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Streamwise Vortices on the Convex Surfaces of Circular Cylinders and Turbomachinery Blading

Paul Gostelow

University of Leicester

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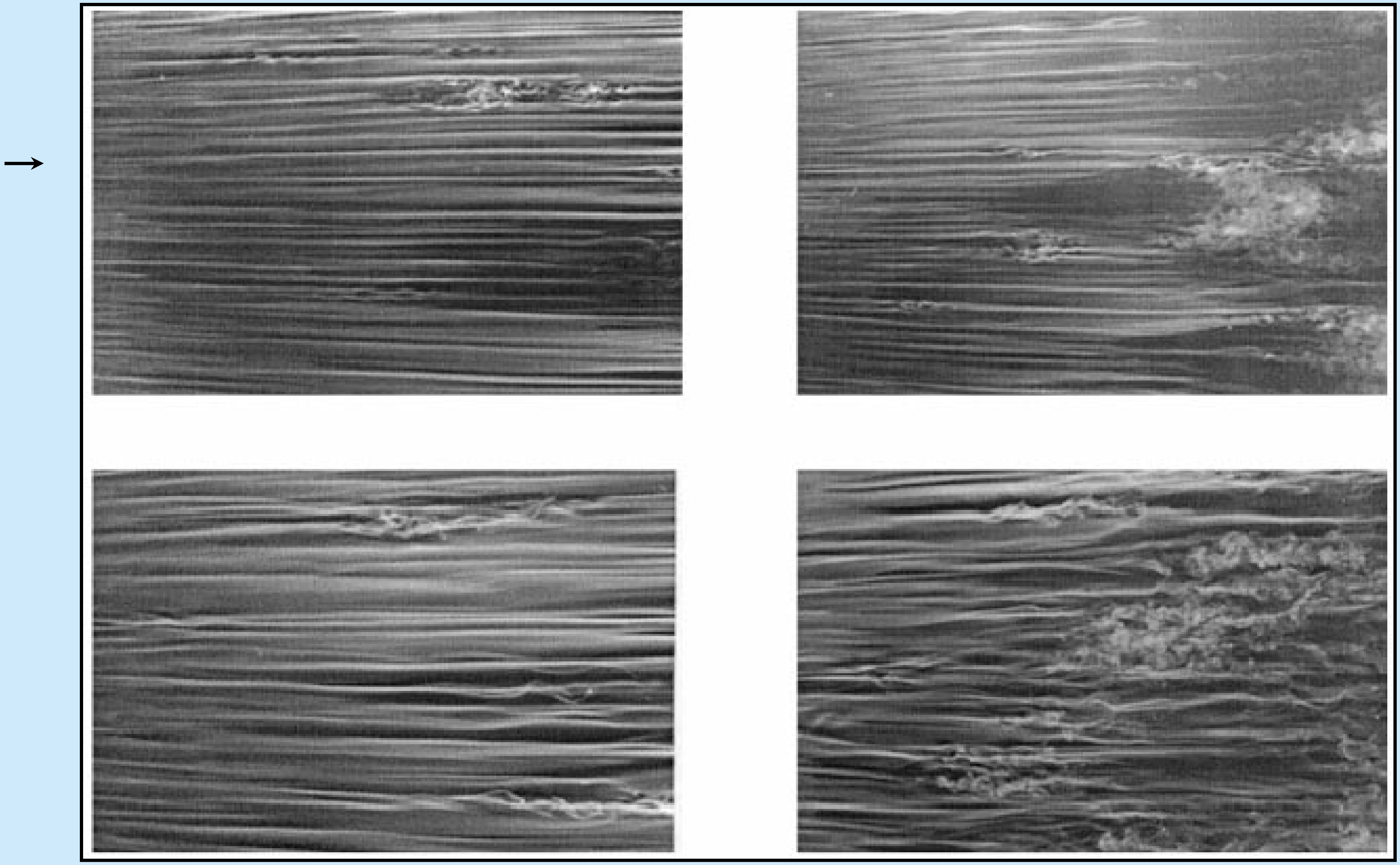
This talk is not really about Klebanoff Modes

