FINAL PLENARY SESSION TRANSCRIPT

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Reports and Discussions of Breakout Sessions

Katz: Reports from the in-house working groups. There was a question as to whether I was to give one of those reports. Thank goodness I don't. Anyway we have three reports: The first report is a joint one on flow control with Mo Samimy and Howard Hodson together as co-chairs. The second one is from Dave Williams sitting there in the corner and the third is from Om Sharma, you are the presenter.

Sharma: Oh, thank you.

Katz: I just wanted to make sure.

Flow Control

Samimy: First, I would like to take this opportunity to thank the organizers of this meeting. This has been a really great meeting and I have enjoyed it very much. This is the first time I have been in this workshop, because this is the first time that external flow control has been part of the meeting. So thank you very much John, Paul, and Mark. And many thanks also to the sponsors; Lou is here from NASA, thank you Lou, and also thanks to AFOSR and ONR. You can see the group membership from the board *(PowerPoint slides appended)*. This was a large group. Howard Hodson and I were the co-conveners. Initially this was two different groups, external flow control and turbomachinery but Howard suggested that we combine them and we did. As you can see from the membership list, this was a large group with very different backgrounds. I normally associate people with the different conferences they normally go to - all the way from APS meetings to IGTI meetings - from the very basic to the very applied. We had two nights of very good discussions. We came up with some ideas that we are going to present today. Of course I am here to present the outcome of our meetings, but I am hoping that other members will step in and offer their ideas in case I missed something or even miss-spoke.

Let's start with the report – as you know – when we are talking about flow control it is a multi-disciplinary type of work. So it involves many people and disciplines. This group first discussed the important issues associated with flow control. As you start doing flow control what are the issues to which you really have to start paying attention? That is the first part I am going to present. Then in the second part I will present some challenges – problems that we should really be looking at. So as far as the issues – if you want to control a flow, you really need to understand the flow physics, because anything that you do comes from the flow physics. The design of the controllers, your decisions on the actuators, sensors, reduced order modeling and all of that, would be helped if you understand flow physics. And you have to have a specific objective – what exactly are you controlling? Are you trying to reduce drag, eliminate separation, reduce noise, enhance mixing? So you have to have very specific control objectives.

From all the talks we have seen here actuation is extremely important and it is very problem specific. It depends on what problem you are dealing with so you have to design and build actuators for that specific problem. Sensors obviously are very important, especially when you are dealing with feedback control.

Consensus was that when you dealing with flow control, you must take an integrated approach; from the beginning you have to take into account every aspect of it and even maybe to modify your experiment, your geometry, to go along with the actuation, sensors and control models.

Development of tools is very important in this multi-disciplinary problem. The tools include CFD, reduced order modeling, controller design, understanding and utilizing the instabilities of the flow, etc. So, in order to have success in flow control, we really need to develop these tools.

Having discussed various issues and development of tool, we can now put forward some problems that we can start working on. So we decided to call it "Flow Control Grand Challenge", to identify problems covering many different areas that you have listened to over the past two days or so, and these problems include many of the issues that we have discussed but also the nature of the problems are very different.

The problems are:

Jet noise control:

This is Howard's idea. With jet noise control, not only we are dealing with multi-disciplinary problems but also this is a multi-agency problem. If you look at our sponsors, Lou is here from NASA. NASA is very much interested in jet noise mitigation, more on the civil aviation side. The Navy is very much interested in noise from tactical aircraft. Aircraft taking off from aircraft carriers make a lot of noise; with all the crew in close proximity of the jet, they really have a tough time to protect their people. If you look at Air Force, up until recently they were not really interested in jet noise, but now they are, because everybody recognizes that in the design of new aircraft, I am talking about tactical aircraft, we are going more and more after performance; and, unfortunately, with high performance also comes a high level of noise. So all the agencies are interested in this very challenging problem.

Aero-elasticity:

This is the second problem. Last week many of us in this workshop were at the AFOSR meeting in DC. For the first time they brought aero-elasticity and flow people together.

When you listen to people on the aero-elastic side when it comes to flow aspects of the problem, they are just dealing with a very simplistic model of the flow. On the fluids side we often ignore fluid/structure interaction. So it is becoming really important that we bring together these two groups. This is a problem that integrates the traditionally two separate disciplines and specifically looks at replacing control surfaces with fluidics, which involves flow-structure interaction. This is a different problem than the first, but also a challenging problem.

