Fundamentals of Combustion for Propulsion

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Lecture - 24

Instabilities in liquid rockets and gas turbine after burners

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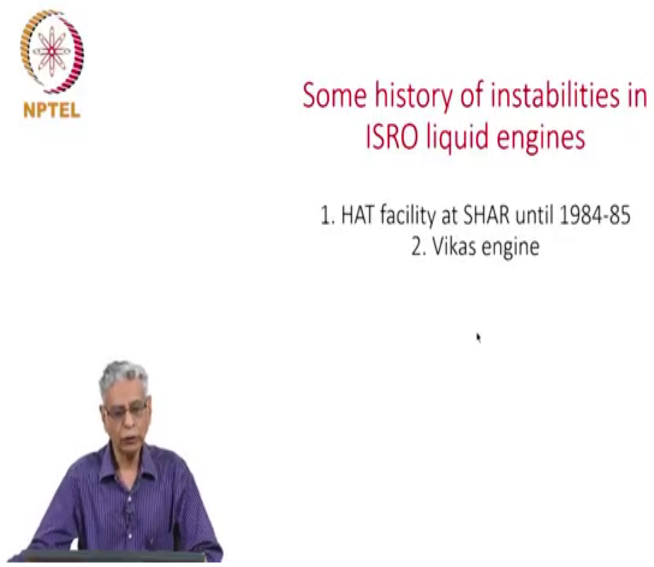

Let us look at some history of instabilities in ISRO liquid engines, I am going back in times of this. Some instabilities were observed at the high altitude test facility at Sriharikota Range until about 1994-1985 and some of course, were also uncovered in Vikas engine.

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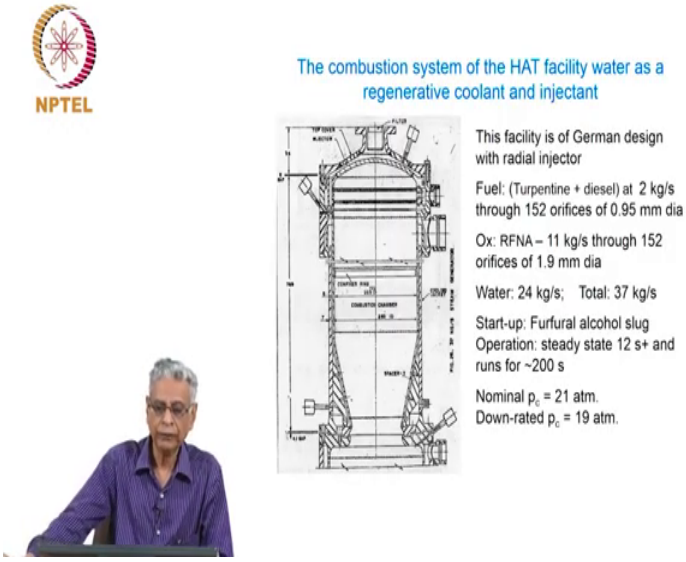

That is a, there was a combustion system at the high altitude test facility as a in a route to get injector operating so that the pressures for the test motors will become low in the test chambers.

The third stage rocket motor was tested in this facility and this facility essentially used a rocket engine based on a German design. The design is some radial injector, some hot like Vikas engine, used turpentine in DC as at some rate as a fuel and retrieving metric acid as the oxidizer. And when the after the combustion was completed injected water, so that you would get steam at high pressure and they should become the agent for creating the injector head.

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So, nominal pressure was 21 atmosphere, when it was operated there were occasional instabilities, what they discovered in the hardware or something like cracks like several places on the injector head. And this damage an injector head, you know there were doubts whether it is instability or heat transfer related problem, because what ultimately you see is, is the damage and it can be due to a local high heat transfer. So, this subject was of debate, took place in Vikram Sarabhai Space Center for a long time and I happened to be a member of a committee and the other members from both VSC and Institute of Science looking at this problem.

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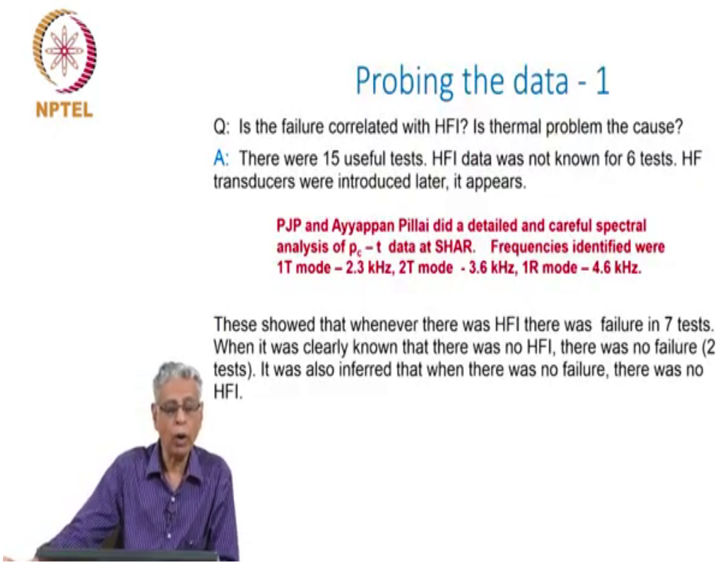

After discussions I just decided to probe the data which was available at SHAR to answer the question whether the failure was correlated with high frequency instability, are each thermal problem the cause. There essentially 15 useful tests at that time. The high frequency instability data was not known for 6 tests. These are inception, periods of inception and not much of instrumentation put together, and high frequency transducers were introduced later, it seems to be so.

There is a colleague of mine by name professor PJ Paul and somebody from Vikram Sarabhai Space Center in liquid propulsion group called Ayyappan Pillai. They spend a month at Sriharikota, did a detailed and careful spectral analysis of the pressure time data at SHAR.

The frequencies identified, essentially were the first tangential mode at 2.3 kilo Hertz and second tangential mode at 3.3 kilo Hertz and the first radial mode at 4.6 kilohertz, but the most dominant one for the first tangential mode. Also, they showed that whenever there is a high frequency instability there was failure in the 7 tests, when it was clearly known that there was no high frequency instability, there is no failure. One quick check that was told to us that they did work, whenever there was a screeching sound which they could hear outside the nest bay area, they knew that they had a problem and they invariably, it would lead to high frequency instability.