Matsubara and Alfredsson

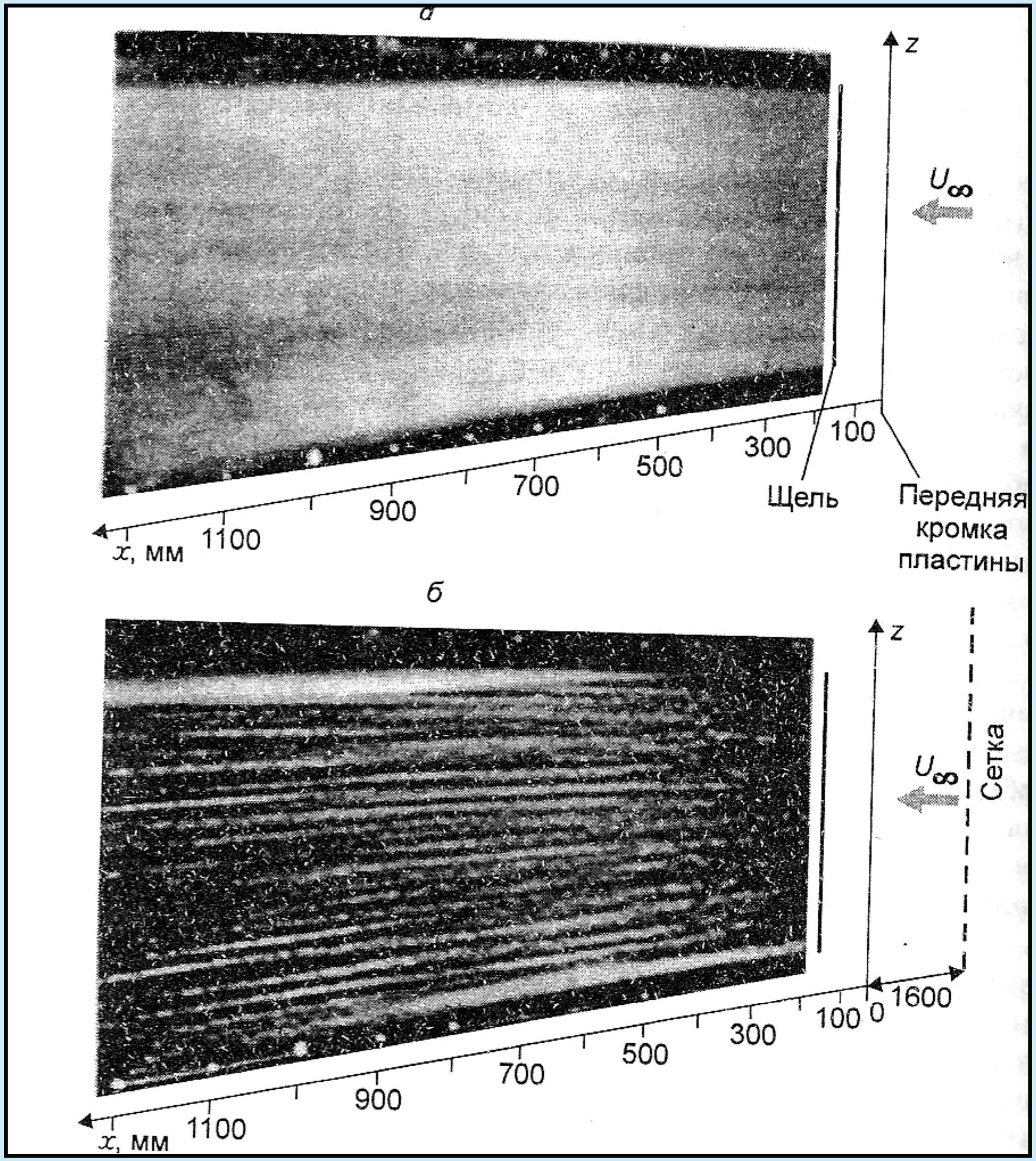


nor about
Flat Plate Streaks

Matsubara and Alfredsson

Top: Turb. level ≤ 0.02%

Bottom: Turb. level 1.5%



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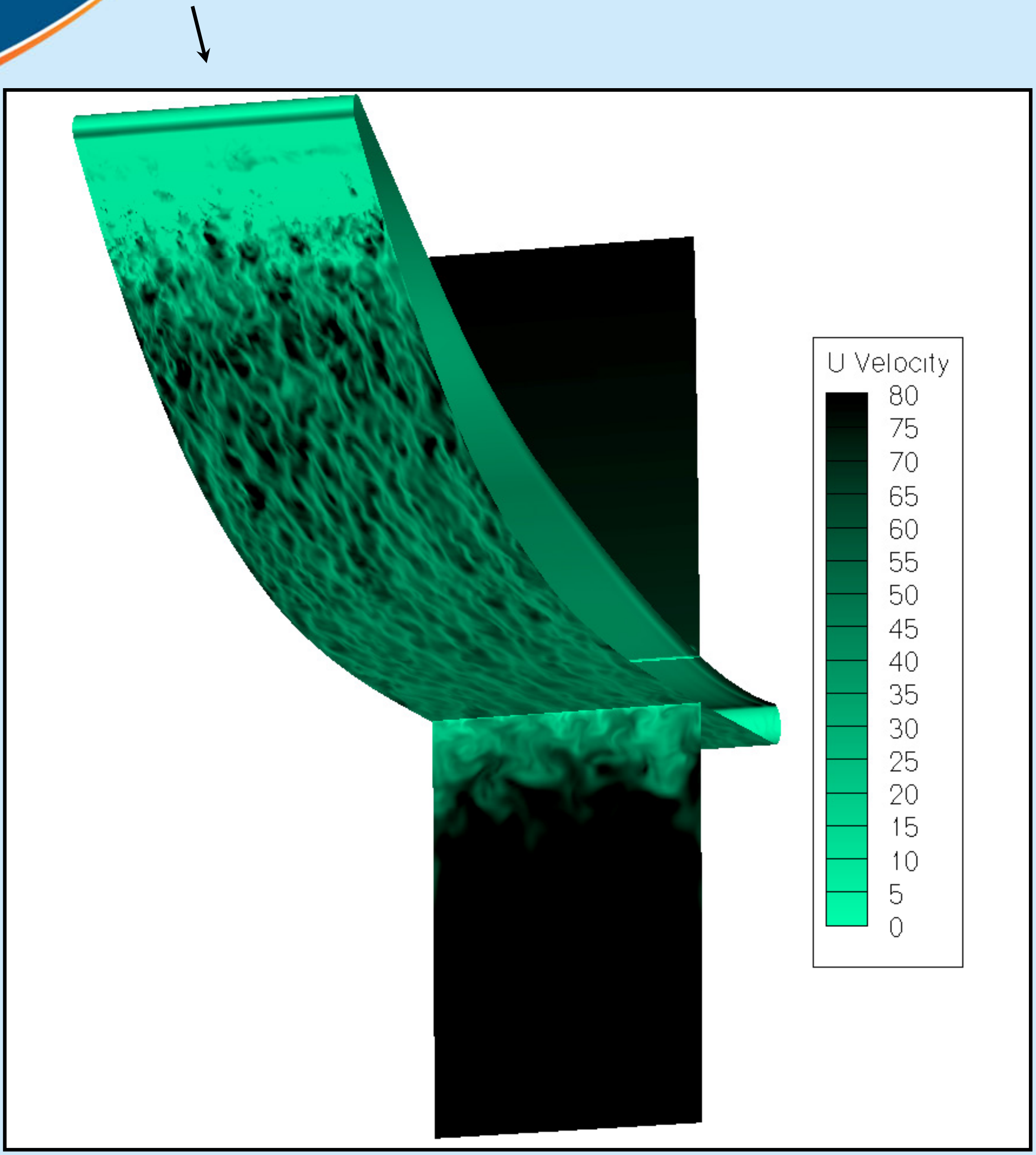
However, this Monterey Compressor Blade is interesting

DNS by McMullan
Re = 740,000
Turb. Level 1.4%



I would like to discuss Streamwise Vortices

The stability of contrarotating vortex pairs is of airworthiness and commercial interest but is not well understood.

Contrarotating Streamwise Vortices

Previous investigators have observed streamwise vortices and "streaky structures" on flat plates and on the suction surface of compressor blades. An organised system of contrarotating streamwise vortex pairs on a circular cylinder or a compressor or turbine blade suction surface gives additional complications.

Experiments were conducted on the flow through a transonic turbine cascade and past a circular cylinder in subsonic crossflow. Organized systems of streamwise vortices were observed for both cases. Although unfamiliar, this behavior, and the associated spanwise wavelength, had been predicted and observed previously in low speed flows. Turbine designers generally assume that Görtler vorticity is confined to the concave pressure surfaces. Examples will be given that should result in questioning this assumption.

