Fundamentals of Combustion for Propulsion
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Lecture – 29
Scramjets – Part II

I just want to bring to you an attention of some operational experience Mach 5, 7 and 10; both NASA and VSSC and you will learn a little bit more about them.

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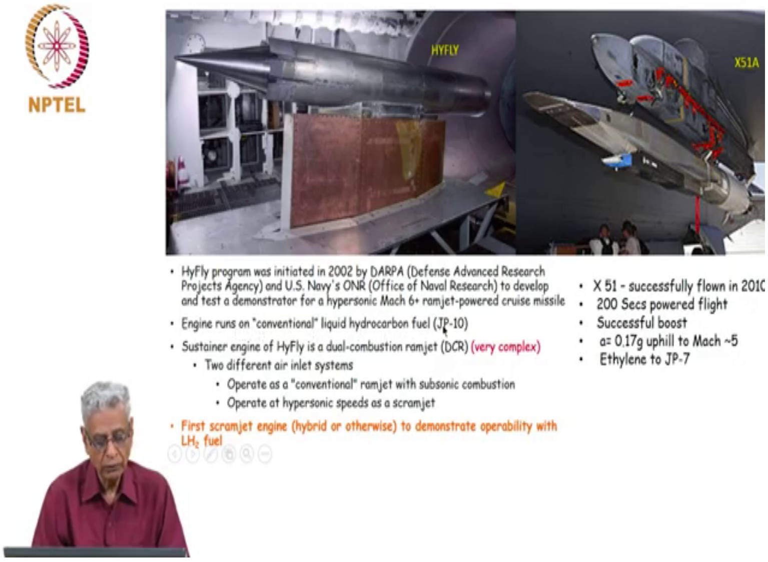

It is the program which was initiated in 2002 HyFly and it ran on what they call is conventional liquid hydrocarbon JP-10. It is not such a conventional hydrocarbon conventional hydrocarbon jet a and well for them it is available so, they use JP-10. It is a very more complex flight profile, it is called a dual combustion ramjet. It operates as air inlet in two systems; subsonic combustion and then later in hypersonic speeds as scramjet.

Well, it was the first scramjet engine to demonstrate operability with liquid hydrogen fuel remember, it happened in 2002. This is that vehicle and you have X-51A it is flow successfully in 2010, for 200 seconds and it had a interesting may be I will come to that later. It use the ethylene as the fuel which is a gas also JP-7 which is also close to jet A.

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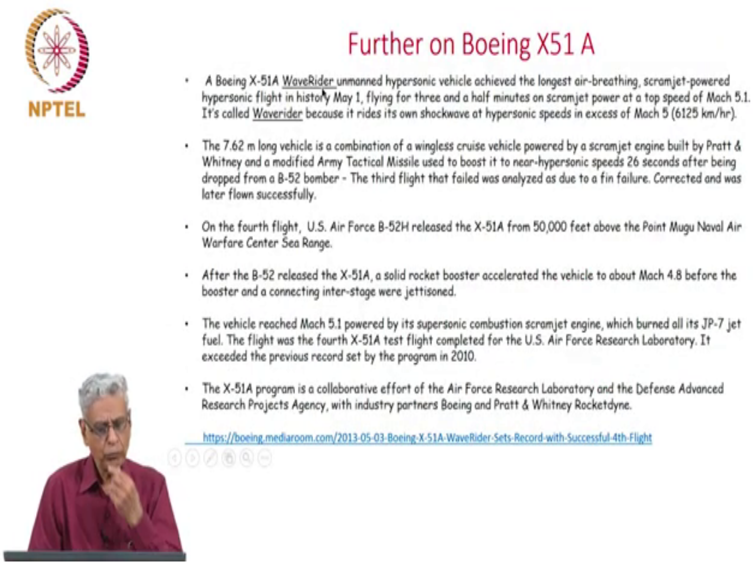

This had a called Wave Rider which I am not going to discuss here. It rides on it is own shockwave and it is lift to drag it is rightly tune by utilizing shock distribution at hypersonic speeds in excess of Mach 5. And this vehicle in combination with a wingless cruise vehicle powered by scramjet engine Pratt and Whitney and some other collaborators 26 seconds after it dropped from a B-52 bomber Mach point 8.