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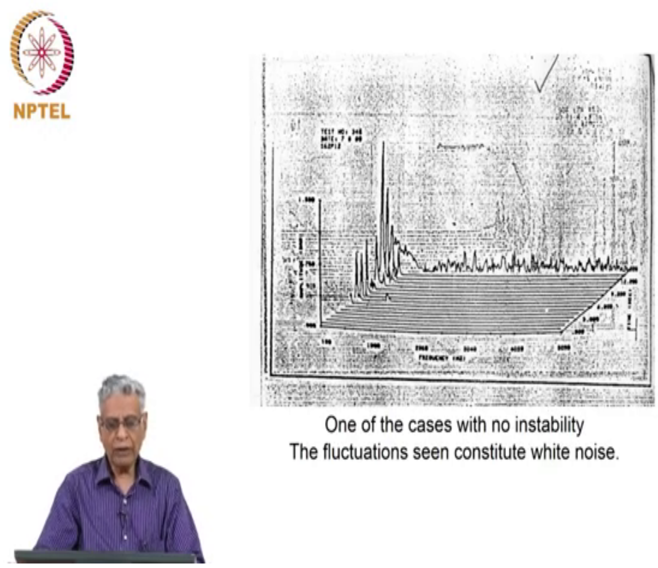

So, if there was no instability you this spectral analysis showed somewhere near DC and rest of it is white noise. There is not much that was happening all around during liberal time.

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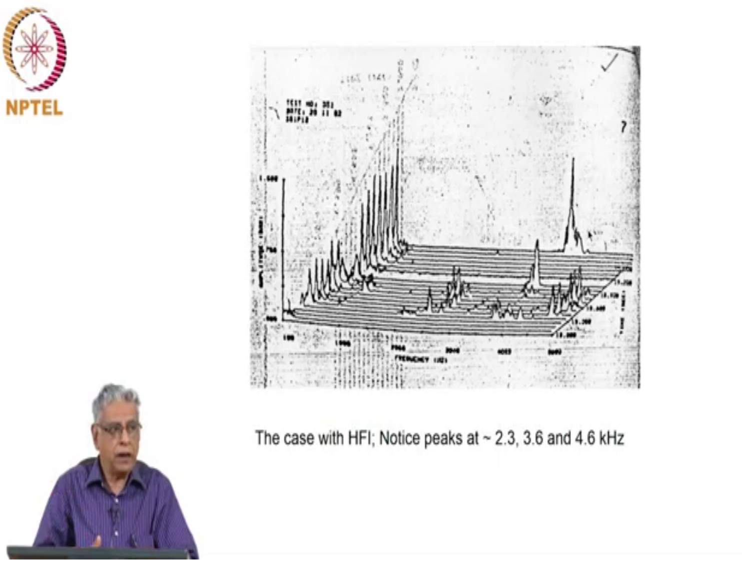

However, when there was a instability you could find amplitude such specific frequencies that I mentioned a little earlier 2.3, 3.6 and 4.6 kilo Hertz, ok.

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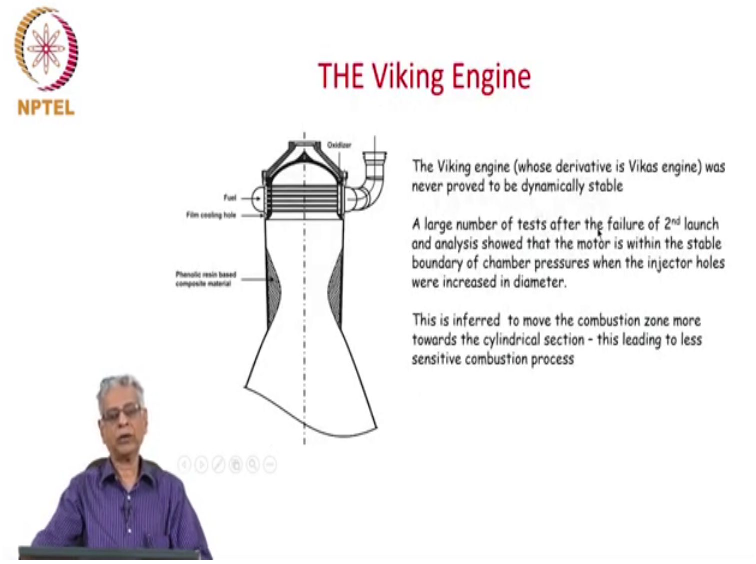

You may ask the question what happened afterwards? We did analysis, we recommended some changes to be done and they offered it additional changes, change the o by f to small extent and by changing the RFU sizes, and it seems to have remove the instability and the system operated for a reasonable time ah, but when the major test facility came in Mahendragiri, this particular facility got shut down, because small the facility at Mahendragiri has much larger.

The Viking engine the it is essentially, the Indian version is called Vikas engine, I must say was never proved to be dynamically stable. The second test we launched we took place from French Guiana of the Aryan vehicle, had a problem of instability that again a committee was appointed, large number of tests were done and the final recommendation was adopted in the system. But what was done essentially was that they found that the combustional very intense, very close to the injector. They said that you will we will actually make sure that the combustion gets you know and delayed fuel slightly down spin zone and the only way of doing that if you there in, their control was to increase arches diameter which is what they did.

And those details are also made available to Indian counterpart, because the Indians work with the team during the development in early stages, and so that is how these Viking engine has been functional over a period of time and the Vikas engine also has the same benefits, ok.

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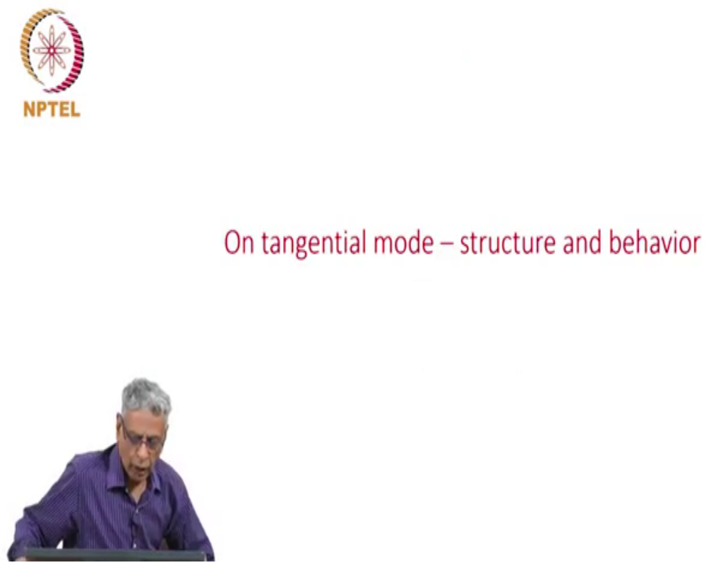

