The *Nordic Wind Tunnel*

a proposal to construct the world's premier turbulence research facility in Sweden

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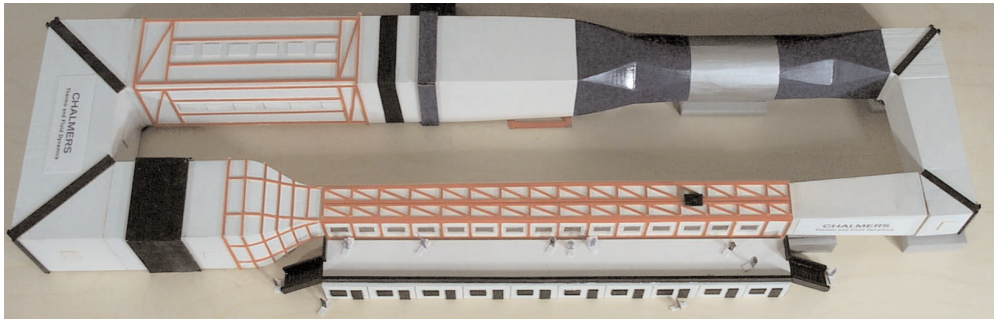
CHALMERS

A world of turbulence...

This is a proposal to construct the world's premier turbulence research facility in Sweden.



The ***Nordic Wind Tunnel...***

...will be a very large (test section: length 40m, cross-section 3m x 3m), low-speed wind tunnel with very low background turbulence ($u'/U < 0.02\%$). It will be the only facilty in the world with this combination of size (length *and* width) and high flow quality.

...will enable turbulence experiments on a scale that will not be achievable with computers for several decades. It will be used to address most of the fundamental questions that have held back turbulence research for half a century. This research will ultimately translate to great value to society.

...also has tremendous potential for commercialization due to its unique size and flow quality. This ensures its long-term viability serving a variety of industries.

Last, but not least, the ***Nordic Wind Tunnel***, operated as a major Nordic and European Facilty, would be a prestigious endeavor for the country of Sweden. The world's leading scientists have enthusiastically endorsed this facility (see appended letters) and they expect high quality, award-winning work to result from it.

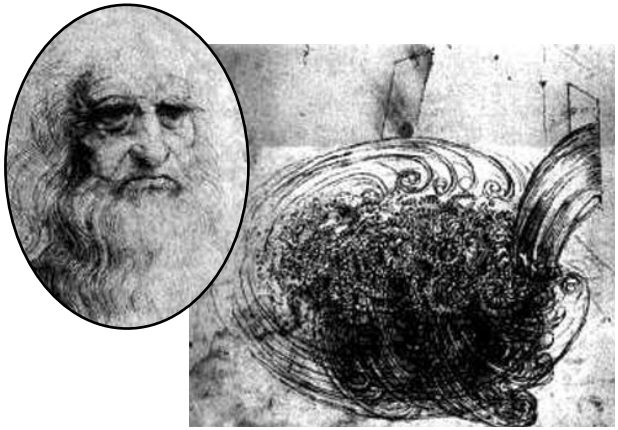
Turbulence...

Turbulence has been studied for a long time, but is nevertheless often cited as the *last unsolved problem in classical mechanics*. The lack of understanding has many adverse effects, which range from poor weather prediction to limitations on engineering design and practice. Scientists and engineers cope, but at a price in safety margins, wasted energy resources and limitations to innovation. Many classical ideas of turbulence theory date back to the 1930s and 40s. These ideas have evolved since, but it has never been possible to truly test most of them because of the absence of large and long enough, high quality (low background turbulence) research facilities.

"Turbulence remains one of the most outstanding research problems facing the international engineering, physics and mathematics research communities"
Charles R. Doering, *Professor of Mathematics, The University of Michigan, USA.*

"The proposal by Professors George and Karlsson is quite a timely one, given the number of significant turbulence research issues that remain unsolved."
Professor **Robert A. Antonia**, *ARC Senior Research Fellow, The University of Newcastle, Australia.*

"Turbulence in the high Reynolds number limit is something that I consider the central problem today in fluid dynamics research. If we have a reliable understanding of flows in the asymptotic high Reynolds number limit, that will provide an anchor for all turbulence research."
Professor **Roddam Narasimha**, *FRS, Director National Institute of Advanced Studies, Indian Institute of Science, Bangalore, India.*



Leonardo's observation of turbulent flow: Drawing of a free water jet from a square hole flowing into a pool (courtesy of eFluids.com).