And then the last one:

Three-dimensional bluff body flow control:

Again this is very different than the two other problems. It is a very rich problem. It has many applications. It goes beyond aerospace application, for example significant automotive application.

So that is all I was going to present with the time limit that we have. So, from the floor, Howard, would you like to add anything?

Hodson: No, I don't think so.

Samimy: First, before I answer any question, do any of the members want to add anything?

Pollard: I wasn't a member of this but when you are talking about jet noise control was there any sense within the group of whether it was considered passive or active? Or is it selective, passive and active, depending on the application.

Samimy: Let me tell you what I think then others can come in. When you are talking about flow control and grand challenges, you are really talking about active. We really did not discuss passive control in this context.

Glauser: I do think, in the context of the Grand Challenge concept, we do need to flesh this out more. Identify what are the specifics that we might want for each one of these for the Grand Challenge to meet. People maybe will use a combination of passive and active and so on. We don't want to be too prescriptive. I think one of the reasons why we liked the Grand Challenge concept is that we feel that it allows innovative, bright people to come up with maybe different kinds of ideas to try to deal with each one of these problems. We are thinking that DARPA has the Grand Challenges; they've done this for various things. It has been widely popular. They have got a lot of people interested in it and so on.

Samimy: One additional comment I have that I did not mention in my presentation: in jet noise or in the flow-structure interaction, we should let the agency come up with the details of the problem. Then you identify what type of, let's say, geometry, structures, experimental arrangement and so forth to use. It is possible, for example, to have an experimental facility available either at NASA or at the Air Force. Then a proposer might want to design their own additional model; to bring actuators, sensors and put it there, run the experiment.

Glauser: One other thing. We feel that all of these things would interact with wind energy, for example, or the automotive industry and so on. Certainly one of the things, when we get this information to John, Rob, Doug and others will encourage them, or at least make the suggestion, that maybe you want to reach out to the Department of Energy and bring that aspect in as well. When you think about wind, it may not be jet noise control but there are noise issues; there could be some commonality there and so on. Certainly with the bluff bodies in the automotive industry it makes a lot of sense.

Solomon: You have stayed away from internal flows in turbomachinery. It is a very difficult challenge to apply active flow control to, but I wondered whether your initial thought was higher pay-back or whether you think the internal flow problem is too hard.

Hodson: The truth of the matter is they never got around to talking about it.

Gostelow: Let me just give an example of a passive flow control device that has been successful in turbomachinery for thirty years or so, which is the so-called “golden rings” over, particularly, industrial fans, ventilation fans even and so on. This is passive flow control which does wonders for stall margin and has potential, and has been used in varying forms, in the aerospace industry in aircraft engines and so on. This is just one example of a passive flow control device which is in successful use these days.

Samimy: Well, also in jet noise, for example, nowadays there are chevrons, that have been successful in reducing noise by 2 to 3 dB. Let’s say one could combine some sort of active control with chevrons for noise mitigation. So I don’t think we are ruling the passive control totally out. So if somebody becomes creative and combines different controls it is fine.

von Terzi: I was on another panel but I was wondering whether issues like multiple objectives came out. You know, you have heat transfer in turbomachinery, unsteady separation, transonic flow. You could use film cooling from the high pressure turbine flow. So those multiple goals might be very difficult to implement. Is this something going on, is it on the radar at all?

Samimy: From my viewpoint it is possible. For example, since I work in the jet noise area, you can have jet noise mitigation or mixing enhancement for reduced detectability. You can use the same actuators but different instability modes, so it is possible to have different objectives. These are very detailed issues that need to be looked at.

Glauser: I guess we didn't talk about it in detail but we did talk about the necessity of understanding the control objectives, how that would play a key role in what you would go about doing. So that could be utilizing multiple components, so I think it could be covered under the control objective in some sense.

von Terzi: The reason why I think it is important is that a lot of the positive for gas turbine control in turbomachinery is the additional cost involved. If you wanted to heat air for example (of course you don't want to) but if you had to do it anyway and you can do it in a smart way, then it is possible that you might even reduce the air for cooling while getting an aerodynamic performance enhancement. And then it becomes very, very attractive. So that is why I was thinking that. It makes it more difficult to achieve both objectives because very often if you enhance one - you have a no free lunch principle and I think it holds very often. So it is very, very tricky. But if you go around it maybe you can achieve it and maybe they start talking to us.