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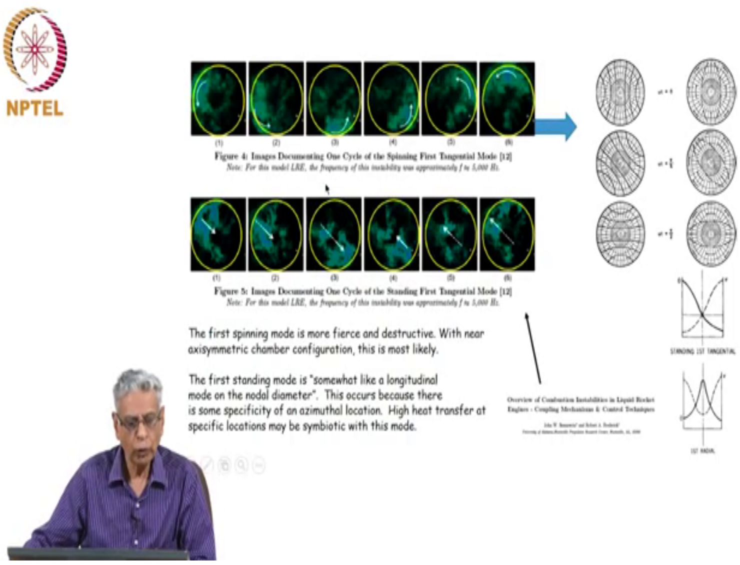

Let us look at what the tangential mode and the structural behavior is. If you look at tangential mode instability you will find that in actual experiments, you will find a travelling tangential mode means the wave high pressure waves will move around like the way shown here. It is also possible that say standing mode which would mean that the mode will go from one end to the other end as you see in this, in these sketches. The spinning mode is far more fierce and destructive and with near axisymmetric configuration this perhaps the most likely are you know experience that one would get if there was instability, this is.

Student: Sir.

Yeah.

Student: In this what is this images which is like.

These are the images and a on a system where tangential mode instability has been simulated in the model system and pictures taken of the flame structure inside, you see the intense radiation here.

Student: Sir is the radial injection.

No, no these are axial injection.

Student: Axial injection.

Injection.

Student: but the (Refer Time:07:01) or the this species are getting transmitted and getting travelling

Travelling (Refer Time:07:05).

Student: (Refer Time:07:06).

Yeah, correct, you see this paper we will get to know the details, ok. Now as I mentioned here the standing mode is somewhat like the longitudinal mode, but on the nodal direction.

You see longitudinal mode in a rocket engine would be in the axial direction to the nodal, but the tangential mode is, you know standing mode is somewhat like the longitudinal mode, because you will find it moving radially across. And one should not imagine it to be the radial mode, because in the radial mode it turns out that the pressure fluctuation as I shown here is the say,the pressure is the same all around the azimuth or the periphery and it only radially changes. Whereas, in this case the pressure wave travels from one end to the other end along the radial direction. So, this is the difference between the tangential, standing tangential mode and the radial mode,

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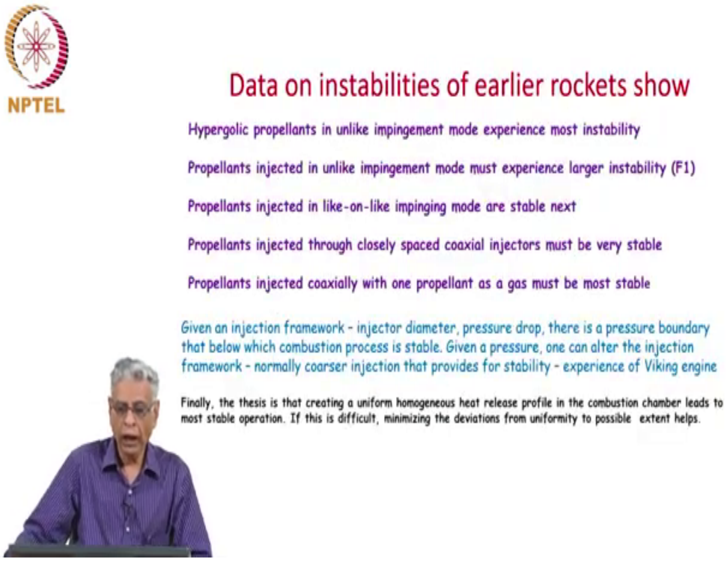

If you look at the data on instabilities of earlier rockets that is you have fair amount of information in literature, there is a document called SP 1 9 4, 8 1 1 3 and several others from, from Russia and other places. You can infer all effectively, the following features.

The hypergolic propellants in an unlike impingement mode experience the greatest instability. We look at possible visions little later. Propellants injected in unlike impingement mode must experience larger instability, but these are not hypergolic. Non hypergolic propellants, you can still inject them in a unlike mode fuel and oxidizer

Propellants injected in a like mode fuel in a fuel oxidizer and oxidizer they are stable next. Propellant injected through closely spaced coaxial injectors must be very stable. Propellant injected coaxially with one propellant as a gas must be the most stable. This is what you will infer from looking at the information

We will see the meaning of this statements through this downstream or whatever I am going to say. Also given an injection framework, injector diameter pressure drop. There is a pressure boundary below which combustion process is stable, given a pressure actually one can alter the injection framework. Normally, coarser injection that provide for stability. This exactly what has been done in Viking engine.

Finally, the thesis is that creating a uniform homogeneous heat release profile in the combustion chamber leads to the most stable operation. If this is difficult minimizing the deviations from uniformity to possible extent helps. Keep this thought in mind, because this principle is not something that you can prove right away. It may need to be efforts may be need to be put in to prove that, but this is the principle which is a guiding principle drawing the conclusion which I have stated here.

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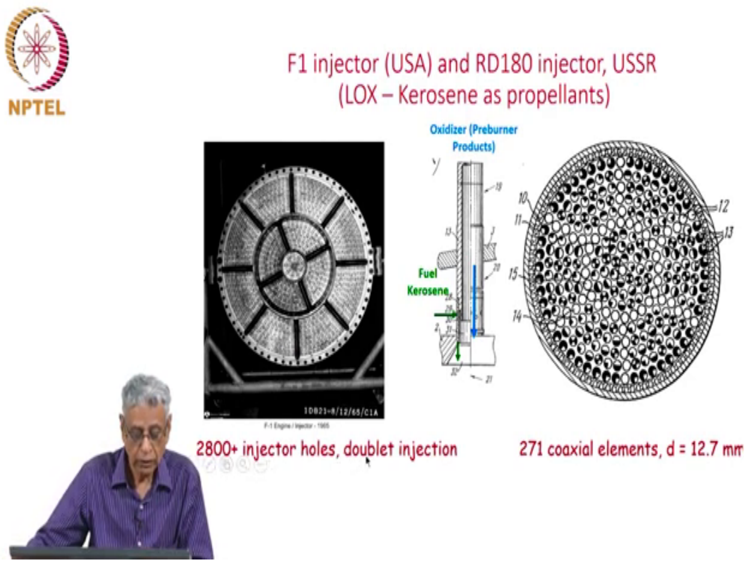

Well, we will ask the question impinging injectors versus coaxial injectors. F 1 engine very famous, extremely well written about in the literature and this is the RD 180 injector written about not as much, most used LOX- kerosene as propellants. F 1 in the injector has more than 2800 injector holes here doublet injection, we have these baffles located here radially and also peripherally this manner. We separate them and give you stated that it gives them stability and that conclusion, this conclusion after enormous number of tests.