Experimental work in a large research wind tunnel is needed to solve a number of fundamental questions and enable scientists and engineers to further improve computations of turbulent flow. Simply put, the problem is how to achieve a separation of length scales, energetic to dissipation, of 10^5 or larger – and still be able to resolve the smallest scales occuring in the flow with the smallest technically feasible probes (approximately 10 μm).

"The most important question is whether or not the vast store of information and knowledge that has been obtained at low Reynolds numbers for a variety of important classes of turbulent flows is applicable to the high Reynolds numbers that are characteristic of most real engineering flows. In order to investigate this question, a wind tunnel capable of reaching these high Reynolds numbers while permitting instrument resolutiuon typical of experiments at much lower Reynolds numbers must be available. this is just what the Nordic Wind Tunnel is designed for."
Professor **James M. Wallace**, *Univ. of Maryland, USA.*

Wind Tunnels

Wind tunnels are ducts through which air is moved, usually by a fan, to generate a controlled experimental flow environment.

Existing research wind tunnels are too small to reach high enough *Reynolds numbers* while still permitting *resolved measurements* of the smallest scales. They are either too short for the turbulence to evolve from its upstream (initial) conditions, too narrow for the large energetic turbulence scales to be free from the influence of the walls, or have too high a background disturbance (free-stream turbulence) level to extract the features of primary interest.

The *Reynolds number:*
Ratio of inertial to viscous forces. In turbulence the most important *Reynolds number* is also the ratio of length scales at which energy is supplied to the turbulence to that at which it is dissipated. In most problems of practical interest this is greater than 10^4, sometimes many orders of magnitude greater...

Example 1: BLWT 2, University of Western Ontario: Good overall size, insufficient flow quality (designed as wind engineering facility).

Example 2: MTL wind tunnel, KTH, Sweden: Good flow quality, insufficient size (limited by available building).

Overview of a selection of wind tunnels

organization	Johns Hopkins	Colorado State	U.W.Ontario	IIT	KTH	ASU	Chalmers
location	Baltimore, MD	Ft. Collins, CO	London, ONT	Chicago, IL	Stockholm	Tempe, AZ	Gothenburg
tunnel name	Corrsin tunnel	MWT	BLWT2	NDF	MTL	UWT	Nordic WT
operational in	1950s	1963	1984	1994	1991	1987	(proposed)
contraction ratio	25:1	9:1	4:1	6:1	9:1	5.5:1	5.4:1
test section							
TS length L [m]	10.00	29.30	38.25	12.19	7.00	7.40	40.00
TS width W [m]	1.30	1.80	3.40	1.52	1.20		3.00
TS height H [m]	1.00	1.80	2.50	1.22	0.80		3.00
test section Umax	32 m/s	36 m/s	30 m/s	120 m/s	69 m/s	36 m/s	40 m/s
turb.level u'/U(%)	0.1	> 0.1	> 0.1	< 0.03	< 0.02	0.01	< 0.02
	("typical tunnel")	(long and large test section)		(low free-stream turbulence)			

Are there alternatives?

Despite the increases in computational power and progress in numerical techniques, it is currently not possible to resolve the small scales at high Reynolds number. Even with computational power doubling every 18 months, it would take several decades before a model-free, direct numerical simulation (DNS) of the simplest flow case of non-decaying isotropic turbulence could be performed with the separation of scales 10^5 equivalent to the wind tunnel proposed here (tremendous resolution requirements for a comparable simulation – number of grid points greater than 10^{15}).