Hodson: All I was going to say about the jet noise issue was if you are after noise attenuation then obviously the standard you start from should be a good one. Things like the chevrons or crinkly edges should be where you start. So whether you actually take that and enhance it or go in a different direction is up to other people.

Samimy: Yes, that is the benchmark, the current technology from where you start your research.

Solomon: That is the trouble. A lot of our passive systems are already pretty good in a lot of ways. It is hard to add enough value to make it worth the expense and complexity of actuating active systems.

Samimy: Yes. When you are looking at control you have to put everything on the table; in terms of expenses, in terms of complexity, in terms of what does it take to put it on the system, its weight and all the other issues. Yes, Om.

Sharma: A couple of points. Jet noise in military engines is very high. It will be of the order of 135 dB. It is higher than what you would expect in commercial engines. This is due to relatively high levels of gas velocities exiting exhaust nozzle of the engine. You may be able to control it by enhancing the mixing of the gas stream and by reducing large scale flow structures in the jet exhaust. We may be able to utilize flow control or design the engine exhaust system; I don't think you can tweak way out of the problem.

Samimy: Absolutely. If you look at commercial aircraft, nozzles are relatively simple. When you look at military aircraft you have variable geometry nozzles introducing all sorts of shock waves; the noise is much higher and of course the control is more of a challenge.

Sharma: You are right. I will make one statement about commercial aircraft noise. The best way to reduce the noise in commercial engine is through reduction in the fan pressure ratio and by increasing the by-pass ratio.

Samimy: But that is what we have done for the past fifty years.

Sharma: But that is what reduces the jet noise.

Samimy: Absolutely.

Sharma: Variable airfoils are used to control flow at off-design operating conditions in fans for military engines and compressors in both commercial and military engines. The variable airfoils are historically designed to provide good flow distribution in a one dimensional sense invariably yielding unfavorable conditions in the end-wall regions for the downstream rotors. This can produce aeromechanical issues as the engine operates at off-design conditions for a large fraction of the operating envelope. A focused effort is needed to develop design strategy for variable airfoils. So looking at a more effective way of controlling the flow using the variable airfoils may be a worthwhile area to get into.

Glauser: I'm wondering if we couldn't, under the fluidic aerodynamics ideas that could be used for flow control concepts to do some fluidics service; this might be something that could be done.

Sharma: I agree. It could be done as part of the same package, because aero-elasticity problems also appear due to the off-design performance issues. Flow control is also needed for the inlets of embedded engines planned to be used for the blended wing bodied aircraft. I wouldn't be surprised if we start using these types of aircraft for transport applications.

Hodson: I think that is a very hard one because you are taking a very thick boundary layer off the fuselage, which basically is vorticity, and you are processing it through an S-shaped duct. The laws of physics say that is a large scale phenomenon inside the duct and flow control isn't about large scale phenomena.

Sharma: It could be flow control, but somehow you want to manipulate the flow so that the fan can efficiently operate in the engine over a wide range of flight conditions.

Glauser: That might be stored between our second and third bullets there, because in some sense one could think of doing this with fluidic concepts.

Solomon: You may not be able to improve the primary flow, but you perhaps could ameliorate the secondary problem.

Glauser: And perhaps if you hit it on the right spot and at the right time you might be able to do something.

Samimy: There was a workshop at NASA last spring on inlet flow control. That was more on supersonic but still similar type of issues. It was on what type of actuators you can use to reduce shock-boundary layer interaction.

Sharma: This one would be just flow and boundary layers so I think the area is one where this community can have some ideas.

Samimy: I think the idea was not to be all inclusive, to list all the possible problems that flow control can address, but to pick some that are manageable and can be put forward. Like these three, we thought that these include many different aspects of flow control but I am pretty sure that there are many other ideas that need to be addressed but we could not include every possible item.