And in this particular case is doublet injection, they have tried variety of injection systems. These are coaxial elements not as larger this 271 and the diameters are large, ok. And you see oxidizer pre burner products come in the coaxial zone and the kerosene is injected inside. This is the way initially injection takes place.

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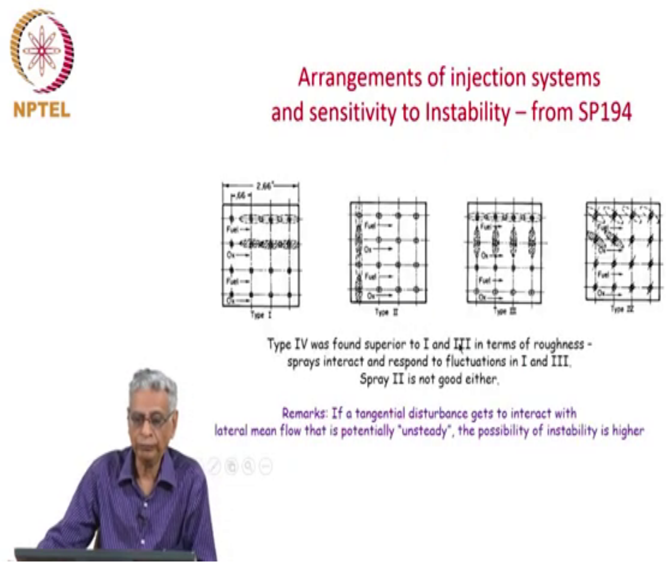

In the impinging injectors and experiments have been done over a large range of you know of, the geometries which been put together in experiments and you will discover that if the injector holes are like this, they are located like this in this chamber as to what it means and at an angle. Now, they are found in this experiments, where they have used sometime gaseous oxygen and gaseous fuel like methane and oxygen and so on. The results are that the 1 and 3 as you see here, they are pretty rough in their. Rough means essentially tending towards instability. I mean in this particular experiment they have essentially use liquid sprays using kerosene and they interact and respond to fluctuations in 1 and 3. And they conclude that the spray 2 is not good either, but spray portion should be not so bad.

So, you ask the question why is it so? The reason is that when impinging action takes place the heat release occurs downstream 30 to 50 diameters of the injector hole. And in that zone, you will see the spray fan, which means in this domain, we will find fine oxidizer fuel droplets floating around.

Now, when there is an acoustic fluctuations which is present all the time, because of disturbances in turbulence and so on. They have an opportunity to interact and with the heat release which takes place, because in the droplets, at the main heat release distributing is affected by oscillations. There is a heat release profile here and because of the vaporization and combustion locally. And this interaction which is taking place between this heat release distribution and the acoustic oscillations disrupts the even the mean energy distribution and that is the reason why and it happens in phase and that is why you have the instability. So, that is why they claim that when the degree of interaction is much more instability higher than where the degree of interaction is lower, ok.

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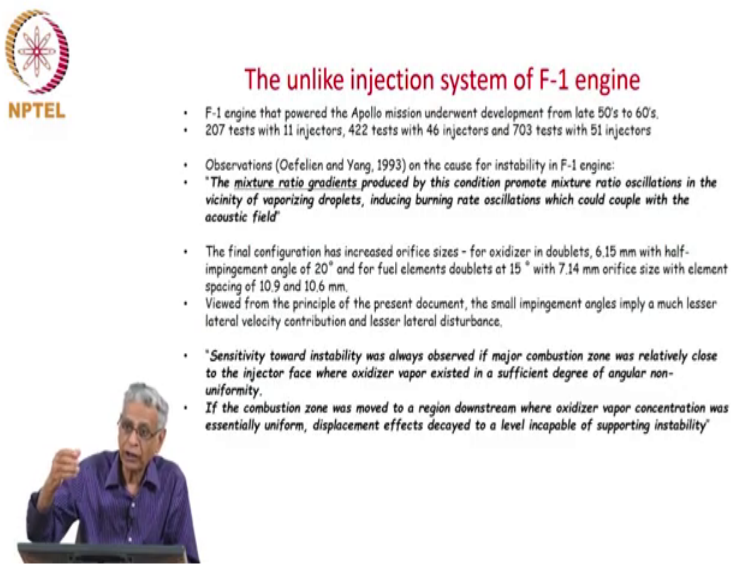

Well, if you look at literature and see what the unlike, what is taken it in the unlike injection system of the F 1 engine. Well this you see you find that the this system was developed in late 50s to early 60s, it had something like 207 tests with 11 injectors, 422 test with 46 injectors, 703 tests with 51 injectors, a few among us referred observations, by these authors on the cause of instability in F 1 engine is a, you know very nice document and those who want to learn about instability should read this.

The mixture ratio gradients produced by this condition of the injection system. Promote mixture ratio oscillations in the vicinity of vaporizing droplets, inducing burning rate oscillations which could couple with the acoustic field. Exactly the kind of point which I have made a few moments ago. Your vaporising droplets and the acoustic on the oscillations interact with burning rate oscillations and the coupling producers, because produces instability.

In fact, their final configuration increased orifice sizes for oxidizer in doublets to 6.15 mm a half impingement angle, not very large 20 degrees and for fuel elements at 15 degrees and so on. I think viewed from the principle that the thesis that I spoke about, the small impingement angles imply a much lesser lateral velocity contribution and lesser lateral disturbance.

Also, further they make a statement; sensitivity towards instability was always observed. If major combustion zone was relatively closer to the injector face where oxidizer vapor existed in sufficient degree of angular non- uniformity. If the combustion zone was moved to a region downstream where oxidizer vapor concentration was essentially uniform displacement effects decayed to a level incapable of supporting instability.

Almost, a different way of saying whatever I said (Refer Time:16:25). I picked out what I said by reading this, I must have to tell you that it is not something born out of nothing, it’s looking at all the documents and considering that a simple way of describing what is the most appropriate way of designing the system well once removing this.