"Despite the impressive developments in Computational Fluid Dynamics over recent decades, [...] many of the fundamental questions still facing the turbulence community cannot possibly be answered in the foreseeable future without recourse to laboratory work."
"There are now a number of relatively small-scale facilities designed to allow study of very high Reynolds number flows (*via* use of very high pressures, exotic gases, or whatever) butt these are all inherently limited by the technical difficulties in developing and applying appropriate instrumentation. In my view, there is much to be said for the only possible alternative approach: going to much larger scales, so that existing, well-developed techniques can be used. Your proposal is therefore very exciting and, if I may say so, very well thought out."
Ian P. Castro, *Professor of Fluid Dynamics, University of Southampton, UK.*

"Computers cannot (and will not be able to in the foreseeable future) explore the high Reynolds numbers that are required to understand the basic properties of turbulence."
Zellman Warhaft, *Professor of Mechanical and Aerospace Engineering, Cornell University, USA.*

"There are many important questions about the physics of large Reynolds number turbulence that could be answered with highly accurate measurements in your proposed tunnel and nowhere else. I can envisage quite a few experiments in your tunnel that will help validate my DNS [direct numerical simulation] results."
Said Elgobashi, *Professor and Chair, Mechanical and Aerospace Eng., University of California, Irvine, USA.*

"I am convinced that the turbulence community really needs a large-scale wind tunnel, with sufficient separation between the large and small scales, with sufficiently low turbulence intensity, and in which the smallest scales can be probed with no special difficulty even for the largest Reynolds numbers. Such a tunnel (none of the presently available ones possess such specifications because they are either too small, or, for the largest ones, they are recycled industrial tunnels with insufficiently clean and controlled aerodynamic conditions) will be of considerable value for testing new ideas or new theories, and even for providing basic clean data on which the present theories will be tested"
Professor **Fabien Anselmet**, *Director of Research at Centre National de la Recherche Scientifique (CNRS), Turbulence Research Group, University Aix-Marseille, France.*

What makes the *Nordic Wind Tunnel* unique?

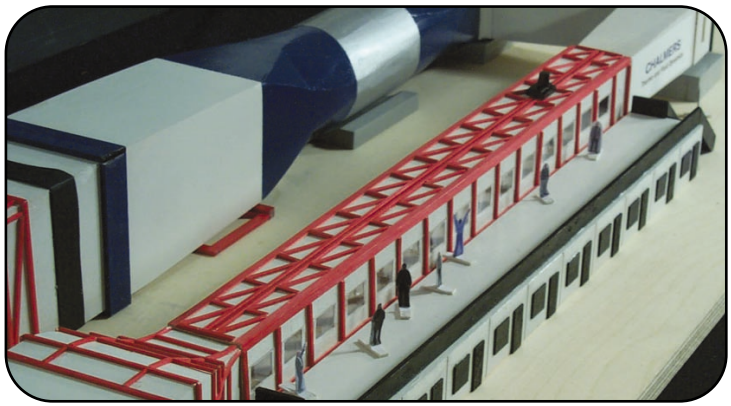
The *Nordic Wind Tunnel* overcomes the shortcomings of present research facilities and is proposed for construction at Chalmers University of Technology. It would be

- wide enough to remove the effect of side walls on the energetic turbulence scales
- fast enough and large enough to get the necessary high Reynolds numbers, yet still resolve the dissipative scales
- long enough and with low enough background disturbances to obtain the necessary downstream development times and will thus provide an experimental facility capable of resolving some of the oldest questions in turbulence while also testing conclusively new ideas.

In the unique *inverse design process* it was asked what length and time scales needed to be resolved to conduct "meaningful" measurements (e.g., resolution of wall layer to obtain shear stress) and what Reynolds numbers needed to be achieved in the experiments to be performed (e.g., zero pressure gradient boundary layer, far wake, decay of isotropic turbulence) to help resolve fundamental questions and sort competing theories. These length and time scales and Reynolds number criteria depend on the flow being measured. The size (length and cross-sectional area of the test section) and performance (maximum free stream velocity) of the proposed wind tunnel facility were then determined by what can be resolved with existing probes.