Povinelli: I have a comment. You certainly have picked problems that would engage everyone's talent that's in this room - possibly beyond that. Just looking at the first one, we heard about jet noise reduction. At least within NASA we are looking at tens of dB reduction, not just two or three. We are looking at problems that tweaking the systems will not give you the answer. We are also not very confident that the high by-pass systems will allow you to reach the kind of goals that we have set for the commercial sector. So it is going to take a lot of innovation, it is going to take a lot of clever understanding of fluid mechanics and flows in order to accomplish these goals. Just to give you some indication, as we push aircraft technology further in the commercial sector, the solutions that we get from the airline and the propulsion companies is that the only way they see to lick these problems to meet future goals is to cut back on the power of the engines so that you are taking off on only 40% or 50% of the total thrust of the engine to keep the exhaust velocities sufficiently low, below 1100 ft./sec., in order to meet take-off and landing requirements. It is only after you get away from this sensitive area that you can start to engage additional power. I say that just because it is an indication of how difficult the problem is, as viewed by the propulsion and the aircraft industry right now. So we are talking about supersonics in order to meet those conditions. Practically all of the engine companies are telling NASA about the way they would solve it. It is just a band on the engine to get below 1100. So it is a very challenging problem. I think you picked one that will engage this whole community.

Samimy: I think that really was the idea to pick very challenging problems.

Katz: If there is nothing else, gents, let's go to the second speaker.

Boundary Layers, Transition and Separation

Williams: This topic made for creative discussions. They were doing some work on it last night and they didn't look quite so good this morning. This was a great group; full of experts in the area so I was quite happy to sit back and take notes and let people talk. We laid out the objectives that Mark asked us to consider, which were to discuss the key issues, list potential paths to explore those issues, to try and identify areas of consensus or no consensus and to try to put together an informative document for program managers. I am not going to read all of this but we came up with eleven points that we thought it important for the community to recognize. I will read the main topics.

The first is *the effects of roughness on boundary layers*, particularly turbulent boundary layers, needs to be addressed. There should be efforts to understand how roughness affects attached flows in zero pressure gradient situations and especially when pressure gradients are present around airfoils. A lot of discussion and consensus on the need for experiments and acquiring these data. The sub-bullets are more specific comments. I hope some form of this will be passed around.

The second area was discussion on *actuators in turbomachinery* and we spent a fair amount of time on this topic. I would say there was not consensus between the turbomachinery people, who had a rather strong statement that actuators are not being used, and while we agree that this is the case for active flow the point was made that you can think of film cooling in low pressure turbines as an example of actuation. The thinking from the flow control people was that if you can do that then there is an example of the existing hardware necessary to do active flow control. So perhaps changes to unsteady types of blowing we can consider, simply as a thought problem. A number of opportunities, I think there was a consensus on. Using actuators, for example, for control of shock interactions, shock attenuation in turbomachinery. I should also point out that our group spent a very significant amount of time discussing turbomachinery issues. So there are quite a few sub-bullets.

Streamwise Vortices. There were many questions raised on this topic. How do they manage to persist, and interpretations of the flow visualization that we are seeing. Some effort needs to be expended on making sure that the interpretations we are deriving about the persistence of these vortices, based on flow visualization, needs to be confirmed in some way.

Topic four was *flow instability modes of laminar separation bubbles*. The feeling is that the physics of the bubble itself are well understood and well modeled. But, if we extrapolate to the bubble bursting problem, that is the limit. How can we improve on our understanding, how can we make predictions, there was a significant amount of discussion on that.

Secondary Flows. After the first night I sent the rough notes out to group members and they made comments and sent them back and this was the brilliant line from the turbomachinery side – "Secondary flows are of primary interest to turbomachinery". RANS is probably not sufficient at this point in the tip region. A number of sub-issues should be investigated. Again turbulence and vortex-shock interaction are effects that are recommended for study.

You can see the list, many, many topics were discussed. For example *heat transfer*, tip clearance flows, how to predict the losses around these flows were all items we spent time on. Heat transfer models used in the turbomachinery community are based on analogy and are considered insufficient. There was a strong push, we have it as a single bullet, it says we need cooperation between experiments and simulations. This, in my opinion, is the best way of making progress in any of these areas. So that is recommended.

The question of benchmark experiments on *corner flow separations* was brought up and is an area of interest to both turbomachinery and the more fundamental fluid dynamics people. We discussed ways of varying pressure gradients in corner flows and you can read the detailed sub-bullets on that.