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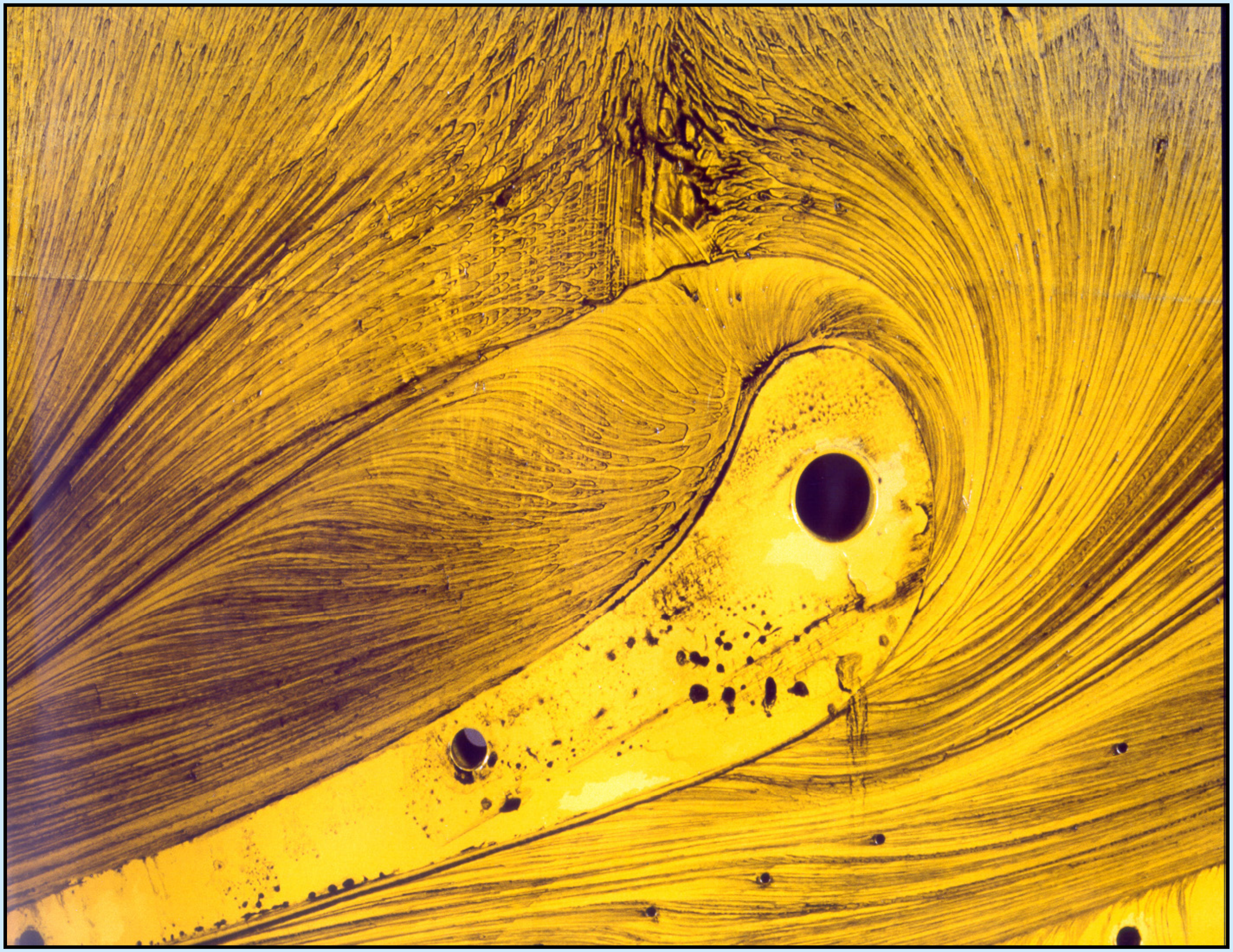
Conditions at the Leading Edge

The leading edge inflow is initially disturbed; then undergoes rapid curvature changes before joining the convex suction surface. Vortex stretching is caused by both turbulence and curvature.