The small scales of the flow become smaller with increasing flow speed or pressure. To quote *Professor* **Tony Perry,** *University of Melbourne*, who realized the dilemma and – before his untimely death – stated that: ``Big and slow - is the way to go''.

Example of one design criterion:
For wall-bounded turbulent flows the requirement was that one viscous length scale can still be resolved (using a micro-LDA or a micro-PIV system, with a measuring volume height of 10 μm) while achieving a Reynolds number based on momentum thickness of at least 100,000.
Other "base case flows", e.g. decaying turbulence or wake flows, also provided further size and flow quality criteria.

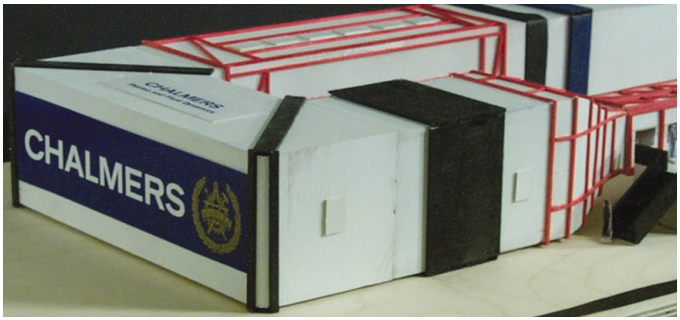


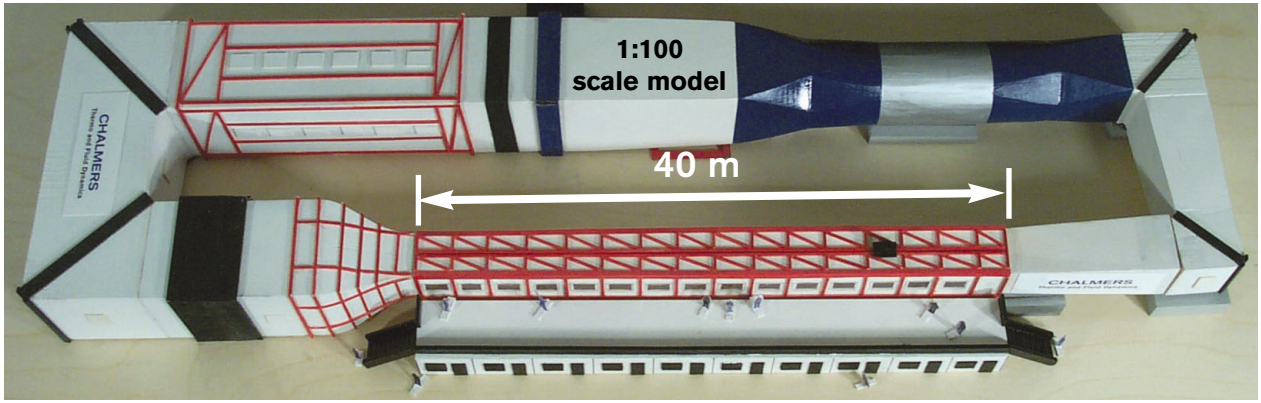
Result of the inverse design and dimensioning process:

A wind tunnel with a
test section of 40 m length,
cross section after contraction **3x3m**,
maximum **free stream speed 40 m/s** and a
free stream turbulence u'/U of < 0.02%.

The total dimensions of the facility are:
length: **79 m**,
width: **21 m**,
height **7 m**.

"It is our view that the facility [...] would be second-to-none as an experimental research tool for basic turbulence research into high Reynolds number incompressible flows. This is particularly true for the range of scales of turbulence resolved."
Poul Scheel Larsen, *Professor of Fluid Mechanics and* **Knud Erik Meyer**, *Associate Professor of Experimental Fluid Mechanics, Denmark Technical University.*





Problems that can be adressed in the *Nordic Wind Tunnel*

First, and foremost, the Nordic Wind Tunnel will enable experiments specifically designed to answer fundamental questions in turbulence.