We talked about *transition* and transition models in industry and how they are being used. I guess I personally do not have much understanding or knowledge of this field but I think at one point we had the comment that any model is better than no model. So the crude models, SST of Menter and Langtry, have been integrated into the CFX code. I guess the results are taken on faith because it is not a physics-based model, it is based on correlations. So limited experimental data is available, was the feeling from this. So there is a need for more experimental data on transition. The last comment here is an example of the feeling of the group that there is perhaps not enough communication between what is being done in the laboratory and that knowledge being transitioned to industrial applications. For example, this note was added this morning: "What is the impact that the knowledge on the relation between roughness-induced transition and transient growth has had on modeling?" This is actually a rhetorical question, because the answer is NONE. There is no correlation.

It is recommended that perhaps *more formal design methods* be used in the way that experiments are being designed. They have a specific name for this and I have forgotten it. It is used by chemical engineers. It's a way to set priorities on how these experiments get designed. Perhaps something like this applies to the Grand Challenge.

Bullet ten is what I mentioned earlier: there is a strong consensus that *experiments and simulations need to be coordinated* with each other and a number of examples are given where an improved understanding of these flow fields could be achieved by cooperative efforts.

The final bullet is that *massive data bases already exist* and should be exploited; a number of examples of numerical and experimental data bases are given, and the question is 'have people spent the time to take advantage of that data'? The feeling is 'No'; more effort needs to be applied in that direction. So those were the brief summaries. I hope you've got something to work with. We need help.

<u>Katz:</u> Comments?

<u>Glauser:</u> I noticed that the issue that was brought up earlier, that of utilizing the current technologies that are being used for cooling in some way. That was, I think, one of your early bullets. That is, I think, a nice intersection with the flow control side. So I think what is nice is that it is there in one of these documents that we are putting together so our job will be to make some connections there.

<u>Williams:</u> You are talking about the use of actuators?

<u>Glauser:</u> Right. And thinking about film cooling as a form of actuator current.

Williams: It is interesting looking at this problem from two different perspectives because you have simulations and the laboratory people saying 'Why don't you do this?' and the industry people rightfully saying 'Actuators will have to buy their way onto the engine'.

Solomon: Bear in mind, for example, that with cooling flows you don't necessarily need the highest cooling flow rates that you needed at take-off when you come back to cruise. But, just to get one actuator on an engine to control the bulk cooling flow rate is a very difficult task. There are lots of questions in getting that to work in the environment, getting it to be reliable enough.

Hodson: Just having a binary switch.

Solomon: Yes. Just an on-off or a high-low switch, one switch for the entire cooling flow, is a massive problem. If you want to actuate undoubtedly you have several orders of magnitude of difficulty. Still it is a very interesting idea.

von Terzi: There may be potential in one topic, for instance secondary flows, which you need to protect the platform, for example. To keep flow out you bleed air all over the place, and even, it doesn't have to be active.

Solomon: This is what I mean. We are already passively blowing and if that was improving the performance, we are already getting it.

Sharma: Mark, maybe I differ a little bit on the direction we are going in. About 30% of the air leaving the high pressure compressor is used to cool the HP turbine and maybe the first stage of the LP turbine. Cooling air is very essential to assure blade integrity. As I was saying the other day, typically gas temperature is anywhere between 800 and 1500 degrees hotter than the melting point of the metal. You cannot afford to have hot spots. Please discuss it with the engine community before you start fooling around with smart cooling flow concepts. We all want to reduce the amount of cooling air, but we cannot afford to create problems that result in thermal issues in turbines.

von Terzi: That's right but the reason for flushing the whole turbine with air because you don't know where and when it grows hot. You do it with an average temperature.

Hodson: That's not fair. They do know where.

von Terzi: No, but it comes out of the combustor and it goes into the first stage of the turbine; you have hot streaks coming out and people were talking about getting to know more about when they occur and how they occur and so on. So all I am saying is, you have to design your cooling to withstand the maximum heat at any time, and if you were to know this in a better way, when it occurs, how it occurs, you can reduce the air required.

Sharma: Please get guidance and requirements from the engine community before you set up experiments to develop smart cooling flow strategies.

Glauser: I think it was just a general suggestion that we might be able to think cleverly about some things we are already doing. Your point is 'if you are going to do that, keep your systems-level thinking in mind'.