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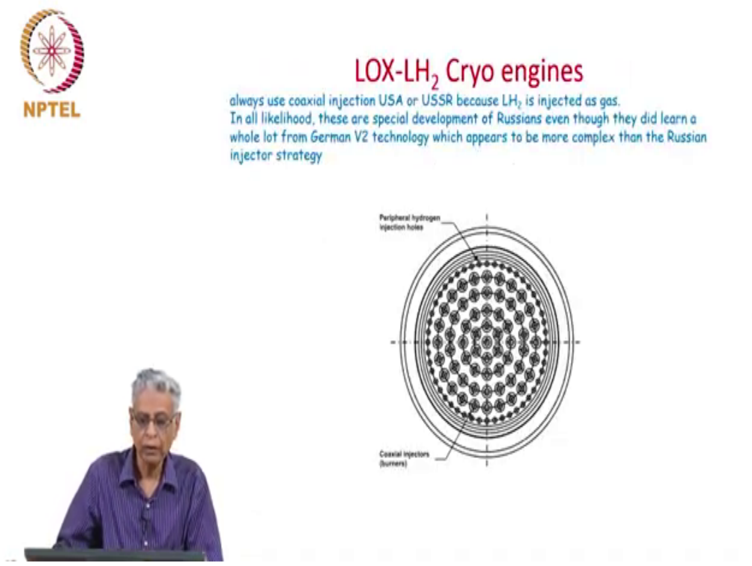

If you look at LOX Cryo LOX L H 2 Cryo engines, they have always use coaxial injection whether the USA or USSR, why? Because the liquid hydrogen is injected as a gas it goes through a regenerative cooling system and comes out from the gas.

In all likelihood these special development of Russians even though they did learn a whole lot from German V 2 technology which appears to be more complex than Russian injector technology. I think I feel that this is a special development of the Russians and I cannot say much more than that this thing. I mean you trace back the history you cannot get precise origin of why they chose this design, because they have similar chosen it for many other applications including storable, you know oxidizer and fuel combinations, ok.

You have essentially you notice the fact that the peripheral hydrogen injection holes. These are for film cooling the surface, so that the heat flux that goes into the walls and its reduced and so, you have get a better protection for the combustion chamber.

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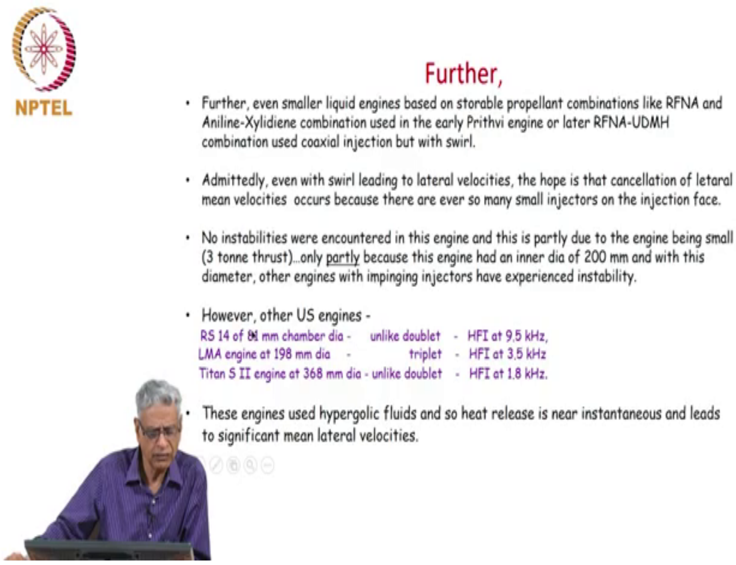

Further, even smaller liquid engines based of storable propellant combination; like RFNA Aniline- Xylidiene combination used in early Prithvi engine or later RFNA UDMH combination used coaxial injection, but its worth. There is a project which there in Hyderabad to re- engineer the vehicle a called a shape 2 and the second stage of that for the liquid engine which again essentially became the engine for Prithvi in the early parts of the development. And that utilize essentially a combination of Aniline- Xylidiene as a fuel and reckoning that citric acid is oxidized. It essentially use the same kind of design we can showed earlier the LOX n h 2 they have swirl.

Admittedly I think given a swirl leading to lateral velocities. The hope is that the cancellation of lateral mean velocities occurs because there are ever so many small injectors on the injection face. And curiously no instabilities were encountered in this engine. And this is partly due to the engine being small 3 tonne thrust. I say only partly, because this engine had an inner diameter of 200 millimeter and with this diameter other engines with impinging injectors have experienced instability. It may look like I am making inject as impinging injectors are the bad boys, but that is in fact, true.

Student: Sir.

Yeah.

Student: Sir, in the previous slide the (Refer Time:19:37) you are not said that interaction between this (Refer Time:19:38) and this is be (Refer Time:19:42) diameter (Refer Time:19:43) injection injector of free system that is the. It you mean to say that there is some (Refer Time:19:50) hydrodynamics that leads to the final (Refer Time:19:53)

What is meant is the following. Suppose, the injector hole diameters are small impingement occurs closer to the injector phase and interaction will be much more intense, the heat released starts closer to the injector phase, ok. Now, when heat release occurs and the to remember when the sprays interact, there will be always a spray distribution around you know with a massless distribution which can be variously oriented.

Now, if the acoustic oscillations, now interact with the heat released profiles and that occurs very close to the point where the droplets are present mean flow which is obtained for the heat releases in that zone. Then the mean free four feed is also affected by the acoustic oscillations. If; however, you take a larger injector hole then the heat released is pushed to a downstream domains, where the lateral flow present in the cross section is not as much as what would happen very close to the injector and therefore, any coupling that takes place will not be picked up by the mean flow which is partially axial.

So, it will not have any tangential component. If there is a tangential velocity for the fluid and if that gets acoustic coupling then you have a better chance of creating a tangential mode of instability, but if you make sure that a mean flow in the azimuthal direction, lateral direction is very small, the chances of coupling between acoustic oscillations in the lateral four field will be very small (Refer Time:21:32),ok.

There are other US engines on this called RS 14 of 81 millimeter diameter unlike doublet at a high frequency instability 9.5 kilo Hertz consistent with the diameter, lower module engine 198 mm diameter not very different from this say triplet 3.5 kilo Hertz, titan S 2 engine unlike doublet, larger diameter 1.8 kilo Hertz.

So, impinging jet injectors have always handy prop. Also these engines used hypergolic fluids and heat releases almost is instantaneous and leads to significant mean lateral velocities and therefore, the coupling takes place. This is logical.