It several flights third flight failed and I discovered it because of the fin (Refer Time: 02:22) back to correct it and later on flown successfully. And in the fourth flight, it was dropped to 50000 feet and released as a solid rocket booster accelerated the vehicle to Mach 4.8 before the boost when the connecting inter stage were jettisoned.

The vehicle reached Mach 5.1 powered by supersonic combustion engine, which burned all it is JP-7 fuel. And well, there is some statement ship recorded, previous record was exceeded as in 2010. You can get more information from this website.

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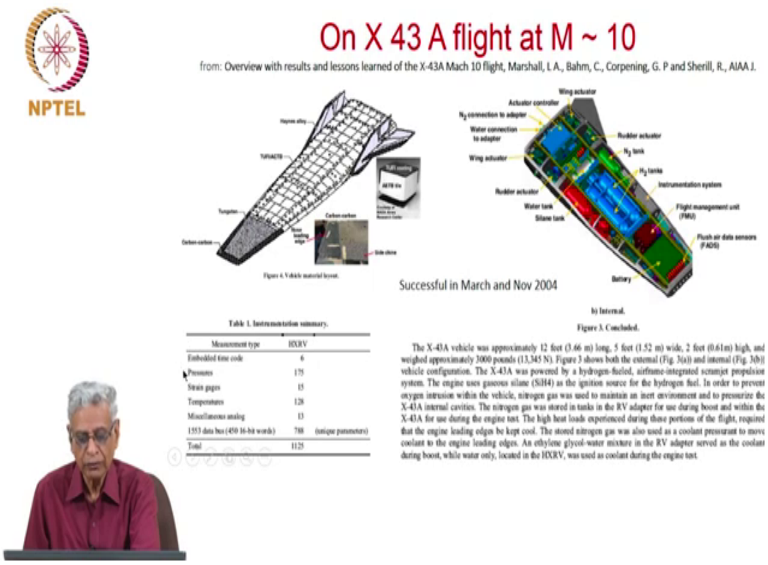

The other important milestone is X 43A which fuel in fact, up to Mach 10. I shown you here the internals of this design, it is not the point is the vehicle is small it you have to make it very compact, you cannot use excessive space. And you have I will read out some of them which has something valuable about 3 3.7 meters.

Engine uses gaseous, it was powered by hydrogen fuel and airframe integrated scramjet propulsion engine understandably, it was gaseous silane rally H 1 as the ignition source for the hydrogen fuel. In order to prevent oxygen intrusion into the vehicle, nitrogen gas was used to maintain an inert environment and to pressurize the X 43 A internal cavities ok. And the high heat loads experienced during the portions of the flight required that the engine leading edges be kept cool. The stored nitrogen gas was used as the coolant pressure and to move the coolant to the engine leading edges.

In ethylene glycol water mixture, in the adaptor served as the coolant during boost the reentry vehicle adaptor and while water body, water only located in the system was used as the coolant during the engine text. So, in the actual flight also they have used ethylene glycol water mixture. So, let us remember that. So, you have therefore, inside this water tank, hydrogen tank, nitrogen tank and in the experiment which I did you find, you will see is to how many system measurements they made to prove that what I did was correct. It may not be required in actual hardware, but in case of test it is required.