"[...] coherent structure identification in turbulent flows, a crucial aspect for drag reduction, noise, vibration, mixing etc."
Professor **J. P. Bonnet**, *University of Poiters and Centre National de la Recherche Scientifique (CNRS), France.*

"[...] this well designed wind tunnel will allow to focus the studies in several directions, spanning from isotropic to inhomogeneous flows."
Professor **Paolo Orlandi**, *University of Rome "La Sapienza", Italy.*

"[...] we seek answers to large eddy and direct numerical simulation results that can only come from experiments performed in an exquisite facility of the type proposed. We expect the data will enable us to critically assess validation issues."
Professor **Andrew Pollard**, *Director of Computational and Experimental Fluid Dynamics Laboratory, Queens University, Canada.*

"For boundary layer experiments this tunnel, with its very large fetch and low background turbulence levels, will offer a unique opportunity."
"[It] will provide key insights into the applied problems of turbulence mixing (and reactions) and drag reduction. Modelling, such as large eddy simulations (LES) rely heavily on experimental insights."
Zellman Warhaft, *Professor of Mechanical and Aerospace Engineering, Cornell University, USA.*

"The current controversies over the law of the wall and the law of the wake imply an uncertainty about boundary-layer behavior at high Reynolds number - which should worry designers of aircraft, ships and other high-*Re* artifacts. My view is that "theoretical" arguments are unlikely to settle the matter so that high-*Re* experiments are needed"
Professor **Peter Bradshaw**, *Flow Physics and Computation, Stanford University, USA*

"[...] the facilty seems suitable for investigation of a turbulent boundary layer at high Reynolds numbers, when its thickness reaches tens of centimetres as, for example, on a plane fuselage in real flight"
Victor V. Kozlov, *Professor of Experimental Fluid Mechanics, Siberian Branch of Russian Academy of Sciences, Russia.*

"Your rationale for the construction of this tunnel is well presented in the *ERCOFTAC Bulletin* paper and the APS/DFD presentation. In addition to the fundamental physical questions about turbulence dynamics that can only be answered in such a facility, there are a number of more practical phenomena in geophysics and technology that are determined by the high Reynolds number behavior of turbulence, and that can be explored in such a tunnel."
"You might consider constructing the tunnel in such a way that it could be stratified at some time in the future. There are a number of interesting questions related to atmospheric and oceanic turbulence that could be investigated in such a tunnel – e.g. transport in stably stratified media, plume development in stable stratification, shoreline fumigation, etc."
John L. Lumley, Carrier Professor of Engineering, *Cornell University, USA.*

Value to society

The questions which will be answered by the *Nordic Wind Tunnel* will ultimately translate to great value to society. Examples of this are more accurate, long-term weather predictions (which could prevent catastropies due to surprise storms) and improvements in energy efficiency in power plants and transportation.
Mixing in industrial processes could be made more efficient and air conditioning systems and air planes quieter. Design costs for a variety of fluid machinery would be greatly reduced.

"A limited deep understanding of turbulence impacts the design of many devices ranging from aircraft and aircraft engines to the cooling of micro-circuits. There has been little fundamental progress in the last 20 years, in part due to a serious lack of experimental data which your tunnel would provide. I can therefore offer my wholehearted support for your project as I believe it will be an important contributor to solving the turbulence problem at the international level."
Professor **P. Hutchinson,** *FREng, Cranfield University, UK.*

"The stated policy of inviting foreign visitors to use the tunnel for their own research is another aspect of tremendous significance. This could be important not only for the local activity by injection of new ideas but would also enhance the standing of the university on the international scene."
Professor **S. K. F. Karlsson**, *Brown University, USA.*

"This unique wind tunnel will be specifically constructed to supplement already existing facilities around the world and the ambitious design goal of the project is to set the stage for a more comprehensive understanding of the fundamental nature of fluid turbulence."
B.A.Pettersson Reif, *Senior Principal Scientist,Norwegian Defence Research Establishment, Norway.*

"[...] existing theories still fail to forecast important environmental phenomena and to describe technical processes especially in multi-component media."
"[...] I have carefully read different versions of the proposal and have come to the conclusion that the idea to construct wind tunnel of rather large sizes (cross-section 3 x 3 m and working area length 40 m) with extremely low background level of basic turbulence (less than 0.02 %) has come in time and looks very productive. [...]
Exact and complete experimental results will help in creating of new generation theory, more directly connected with basic laws of nature than part of contemporary heuristic theories of turbulence. The results can be compared with measurements obtained in other media (stratified, multiphase) and leads to new more deep understanding of flow phenomena and essential improving of technologies. "
Yuli D. Chashechkin, Professor of Fluid Mechanics, Head of the Laboratory of Fluid Mechanics, Russian Academy of Sciences, Russia.