Avancha: One important topic that should be given more attention is related to translating knowledge that one obtains from LES and DNS simulations. A lot of people are doing LES nowadays in combustion and with moving planes. Building these big data bases helps to improve RANS models. I have not seen a whole lot of that happening. Whether we like it or not RANS is the mainstay of all the engine companies for design. But I believe there is room to tweak RANS models, specifically targeted with an eye towards the flow. I think that is important, bridging that gap, using the information that you get from LES and DNS predictions to improve RANS models. I think that could be crucial.

Williams: Somewhere there is a subtitle that is addressing the issue of studying the basic assumptions that are behind the models of RANS and testing them in that respect.

Katz: I just wanted to add that even LES has substantial uncertainty associated with it, especially in wall-bounded flows. So for the flow within turbomachines, I don't know if I would class LES as suitable. So, around the end walls I have seen some funny things turning up in simulations.

Williams: I think it is a very extensive effort. Thank you.

Katz: He's an impressive guy. We were all sitting and arguing and he was sitting in a corner typing.

Williams: I selected my chair wisely.

Katz: Any more questions, comments or complaints? Now we will invite our third speaker.

Efficiency Considerations in Low Pressure Turbines

Sharma: Efficiency Considerations in Low Pressure Turbines, that was the topic. It was, I would say, a little bit more focused, just because we were well directed by Dr. Gostelow. We had eight participants: Howard Hodson stepped in a couple of times and made some good comments. Ravi from G.E., John Clark from the Air Force, Paul, Howard, Inga (she's doing the design studies at MTU, so I would say that in the whole of this group probably Inga is the only designer), Lou has a lot of experience, and we had Ken, from academia along with Howard and Paul.

I would say we focused it on trying to look at the low pressure turbine. Could we improve the performance of the low pressure turbine, as it is operating in commercial and in transport aircraft?

We started off from a couple of publications from Aviation Week indicating a *shortfall in low pressure turbine efficiency* by two major aircraft engine companies when they started using high lift airfoils. I would say that high lift airfoils in a way originated as a result of the work that was started at the first Minnowbrook meeting some 16 years ago. We held a workshop to discuss issues in low pressure turbines at NASA in the late 1980's, early 1990's. The information provided at the workshop indicated that there was a large lapse in the efficiency of LPTs operating at the sea level take-off and altitude cruise conditions. The technical community at the workshop concluded that the observed change in the efficiency of the LPTs was due to the effect of Reynolds number on turbine airfoil boundary layers which encounter a change in Reynolds number by almost a factor of two. NASA initiated research programs in this area and funded the first Minnowbrook workshop. From there on we put in a lot of effort in the area of trying to understand boundary layer behavior on turbine airfoil surfaces that was dominated by the transitional nature of the flow. A number of publications came as a result of this research and it generated good interaction between industry and universities. High lift airfoils originated, in a way, as a result of this interaction. Applications of the high lift airfoil to-date, by the three major companies, showed that the performance gain was not to the level they had expected. The reasons for the disagreement between the expectations and results are not understood and this was the main issue.

We have made significant progress in developing advanced design tools for designing LPTs over the last 20 years. We have started utilising the RANS-based CFD codes and we have also started using models to acknowledge the existence of laminar and transitional boundary layers on airfoil surfaces. How has this changed design technology? Have we improved performance? I had discussions with a number of turbine technologists from designers of large commercial engines. Their comments were: 'We haven't made progress during the last twenty years. We haven't improved the LPT performance. Maybe the performance is now at the level that we can't improve further. We expected to improve performance and we didn't get it'.

Next was to discuss opportunities to enhance the low pressure turbine efficiency further for commercial aviation and military transport aircraft. Fuel burn is becoming a big problem for the air force as well. Fuel costs are billions of dollars a year. The air force is transporting fuel and the low pressure turbine again plays a big role in the fuel burn for both transport and commercial aircraft.

We have two recommendations. The first is to *hold a workshop* with participants from the aviation propulsion industry in the USA and the European Union to benchmark status and to identify opportunities to improve the specific fuel consumption, and reduce emissions through the enhancement of low pressure turbine performance.

Some of us were worried about 'Do we have the right information from the Aviation Week publications?' Some of us thought the use of high lift airfoil design technology really was focused on reducing the weight and the cost of the engine. Not necessarily performance. So there was confusion. At the moment the design communities and marketing organisations within the large engine manufacturers are not happy. They think 'we have invested in a lot of resources to make progress on this problem but we haven't really got back from our investments'.