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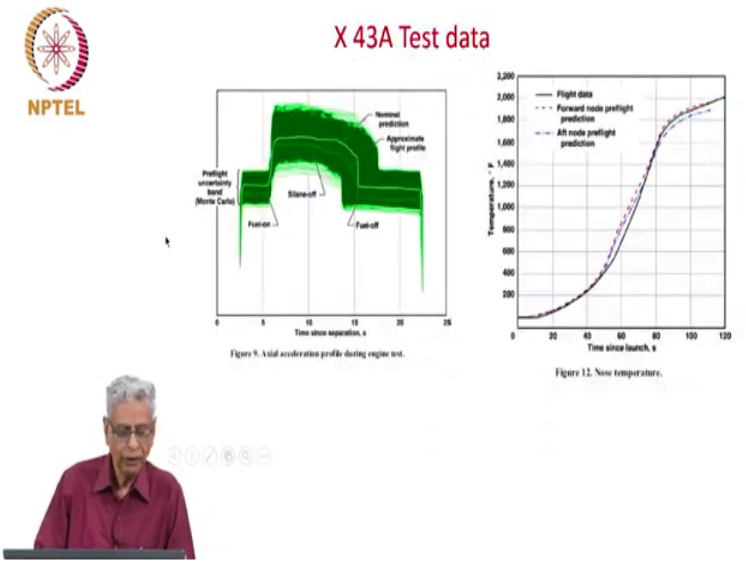

Well, the results seem to be pretty good. Fuel was put on; silane is going to be helping ignition time to be brought down along with that, but then combustion can proceed later; fuel has put off here. And you will find the temperature in the front end their predictions and also the experiment. So, this is the measure. Equivalent performance for ISRO vehicle also had been obtained you know whenever they did flight (Refer Time: 05:38), they make good comparison; the comparison can be an excellent.

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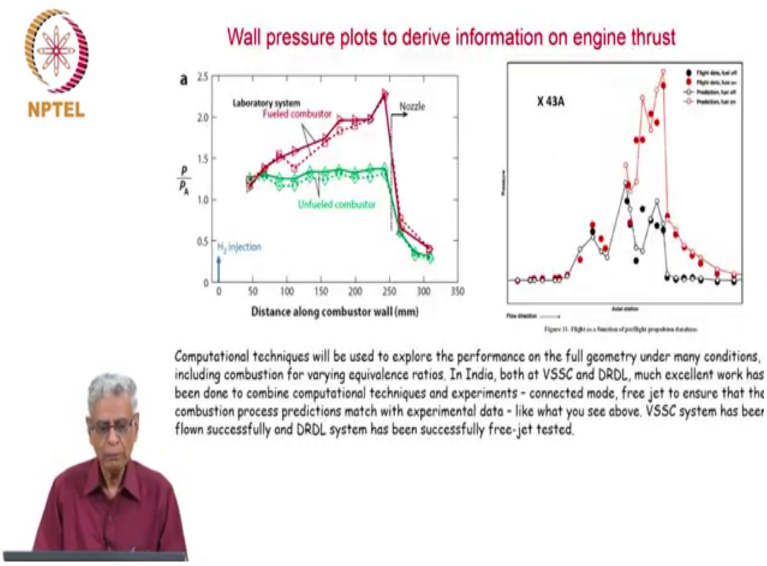

Well, I want to show you the key point about the wall pressure plots. We look at in this plot distance along the combustor wall, which is you know 250 mm; you can go up to a meter as I mention to you. The pressure ratio if it is no fuel just running at as an engine without any combustion process, you will discover that the pressure that is obtained is of this nature and this is a nozzle portion were expansion takes place. But when you put in the fuel and ignited, the pressure goes up and then it expands through the nozzle ok.

Now, it takes 43 A similar measurements have been made. You see with combustion the pressure rise the actual number is not known understandably they would not tell you what the number is. And then it expand through the nozzle and gives you the thrust. The key point to be made here is, when you are looking at measuring performance of a scramjet, a simple and a good measure is the wall pressures. Temperatures are very high, you cannot measure them easily unless you take spectral means, but then it is not possible to do that in reality. But wall pressures can be measured. It was measured also in the case of the ISRO vehicle and the surface of the nozzle if you measure the pressure and integrate that you will get a thrust. Just a just a principle which has been used everywhere and it is pretty good.