"I am convinced of the scientific need for this tunnel, and expect it will be fully subscribed by workers world-wide. It should place Chalmers University and Sweden in the forefront of modern turbulence research, where it should be, considering the long and distinguished history of Swedish investigators in modern fluid dynamics."
Professor **Russell J. Donnelly**, Director of Cryogenic Helium Turbulence Laboratory, *University of Oregon, USA.*

Viabilty as engineering facilty

The *Nordic Wind Tunnel* will be designed as a facilty for turbulence research, but has tremendous potential for commercialization due to its unique size and flow quality. This ensures its long-term viability as engineering facilty serving a variety of industries.

"I am also convinced that industry in Sweden and abroad will find such unique facilities indispensable for development and advancement of many technologies, to mention especially aviation, space research, road-, rail- and water vehicles, as well as for studies of atmosphere and ocean dynamics. Last, but not least, such facilities will add much to the already enviable international prestige of Chalmers University of Technology and Sweden as a whole."
Professor **Kemo Hanjalic**, *Head of Thermo-Fluids Section, Delft University of Technolgy, The Netherlands.*

"Thus, results obtained in facilities such as yours will be extremely useful to the fluid engineer designing practical devices as well as to the scientist involved in fundamental research. [...] your planned facilty will attract top scientists and engineers for unique opportunities to work with you and your high Reynolds number tunnel. I myself will be honored to work with you and your research team"
Professor **Mohamed Gad-el-Hak**, *Notre Dame University, USA.*.

"A test case for flow control. [...]The size of the models in the *Nordic Wind Tunnel* will be more appropriate to test demonstrators close to the industrial applications."
Professor **J. P. Bonnet**, *University of Poiters and Centre National de la Recherche Scientifique (CNRS), France.*

"Perhaps we have learned nearly all we can from research done in small wind tunnels. The proposed *Nordic Wind Tunnel* will allow research to be conducted at higher Reynolds numbers with fewer wall effects. This will give us greater insight into turbulence and its control"
Professor **David E. Stock**, *Washington State University, USA.*

"These [fundamental physical questions] should not be confused with the atmospheric, wind engineering and sporting commercial applications which are also a possibility.."
John L. Lumley, Carrier Professor of Engineering, *Cornell University, USA.*

Location

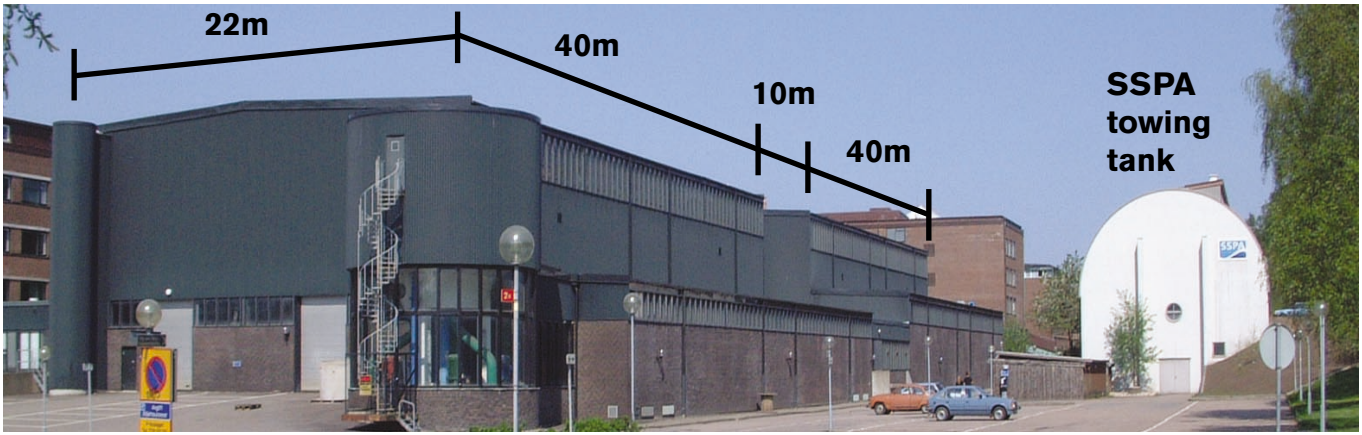
The *Nordic Wind Tunnel* will be built at Chalmers University of Technology. *Chalmers* is a major technical university located in Gothenburg on the west coast of Sweden.
The *Nordic Wind Tunnel* will be housed in an existing, currently underused building, adjacent to SSPA. Finding this building was a coincidence, it happenend *after* the basic design/dimensioning process. Surprisingly, the two laboratory halls (pictured below) combined can actually house the *Nordic Wind Tunnel* in its current configuration!