The second recommendation was that: '*We should focus the low pressure turbine research effort to align with the NASA's Environmentally Responsive Aviation (ERA) initiative*'. LPT has larger impact on the fuel consumption of the engines used in commercial aircrafts than any other component. If we improve the LPT efficiency by 1% then the fuel consumption for the engine reduces by anywhere between 0.7-0.95%. An improvement in the efficiency for HP compressor, HP turbine and fan yields reduction in fuel consumption by is about 0.6%, 0.6% and 0.8% respectively. So, if you really want to reduce carbon dioxide signature, emissions and noise then we need to focus on improving the LP turbine efficiency for the best return on investment. Over the last twenty years, the large engine manufacturers have outsourced LPT design tasks to other companies. These companies have come up to speed with the LPT design technology but they have not produced improvement in the turbine efficiency as observed in other components (HPT, HPC & Fan efficiencies have improved by 1-2% over the last two decades). There are also indications that the major engine companies are losing expertise in the LPT designs.

That's what we talked about, now I would encourage the rest of the participants to make comments.

<u>Gostelow:</u> I certainly think we ended up converging on just what Om has outlined. We probably started out reasonably far apart and we were pretty much in agreement by the end of the day. Right?

<u>Povinelli:</u> All I would say is I think the focussed comment at the end of the chart here is consistent with the national aeronautics policy as signed by the President two years ago. So it involves all of the government agencies in this country and I am sure is in alignment with European objectives as well. So I think if we were to provide a focus of this sort it might supply advances similar to what Om mentioned at the start of the charts. It's kind of a parallel activity to what we did some ten or fifteen years ago and was a topic that was vigorously pursued by Minnowbrook and the engine companies as well.

<u>Sharma:</u> I would agree with Lou and say that in addition to focussing on fans and combustors; look at the low pressure turbine as well.

<u>Avancha:</u> Yes. Om, I think your outline reflects what we had discussions on during the working group. I am seeing steps going forward and the benefits of understanding more about the achievements of what has happened.

Sharma: Yes. Again, there is an important role for rigorous numerical and physical experiments. We may have to resort to DNS simulations to perform numerical experiments to ensure that the flow-field (especially the laminar to turbulent transition process) is predicted from first principles. These experiments need to be conducted to answer clear questions to provide guidance for developing performance improvement concepts.

Seume: Do you feel that you have a fruitful way of going about analysing the DNS results? In a previous Minnowbrook meeting it was felt that a lot of information generated by DNS could not really be captured and translated to understandable data sets and I wonder whether the community has any progress on that or not. I think that the level of detail that DNS provides is, of course, much higher than the detail that we gain from most experiments, but integrating that detail to tangible flow properties seems perhaps to lag the development of DNS techniques.

Sharma: In my opinion, DNS simulations could be utilized to answer some fundamental questions about the nature of loss generation mechanisms on airfoil and end-wall surfaces in turbine passages. On the airfoil surface these could provide guidance on the impact of shape of the pressure distribution, airfoil surface curvature, Reynolds number and inlet turbulence levels on the nature of boundary layer development and loss development. This could guide the development of optimal pressure and curvature distribution for airfoil surfaces and assist in developing optimum lift airfoils. DNS simulations could also provide additional guidance on the impact of flow-path divergence, aspect ratio, gas turning and load coefficient on the loss generation in end-wall regions. I must remind you that I'm recommending DNS simulations because of their ability to predict flow features such as the breakdown of laminar flow, the evolution of downstream losses and the prediction of secondary flows.

Katz: I think G.E. is bringing up another issue, based on experience associated with DNS data, for example for isotropic turbulence. The people who did the original simulations made the data available to the entire community. And twenty years later you still have people extracting information, doing their data mining and further analyzing it. Analysis of data, and extracting knowledge out of DNS data, is a totally different process from the simulations themselves, and is a long term process. Interested people have to invest the time and effort to do that.

Sharma: That is why you want to do these simulations where there is a receptor of your research. As opposed to 'I've done this calculation. Guys, learn and improve your model'. That is a hard thing to do. I need an answer to the question: 'What kind of a shape of pressure distributions should I design, so that I don't have high loss?' Because experimentally I see what type is better. But I don't know in a hostile environment which one would produce the lowest loss.