And the computational techniques have been used to explore the performance on the full geometry under many conditions including combustion for variety of equivalence ratio. In India both at Vikram Sarabhai Space Centre as well as DRDL, I would say much excellent work has been done to combine computational techniques and experiments. The experiments are on connected mode which means you system connected to air supply and then run the system to measure the wall pressures and you can estimate from that the thrust.

More importantly, they are something called a free jet. So, you have a system which produces Mach 6 air jet coming into a large size, you put your text hardware at a smaller cross section. And therefore, your creating conditions as close to the flight as possible and you can make measurements of thrust. It is possible to do that and also pressures and this predictions have actually if pre-test predictions have matched with the actual experiments and therefore, it is much good to cheer about.

And of course, we must know that VSSC system has been flown successfully and DRDL system has been tested successfully in a free jet.

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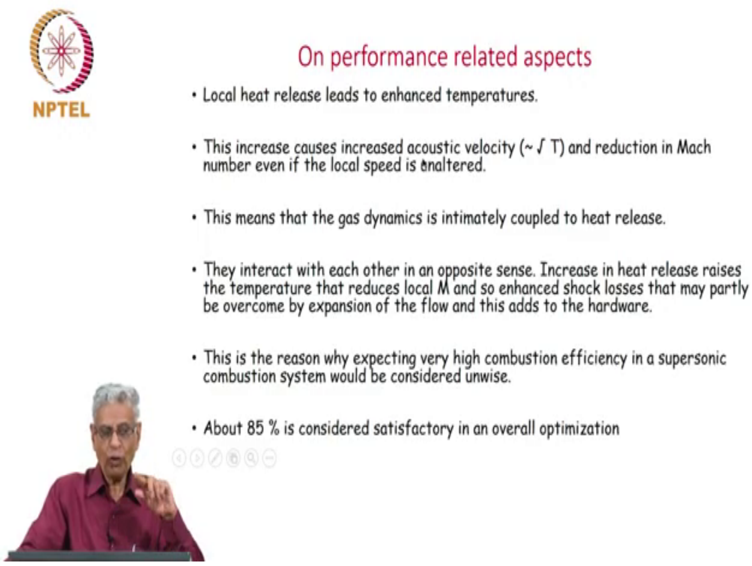

Let me quickly go on the performance related issues. We must know that local heat release leads to enhanced temperatures. This increase in temperature also increases a acoustic velocity.

Student: Ok

The flow velocity is may not be chained, but if acoustic velocity increases. Now, because temperature is increased, what does this do? Locally, if you divide the velocity by the acoustic velocity; the acoustic velocity is increased the Mach number has come down. When Mach number comes down, essentially the it is look like deceleration. Earlier the Mach number are some level; now Mach number has come down that is a deceleration. This means that the gas dynamics is working somewhat against heat release and expansion. We must know that they interact with each other in an opposite sense and therefore, increase in heat release raises the temperature that reduces local Mach number. So, enhanced shock losses that may partly be overcome by expansion of the flow, but this adds to the hardware as well.

This is the reason why expecting very high combustion efficiency in a supersonic combustion system would be considered unwise. In case of a subsonic combustion system, if you are lower than 90 percent; you are considered poor. You should be beyond 95 percent even in the rocket engine combustion system or efficiency 95 percent, they considered reasonable, but you bring it lower than that you say something is not right.

So, in the case of you know supersonic engine 85 percent around is considered satisfactory in terms of overall optimization. If you try to increase it, then the operational efficiency comes down. When I say operational efficiency what matters is a thrust minus drag that is what gives you the ability to fly the vehicle. So, that is not going to be enhance because of this.