"The team at Chalmers is very strong, the project is timely and clearly stated. It could well become a major resource for Europe, the US and other countries – a CERN for turbulence."
Zellman Warhaft, *Professor of Mechanical and Aerospace Engineering, Cornell University, USA.*

The scientific infrastructure at Chalmers is already in place with both W.K. George and R.I. Karlsson joining the faculty at Thermo and Fluid Dynamics, and the moves of their respective laboratories to form the new Turbulence Reseach Laboratory (TRL) at Chalmers.

"The two researchers (Prof. W.K.George and Prof R.I. Karlsson) have an outstanding international reputation in the field and will be first-rate users of the proposed wind tunnel facility. Moreover, such a facilty will greatly enhance the already high visibility of Chalmers in the area of turbulence and fluid mechanics. I wholeheartedly support construction of the wind tunnel facility."
Professor **Charles Meneveau**, *Director of Center for Environmental and Applied Fluid Mechanics, Johns Hopkins University, Baltimore, USA.*

Available laboratory buildings on Chalmers campus.



Cost estimates for construction

The cost of construction has been estimated at **SEK 60 million**.
The estimated engineering design cost is one tenth of the total cost, **SEK 6 million**.

We are hereby asking for funding of the design phase. The engineering design phase will end with a *bidding conference*, at which the facility – in parts or whole – can be bid on by contractors.

Timetable:

- design:	1 year
- construction:	1-2 years

"I am thus heartened that you are undertaking to build a wind tunnel that will be able to resolve a number of the outstanding questions in turbulence. [...] I have no doubt that the expenses involved will be amply justified if sustained research activities in it can be pursued."
Professor **Katepalli R. Sreenivasan**, Director of Institute for Physical Science and Technology, University of Maryland. Also in Engineering, Physics and Mathematics, Yale University, USA.

"I admire the careful thought which has gone into this facility design, which when built will surely put Sweden in a leading position in wind tunnel research. I also admire the great ingenuity in picking a design for building this facility at a very modest total cost."
Professor **Russell J. Donnelly**, Director of Cryogenic Helium Turbulence Laboratory, *University of Oregon, USA*.

Operation of Nordic Wind Tunnel – International Collaboration

There is great and increasing interest for the project throughout the international fluid mechanics community. The *Nordic Wind Tunnel* will be made available for researchers from all over the world.

Leading international scientists are looking forward to use it in their experimental, theoretical and numerical research. They anticipate that very high quality work will result from the *Nordic Wind Tunnel*.