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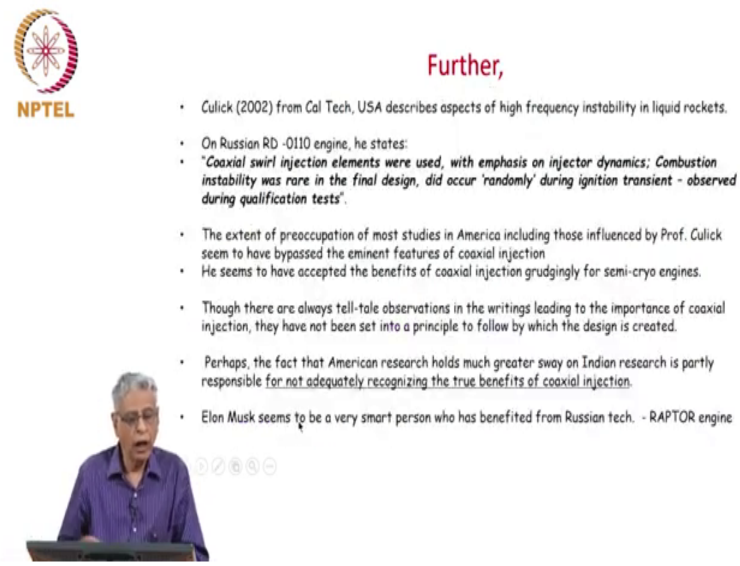

Culick ku is a distinguished academic from Cal tech. In fact, it is written an article and it describes many aspects of high frequency instability liquid rockets and on the Russian already 0 1 1 0 engine he states. Coaxial swirl injection elements were used with emphasis on injector dynamics. The in combustion instability was rare in the final design, but did occur randomly during the ignition transient observed during a qualification tests.

Now, if this in fact, an argument made saying that they also used to provide baffles, but the provided a baffles in a interesting way. They just introduced the officer force or the injection force into the combustion chamber in specific direction, so that you have essentially baffles created, but I think the extent of preoccupation of most tradition America including those influenced by personal Culick seem to have a bypassed. I think the eminent features of coaxial injection and it does not seem that he was very happy, that wonderful it is, ok. They have done this just the situation.

Though there are tell tale observations in writing leading to the importance of coaxial injection, they have not been set into a principle to follow by which the design is created. See, if you do not make the statement emphatically and literature is full of many statements you will get confused and you will have to ask question, who do I trust? So, these are the problems which arise when you go to complex designs.

I also want to say that American research holds much greater sway and we do not have access to American, Russian technology and academic discussion, because probably cause of language. And I think we have not been able to derive enough benefits recognizing the coaxial injection approach, but Elon Musk you know he is quite smart. He figured out that the Russian technology is good, he benefited from them. And In fact, he is building a ringing of locksmithing at much high traces of 300 process using the same class of ideas called the raptor engine.

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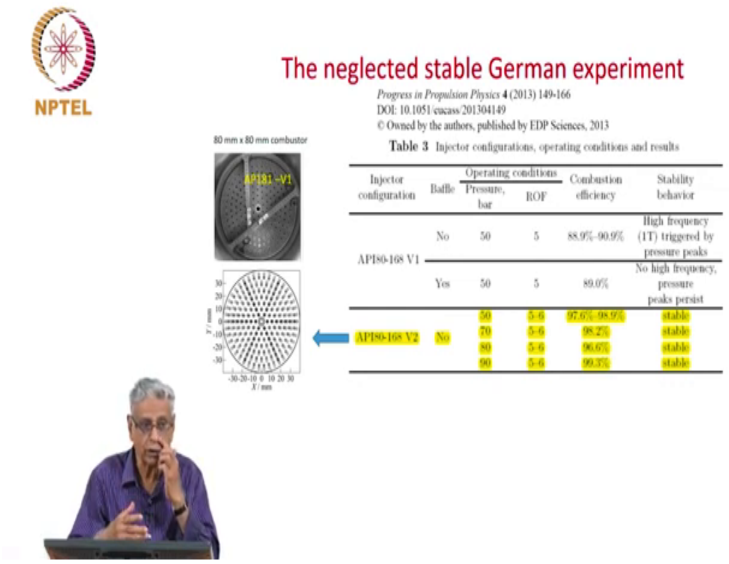

There is a very interesting what I consider is neglected stable German experiment, where the same here reference here what they did is here two combustors, you can see, small combustor 80 mm by 80 mm. One of them had baffles, one of them did not have baffles. And you see the details in one case no and in case, yes.

And if you see that in this particularly design a high combustion efficiency, all effect was stable. The oxidative fuel ratio is 5 to 6 typical of LOX L S 2 engines. I will say little more and the pressures are high going up right to 90 atmospheres, ok.

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And if you see further, they did also perform experiments where the hydrogen is a gas was like true; the small ports and this called Rigimesh and a LOX posts also well introduced so that one they claim is cheap pipe material, this just copied from their paper. The holes so, the LOX posts simply drilled into porous plate etcetera, etcetera.

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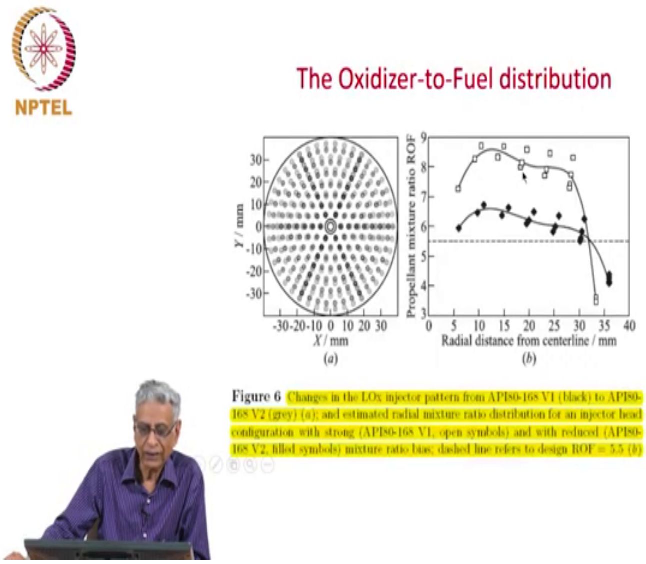

And we found that the system was quite stable and the argument that they I have given. Even, if you look at the propellant mixture ratio, in one case where the instability the variation is much more than in the case where there was no instability. You will read this here changes in the LOX pattern for this black or gray and estimated radial mixture ratio distribution of an injector head. And you can see that the one which was stable belong to this particular design, you can see that A P 180 168 V 2 grey is the one which produce V 2, the one which is very stable.

Student: Reason.

The reason therefore, is that you make the mixture ratio uniform, making mixture ratio uniform also means that the lateral distribution is not, velocity distribution is not very much, the whole flow is axial.