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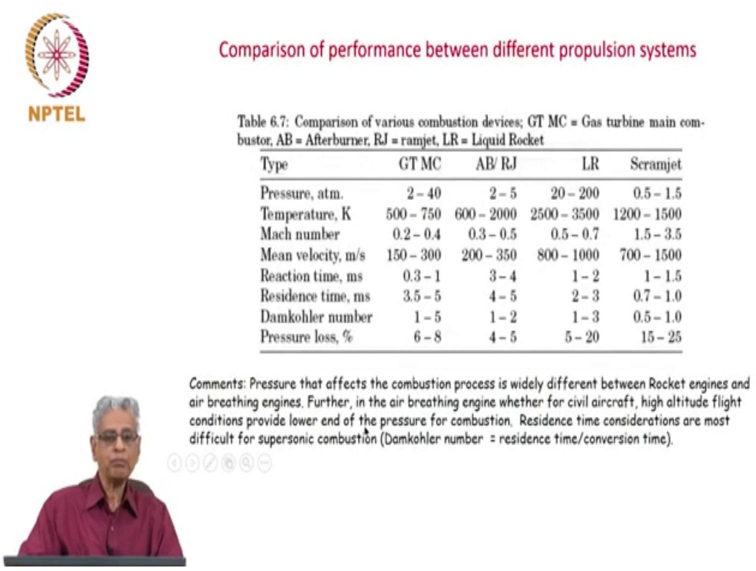

Table 6.7: Comparison of various combustion devices; GT MC = Gas turbine main combustor, AB = Afterburner, RJ = ramjet, LR = Liquid Rocket

Type	GT MC	AB/ RJ	LR	Scramjet
Pressure, atm.	2 – 40	2 – 5	20 – 200	0.5 – 1.5
Temperature, K	500 – 750	600 – 2000	2500 – 3500	1200 – 1500
Mach number	0.2 – 0.4	0.3 – 0.5	0.5 – 0.7	1.5 – 3.5
Mean velocity, m/s	150 – 300	200 – 350	800 – 1000	700 – 1500
Reaction time, ms	0.3 – 1	3 – 4	1 – 2	1 – 1.5
Residence time, ms	3.5 – 5	4 – 5	2 – 3	0.7 – 1.0
Damkohler number	1 – 5	1 – 2	1 – 3	0.5 – 1.0
Pressure loss, %	6 – 8	4 – 5	5 – 20	15 – 25

Comments: Pressure that affects the combustion process is widely different between Rocket engines and air breathing engines. Further, in the air breathing engine whether for civil aircraft, high altitude flight conditions provide lower end of the pressure for combustion. Residence time considerations are most difficult for supersonic combustion (Damkohler number = residence time/conversion time).

Let me now compare various classes of propulsion systems which we have known. I have shown here a gas turbine, main combustion chamber, afterburner or a ramjet. Both of them has similar features; liquid rocket engine and a scramjet. Look at pressure gas turbine combustion main combustion chamber goes up to 2 to 40 atmospheres; it goes to low pressures when you are flying at high altitude. Therefore, the pressure is lower in that sense.

And if you have main combustion chamber pressure is up 10 atmospheres or looking at 3 atmospheres is the actual pressure at high altitudes. In the afterburner in the same range 2 to 5 atmospheres, liquid rocket engine 20 to 200 it can go to 300, scramjet 0.5 to 1.5 atmosphere. The operational temperatures of the inlet is 500 to 750 kelvin at the end of the compressor and delivery to the combustion chamber, after burners 600 and in a ramjet, where the peak temperature can go to 2000 kelvin. And the liquid rocket engine the combustion chamber temperature is go to very high values.

Scramjet inlet temperatures go to 1200 to 1500 kelvin. Typical Mach numbers inside the combustion chamber 0.2 to 0.4, 0.3 to 0.5; liquid rocket can go up to 0.7 scramjet the exit Mach number can go to 3.5 as well. Mean velocities, this we must know that these are not synonymous, 150 to 300 meters per second 200 to 350 800 to 1000 meters per second and in scramjet, it goes to 1500 meters per second.

Student: B B must be (Refer Time: 12:38).

Pardon me pardon me.