It is anticipated that a significant part of the operating costs of the *Nordic Wind Tunnel* can be covered by the EU, particularly by forming Networks of Excellence and utilizing the concept of Mobility of researchers.
(E.g. inclusion by ERCOFTAC (European Research Council on Fluids, Turbulence and Combustion) as part of their Sixth Framework)

"I welcome this proposal, not just because it will provide a proper modern experimental facility in Europe, but because it will also provide a focus for collaboration from all sides of the European turbulence community."
Professor **J. D. Gibbon**, *Imperial College, London, UK.*

"I can envisage this wind tunnel becoming a strong catalyst of European research in turbulence and Chalmers becoming an important center for turbulence research as a result."
J. C. Vassilicos, *Imperial College, London, UK.*

"We would liked to express our general support for the initiative, also because it would provide new opportunities for Nordic research collaboration."
Poul Scheel Larsen, *Professor of Fluid Mechanics and* **Knud Erik Meyer**, *Associate Professor of Experimental Fluid Mechanics, Denmark Technical University.*

"I am very exited about the prospects for your proposed new wind tunnel, as I believe that the collaborations and state-of-the-art research that will arise will lead to noticeable advances in our understanding of turbulence."
B.A.Pettersson Reif, *Senior Principal Scientist,Norwegian Defence Research Establishment, Norway.*

"The outstanding features of the Nordic Wind Tunnel should involve the entire global turbulence community and would be an excellent base for the international cooperation of experienced research groups and scientists. This certainly would improve the international position and importance of the Chalmers Laboratory. [...] the outstanding features of the laboratory would certainly motivate the international organizations like EC, various branches of industry etc for co-financing serious research of international teams which might be an unusual chance for many."
Professor **J. Krzyzanowski**, *Polskiej Akademii Nauk, Gdansk, Poland.*

“Build it and they will come...”

(from the movie: *A Field of Dreams*)

“The scale and quality of the proposed *Nordic Wind Tunnel* is truly world class. A facility that will enable us to explore turbulent wall flows, and other canonical flows, such as introducing curvature, temperature gradients and even concentration gradients, at such high Reynolds numbers while maintaining a very low level of background turbulence is exactly what we need. It will enable for the first time the dissipative scales to be explored as well as how these interact with other mechanisms. It will enable us to answer the question whether turbulence is wholly or partially dependent on initial conditions and may lead to passive control strategies.”
Professor **Andrew Pollard**, *Director of Computational and Experimental Fluid Dynamics Laboratory, Queens University, Canada.*

“With our own research facilities, we cannot achieve the high Reynolds number flows we would like to investigate and we therefore hope to collaborate with you on boundary layer research at high Reynolds numbers. We are also interested in flow around obstacles and we would like to carry out this experimental work at low blockage ratios. Your planned wind tunnel will permit this kind of research.”
Dr.Dr.h.c. **Franz Durst**, *Professor of Fluid Mechanics, university of Erlangen, Germany.*

“I attended with considerable interest your detailed presentation describing the project at the APS/DFD meeting in San Diego last November 2001. I would like to state in no-uncertain terms that building such a large wind tunnel facility is of timely and crucial importance for our turbulence research community.”
Fernando F. Grinstein, Chair Elect, AIAA Fluid Dynamics Technical Committee, Research Physicist, Naval Research Laboratory, USA.

“Together with many of my colleges I would be very keen in research collaborations with the *Nordic Wind Tunnel* once this project is completed. I see the boundary layer and wake flows as the main topic of collaboration between the BLWTL and the *Nordic Wind Tunnel* .”
Professor **H. Hangan**, *Boundary Layer Wind Tunnel Laboratory, University of Western Ontario, Canada.*

“[...] the proposed *Nordic Wind Tunnel* will be a unique opportunity to create a somewhat European center for experimental research in turbulence, that will be used for several groups in Europe and overseas, among those, my laboratory will take an active part”
Professor **J. P. Bonnet**, *University of Poiters and Centre National de la Recherche Scientifique (CNRS), France.*

Jan-Eric Sundgren, *President*
Chalmers University of Technology

William K. George, *Professor of Turbulence*
Rolf I. Karlsson, *Professor of Experimental Fluid Mechanics*
T. Gunnar Johannsson, *Associate Professor*
Martin Wosnik, *Assistant Professor*
Department of Thermo and Fluid Dynamics
Chalmers University of Technology

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for more information on the
Nordic Wind Tunnel

http://www.tfd.chalmers.se/trl/windtunnel/