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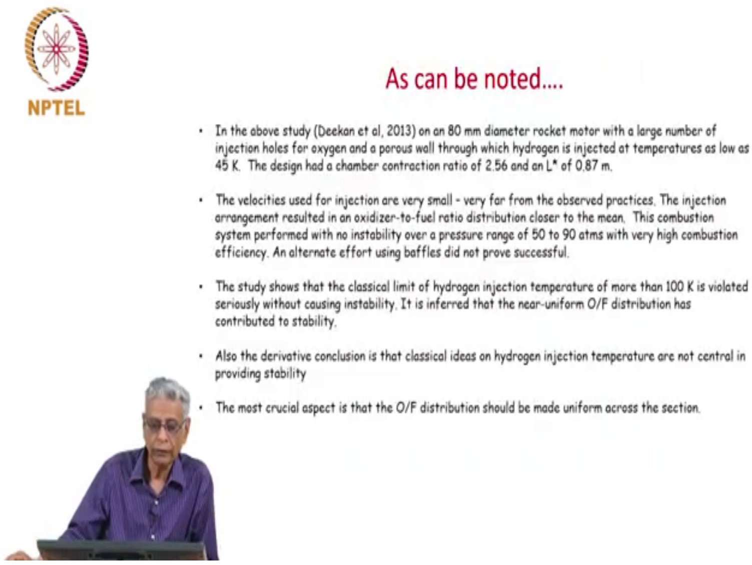

So, in this study large number of injection holes for oxygen and a porous wall through which is hydrogen is injected at temperature as low as 45 k. Perhaps we how to good to know that there is a well- known unstated, well stated principle that instability will be much more when the liquid hydrogen temperature, when the hydrogen injected in lower temperature you know compared to higher temperature.

So, people do experiments what is the temperature below which you will get instability. So, they keep producing the temperature and find out at what temperature will get instability. And that temperature for example, injection in the engine which we built like LPSC, the injection temperatures more that 100 K Kelvin. And you see luminous temperature 45 K, they found it to be stable. It has a certain contract in ratio and so, on. And therefore, it looks like what drives thein stability is simply the fact that you have lateral mean flow on which acoustic flow field really works on and therefore, this leads to copy which is unfavourable, ok.

I think the most crucial aspect is that the o by f distribution made uniform across the cross section. I think, I have said what I need to say about (Refer Time:28:27) droplet engine. The ideas are very similar and you will discover this in the cases gas turbine as well afterburners as well.

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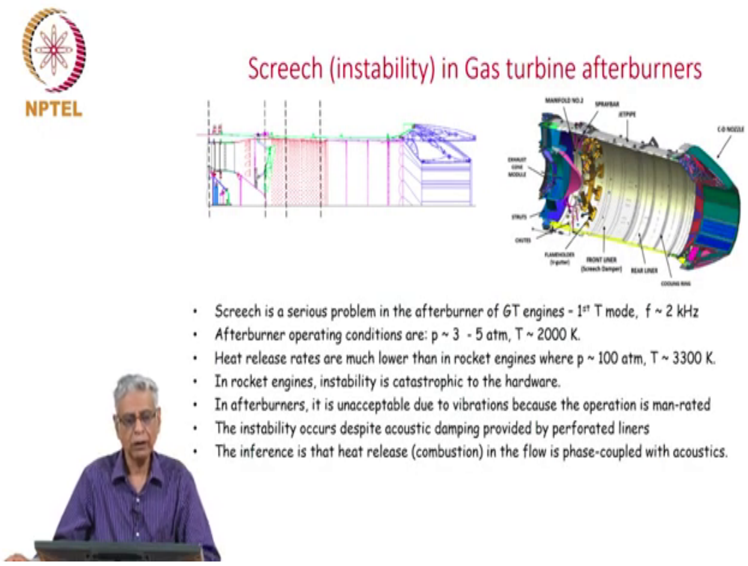

Let me look at this, this is a gas turbine engine taken from DC and his talking and taking. You have the flow coming from the turbine and you will find number of hole a perforated sheet here as I mentioned earlier it becomes acoustic absorptions absorbers. Then you have a geometry where fuel is injected, your spray bars to inject the fuel and your flame holders here, large number of them around the periphery. And this is the cone and the flow comes like this gets mixed then fuel is injected combustion takes place here and goes out to the nozzle.

Now, this say serious problem of tangential mode. I think I mentioned this earlier in an earlier presentation I brought out all these features. This instability occurs despite acoustic damping provided by the perforated liners. The Helmoltz effect of the gases coming in from the outer periphery through the holes, taking away the acoustic energy is also applied here and they have used advanced design tools to get to that and yet you find the instability being present.

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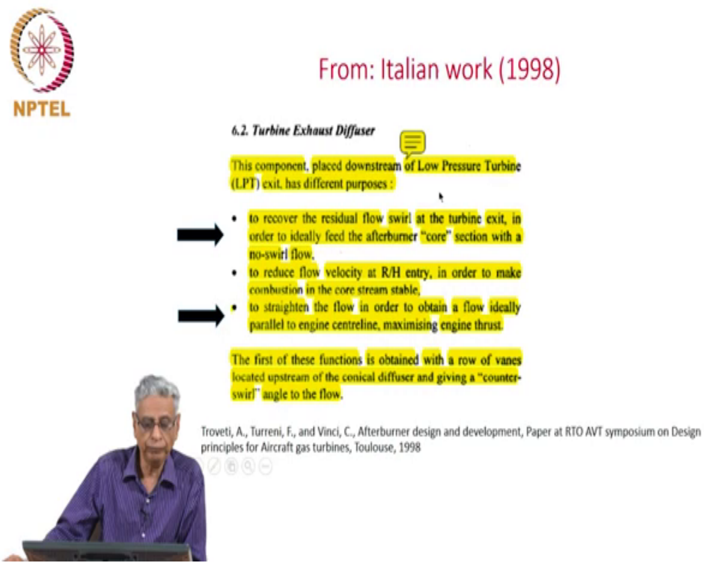

And there is an interesting Italian work which you will see referenced here 1998 and its titled afterburner design and development. And you will find this passage which I think is worth of being read and understood.

The turbine exhaust diffuser that is the gases which delivery to the afterburner. This component plays downstream of the low pressure turbine, exit has different purposes. One to recover the residual flow swirl at the turbine exit in order to ideally feed the afterburner core with no swirl flow. To reduce the flow velocity at the entry in order to make combustion in the core stream stable. To straighten the flow in order to obtain a flow ideally parallel to the engine centerline maximum maximizing the engine thrust.

The first of these functions is obtained with a row of vanes located upstream of the conical diffuser and giving a counter swirl angle to the flow. This word counter swirl is used, because any flow which comes out of the turbine will have a certain swirl the, because the rotation of the turbine blades you will find a swirl. So, you need to put in some effort of design to make sure it is axial that is the statement made here.