Student: B must be.

Inside the combustion chamber.

Student: Inside the chamber.

Reaction time 0.3 to 1 millisecond in case of main combustion chamber; 3 to 4 milliseconds in the case of afterburner, liquid rocket engine 1 to 2 milliseconds in the combustion chamber, scramjet 1 to 1.5 millisecond; this for absolutely lowest in some way. Residence time will be larger and this residence time I mean you will have a length of the combustion chamber divided by the mean velocity gives you a gives you essentially residence time.

You can also look upon that volume of the combustion chamber in the volumetric flow rate in the cyclic system or volume multiplied by density divided by mass flow rate it gives you a mean time scale.

Now, it is important to estimate them whenever, you are in question the simple way of estimating is this. So, you will find numbers like this and if you divide one by the other that is the residence time by the reaction time, you get what is called the first Damkohler number which is measure of the quality of the combustion process. If it is large it means, you are near equilibrium; if you are very close to one not below you are not you are far away from equilibrium.

So, in a in this system it is about 1 to 5, afterburner 1 to 2 and scramjet you go very close to 0.5 sometime. So, you should be very careful about in this case of a scramjet because pressures are low reaction rates are low reaction, times are large and comparable to no time scales. The pressure loss in the case of gas turbine main combustor about 6 to 7 percent, afterburner 4 to 5 percent, liquid rocket 5 to 20 percent is dependent on the on the area ratio reduction that is combustion chamber to throughout area.

In scramjet, you have to allow for a larger pressure loss because entire flow is supersonic in a and the wave loses are very significant.

Student: Sir, any (Refer Time: 14:46) thrust level also (Refer Time: 14:47) thrust means not given in the (Refer Time: 14:50).

When you say thrust levels, see the afterburner, we will only enhance a thrust nevertheless, let me respond to you um. Well, liquid rocket engines go to very large thrust levels, gas turbine combustion chambers refer to thrust levels which are not as large. See in liquid rocket or rocket engines, it is an impulse device. You run that for 100 seconds and you must you must push as you can put as much thrust as you like it is not so, difficult. In the case of a gas turbine main combustor, you wanted to run for 20 hours, you fly from Sidney to some other place your San Francisco, you have to run for 16 hours and that engine has to function all the time.

So, the thrust level is not expected to be large, it is the total impulse which matters ok. So, I mean their numbers which you can check, but their numbers are varying and it is no measure of the quality of whatever you are looking for low because right. Now, you are looking at demonstration systems, the time and you can fly from Sidney to San Francisco in a scramjet in 2 hours and that [laughter] time when the thrust level will be appropriate.

Student: Sir, (Refer Time: 16:14).

Yeah go ahead.

Student: What is the highest flow rate for the scramjet (Refer Time: 16:19).

200 seconds of one of the systems in US and in this country about 20 seconds something like that. There is an intent to design a system in defense laboratory to take it to 1000 seconds or may be 2000 seconds, but I think this touch and go in sense see unless you build the foundation properly what do what is at limit (Refer Time: 16:47) materials. See you need something which runs for you know 20 seconds, you can make some choice of materials. But when you go to I can see, it means it the whole system as achieved steady state and under no condition should erosion in case of any component that is the key issue. The other key issue is it was about the cooling as you increase Mach numbers the heat load into the system will become excessive.

Now, one can ask a question, can we not use regenerating cooling as in liquid rocket engine you cannot because liquid rocket engine, you are carrying both of them in the very oxidative fuel ratio is 3 or 2.7 and so on and operating time is something, we can use that there is generating coolant, but in the case of air breathing engines 1 is to 14, 1 is to 20 is the kind of ratio which is there. The fuel available for you to cool is very small the surface area for cooling is large. So, the question rises how do we handle it is.

Now, there are methods of handling them, but designs have to take place, experiments have to be done all these are in the preliminary stage not only in our country everywhere else. So, it may take time to further to happen.

Student: Sir.

Yeah.

