us how do I interpret it that is an important thing to do.

So, that will be one step, then one where we have rigorous statistics coming in this is what we will do as our next step.

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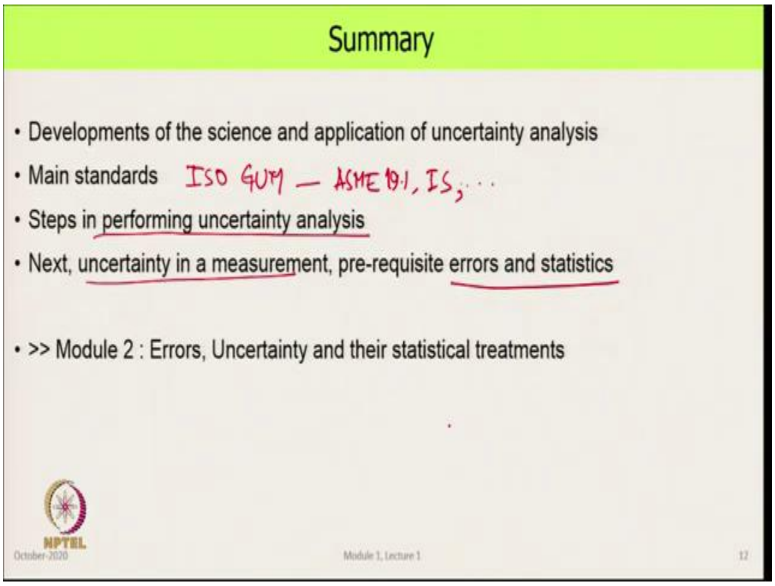

So, we conclude this lecture and in this lecture, I have tried to put out a brief history of uncertainty analysis, how it evolved, what were the various ways in which people thought about it. And how scientists from various branches disciplines and applications came together to harmonize all of them and come up with one uniform standard, one for uncertainty and also the accompanying statistics.

So, that is where we learnt of the main standards which we said will be the ISO GUM which is harmonized with many standards like the ASME PTC 19.1 various Indian Standards and so on, and we will learn both the science of why it is like that and the tech engineering and technology of how to apply it we will learn both these things.

Then we showed what are the steps in performing an uncertainty analysis that we start with some data and information about the measurements, we will establish the uncertainty in the measurement using that we establish the uncertainty in a result that is most of this course. And to understand that we said that uncertainty in a measurement we have to have a knowledge of errors and statistics.

So, this concludes module 1 and in the next module we will start studying about errors, uncertainty and the statistical treatment. With that we conclude this lecture.

Thank you.