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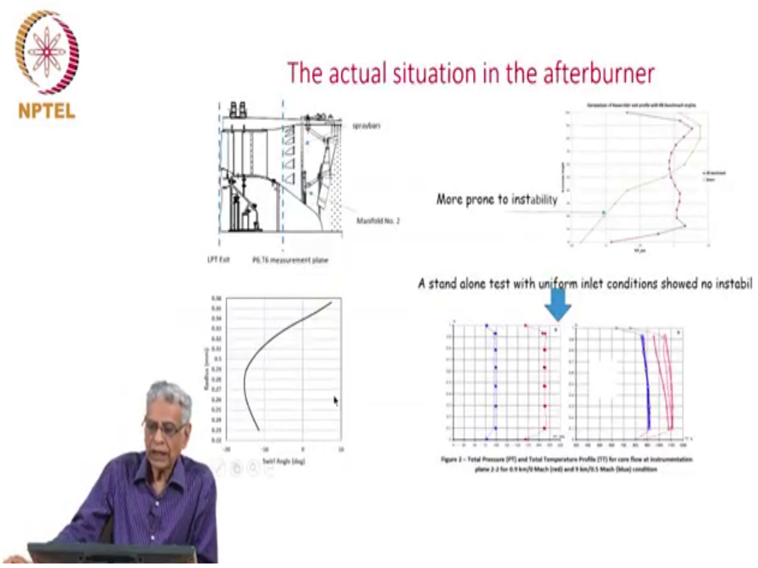

If you look at the actual situation in the afterburner this is data which was provided by GT RE for the first design which they had put together. You see the swirl angle which is presented here is plus 10 in the outer part and is minus 10 in the core; that means, the flow comes in one direction is opposite direction is swirl in the core. In fact, is quite contrary to what you expect to get stable combustion. So, if you are desiring it for instability if you do what is being observed.

So, this was done without necessarily appreciating this particular effect. And what more you will see that the pressure profile for the current situation is like this, whether the expected pressure profile from a benchmark design from Rolls Royce is like this. And the pressure must be uniform flow rate must be uniform is what we what the expectation is, ok.

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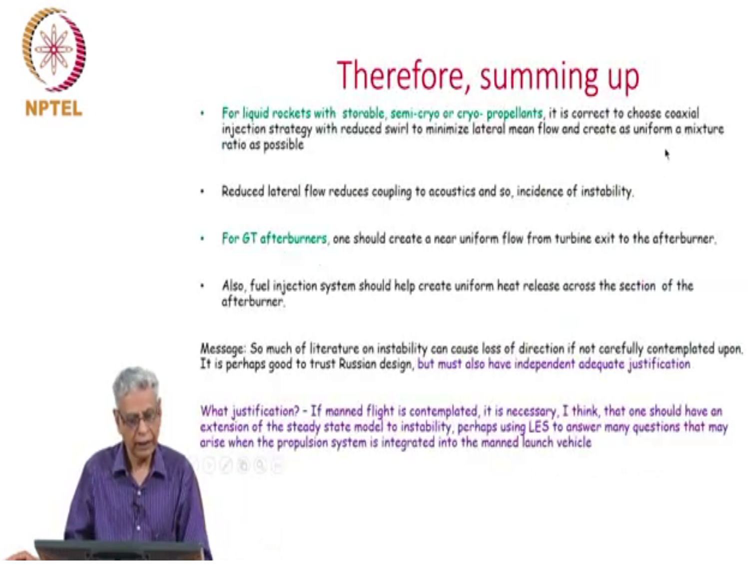

But if you violate that, to some extent it will work, but if you violate it much more it will kick back and give you instability that is the inference, ok. Therefore, if I have to sum it up. For liquid rockets with storable semi Cryo or Cryo propellants this correct to choose coaxial injection strategy with reduced swirl to minimize lateral mean flow and create a uniform mixture ratio as much as possible.

Reduced lateral flow reduces coupling to acoustics and so incidence of instability. For gas turbine afterburners one should create a near uniform flow from turbine exit to the afterburner. Also I must tell you the deteriorate team took their afterburner was tested in Russia. There the connected pipe mode test had uniform flow there, there is no instability. This is a proof of this idea came out in the actual test, but if you if you have known that alone was responsible then you will take the corrective action in their direction, but if you were not sure that there is the only thing that responsible for your instability, you will keep looking at many other reasons and therefore, geometric features which may be responsible, ok.

So, also fuel injection system should help create uniform heat release across the section of the afterburner as much as possible. What is the message as well I can see? there is so, much of literature on instability and it can cause loss of direction if not carefully contemplated upon. It is perhaps good to trust Russian design, but i think we must also have an independent adequate justification.

What do you mean by justification? If for example, a man manned flight is contemplated, it is necessary I think one should have an extension of the steady state model to instability, perhaps using large assimilation to answer many questions that may arise when a propulsion system is integrated into the manned launch vehicle. This was not available earlier so people had to go by trust saying, I know it works; it works.

So, slowly and steadily the confidence improves in the person and whatever he says is accepted, but we must move away from that we must have a design tool and a design tool must be capable of being used by many and therefore, we get confidence come from that analysis.

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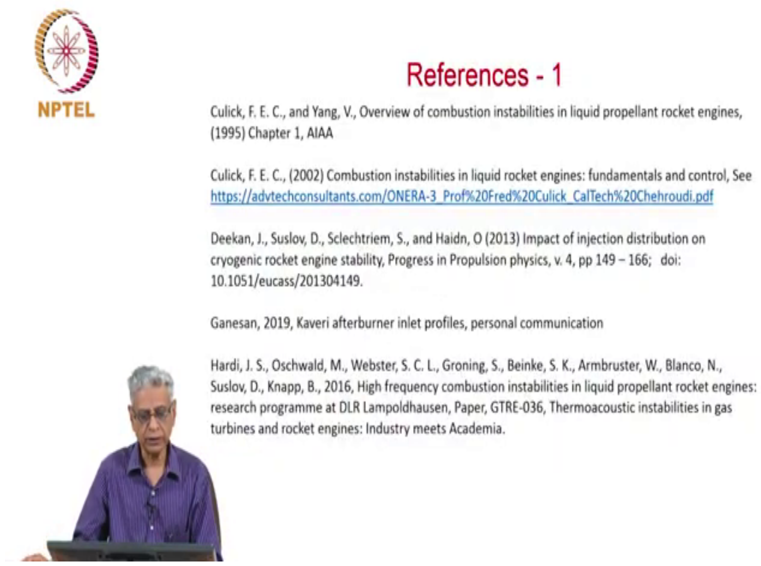

I have described some references here from for the work. And this concludes discussion on tangential mode instabilities in liquid rockets.