Student: When (Refer Time: 18:13) is.

Student: Till rally criterion plane in only in the functions of (Refer Time: 18:17).

Sorry.

Student: Rally criterion.

Rally cycle.

Student: Rally; rally criterion.

Student: It is anything to fly with this supersonic combustor.

I am I am did not get the precise focus.

Student: rally criterion.

Rally cycle.

Student: Rally criterion; criterion in the rally flow.

Rally flow.

Student: Yeah.

Yeah look all aspects of frictional losses have to be accounted for there is no need to doubt that fact how do you account for it.

Student: Ok.

You can actually physically compute the flow, if you want, but that is very difficult and you may not be able to do it in a complex situation like what you have. So, what do you do? We are write conservation equations. Conservation, equations contain the fact that there is a rally flow, rally flow comes from conservation equations right.

So, all aspects related to frictional losses or wave losses or accounted for in an actual computation. So, you may be rest assured that all aspects are accounted for in the design. Is that answer your question?

Student: Yeah, as an similar (Refer Time: 19:28) these two spin add of heat to the supersonic stream.

Yeah.

Student: As suppose it will distillate the flow.

I am not disagreeing I am saying all that is accounted for in the design, it is accounted for I am I have no designating point you are making yeah.

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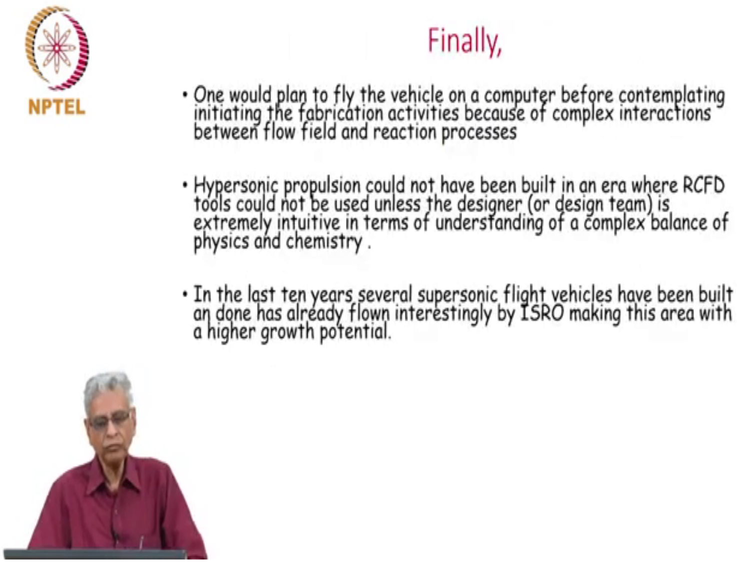

So, finally, I want to say, that you want to fly a vehicle on the computer before contemplating initiating the fabricational activity because their complex interaction between the flow field and a reaction.

So, all aspect that you mention have to be put together in the code it is there. I mean if you write conservation equations, how can you be outside of rally flow? It is there in it. Hypersonic propulsion I think would not have been possible in an era where reacting computational fluid dynamics could not be used unless of course, the designer or design team is extremely intuitive in terms of understanding complex balance of physics and chemistry.

I am saying that somewhat carefully because if you see S R 71 which was built by John Kelly if I had been ask the question little earlier to that; suppose you want to build a Mach 3 engine aircraft and then therefore, the engine corresponding to that would be able to do that it was not I would have made may be made a very similar statements.

But you know he took he is such a such a spark man, if you built things which are far out in time at his time. So, it is possible somebody understands all have quickened puts down this number simply I work otherwise for common man computational fluid dynamic is the right tool. In the last 10 years several supersonic flight vehicles have been built 20 years in (Refer Time: 21:28) if been flow and one interesting development there in ISRO and something will be done in D R D O and so, there are much that you can look forward towards possible participants in (Refer Time: 21:41) coming types that is about all that I want to tell you at this time.

Thanks.