Pollard: One of the issues, I think for the DNS community, is finding a mechanism for mounting these data bases so that the broader communities know that they exist. And so I'm wondering whether an agency, maybe NASA, could, or they do already have, ways of collecting these data, and then making them available to the broader community by advertising that these are there and 'here are some of the questions that we are receiving answers to'.

Solomon: Maybe it is time a Google or somebody took an interest.

Pollard: Actually this is an issue that is being discussed in the high performance computing community. And trying to say 'Who is going to be the manager of these datasets to make sure that they don't go up in smoke'? and to have these important back-ups. You are on very unsafe ground in the long term; so you need some agency to take this on. You can look at Charles Venables' data base, you can look at the data base at Stanford, or Bob Moser's or stuff in Europe, but it is all over the place, different formats and so on and so forth. So it is tough to access.

Katz: Well you know, for journals, we have a way of generating and maintaining information. This can even be coordinated with some publishers and you can have a data base which is a supplementary to some publication and that will become an agreed maintainer. We are maintaining massive amounts of data - supporting information for journals. That can be a mechanism - either with the publisher or even the society. AIAA in this particular case - they have the mechanism actually to maintain substantial amounts of information.

von Terzi: Maybe I can give some information here because in Europe, with ERCOFTAC, there is something. It was negotiated over two years in ERCOFTAC; they had several data bases over the past; they were consolidated now. And they are in Wiki form so that they can be allocated to it. So it will be permanent. It will have a video process added to it. It will have different sections. Like applied sections - turbomachinery will be one of them and also a fundamental flow section. It is currently in a testing phase and I think the scuttle is that maybe by the end of the month it will go on line. So in October it will be presented at a meeting I organized in Stuttgart - this data base. So this was realized that we were working on that. It has taken over ten years to get to this end and that is the form we will follow. It is the form which I will add and contribute data to. In Europe this is happening right now. We gladly would have Americans participate with all their wealth of data and also their expertise. For turbomachinery we also consider it important to have people who look at the data coming in and say "This is what is going on". There are always some guidelines behind - like best practice. Is the data experimental, DNS? There will be figures to be assessed. There will be guidelines. It will be a big process.

Katz: Mo - you wanted to say something before.

Samimy: I was going to make a similar point. One case that I know quite well is John Friend's simulation several years ago. He did the DNS of a Mach 0.9 jet. One important issue here is when you do such simulation, it is a major undertaking, do it right, and then verify and make sure that the solution is correct. Over the years many different people have used his results in many different ways. For example, for the verification of models. To verify LES type of modeling and so forth. Documentation of results of such simulation is extremely important and so is its accessibility. So if there is a sense that NASA or another organization is interested in stepping in and helping with the management of such data set, that would be good.

Sharma: One of the things we could do if we hold the workshop at NASA, Lou we could discuss this at that place. And I think that natural facilitators for this data base would be Glenn Research Center and the Air Force. Both of you are here.

Povinelli: It might be more timely. You may recall that we had this discussion perhaps ten years, perhaps six years ago. Unfortunately it didn't go very far but maybe this is a more opportune time to bring it back up again.

Glauser: We should learn from what the Europeans have done though too. I mean, if they have already gone through the process and come up with a clever way to bed the data and so on then I don't think we need to reinvent the wheel. Let's partner and do what we can; there may be some subtle things that we might have to keep separated. But let's team with the Europeans and utilize their infrastructure as best we can.

Sharma: I absolutely agree with you. I was just saying 'facilitators' for NASA and the Air Force.

Solomon: I think discussion diverged a little bit from your workshop content, which I think was a very good idea, but we had better make sure obviously that we don't repeat what was done. I don't think the reasons the performance enhancement didn't occur was because that previous work wasn't good. I think we really have to go back and question what the problem is.

Sharma: Yes we need to define what has been learnt during the last two decades and how has it impacted the LPTs. In addition, we need to identify areas which can help us further enhance the efficiency. I should point out that during the last two decades we have been able to develop LPTs for engine applications with very limited design iterations. Our focus now needs to be to enhance the performance further. This is where I think we are going to get some help from Lou if we can hold the workshop.

Povinelli: I said I shouldn't have come to this meeting, Om.

Sharma: Then we would have given it to you *in absentia*.

Povinelli: Thank you.

Katz: Anyway, unless there is anything urgent I think we should close the discussion, on the instruction of the boss.