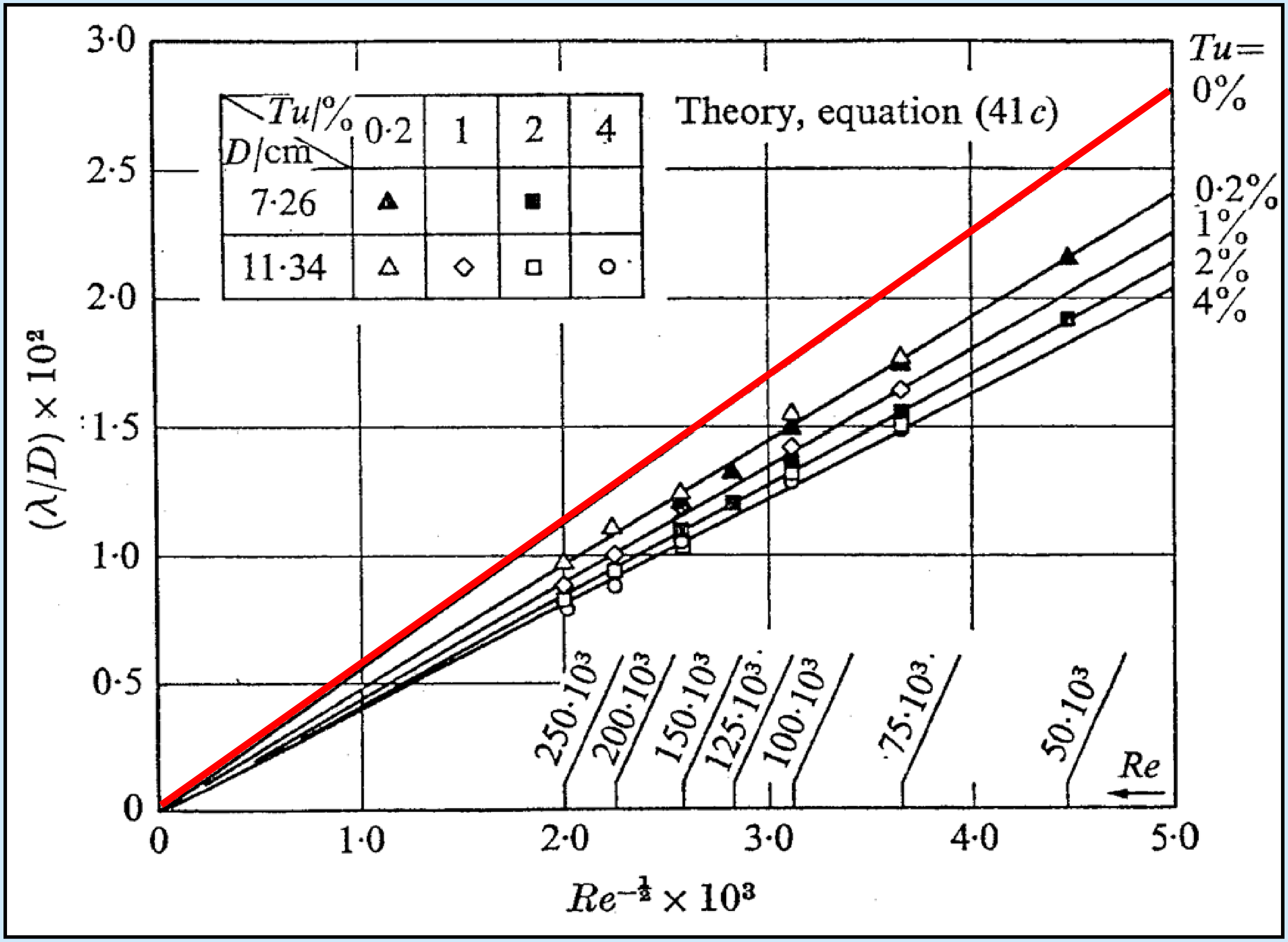
Contributions of Stability Theory

For a convex surface the occurrence of streamwise vorticity is consistent with the later predictions of Görtler (1955), who postulated instability on a convex surface from the concave streamlines ahead of the leading edge stagnation region.

For the types of geometry considered a useful approach is that of Kestin and Wood (1970) for a circular cylinder. Their stability analysis for the approaching flow led to considering regularly distributed contrarotating eddies strengthened by eddy stretching in free stream turbulence. They predicted a theoretical value of pitch wavelength between pairs, **λ***, for a cylinder of diameter,* **D***, given by:* $\boldsymbol{\lambda = 1.79\pi D Re^{-0.5}}$**.**

Prediction of Wavelength

Kestin and Wood, 1970



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Suction surface flow visualization

NRC Turbine Blade; $M_e = 1.16$

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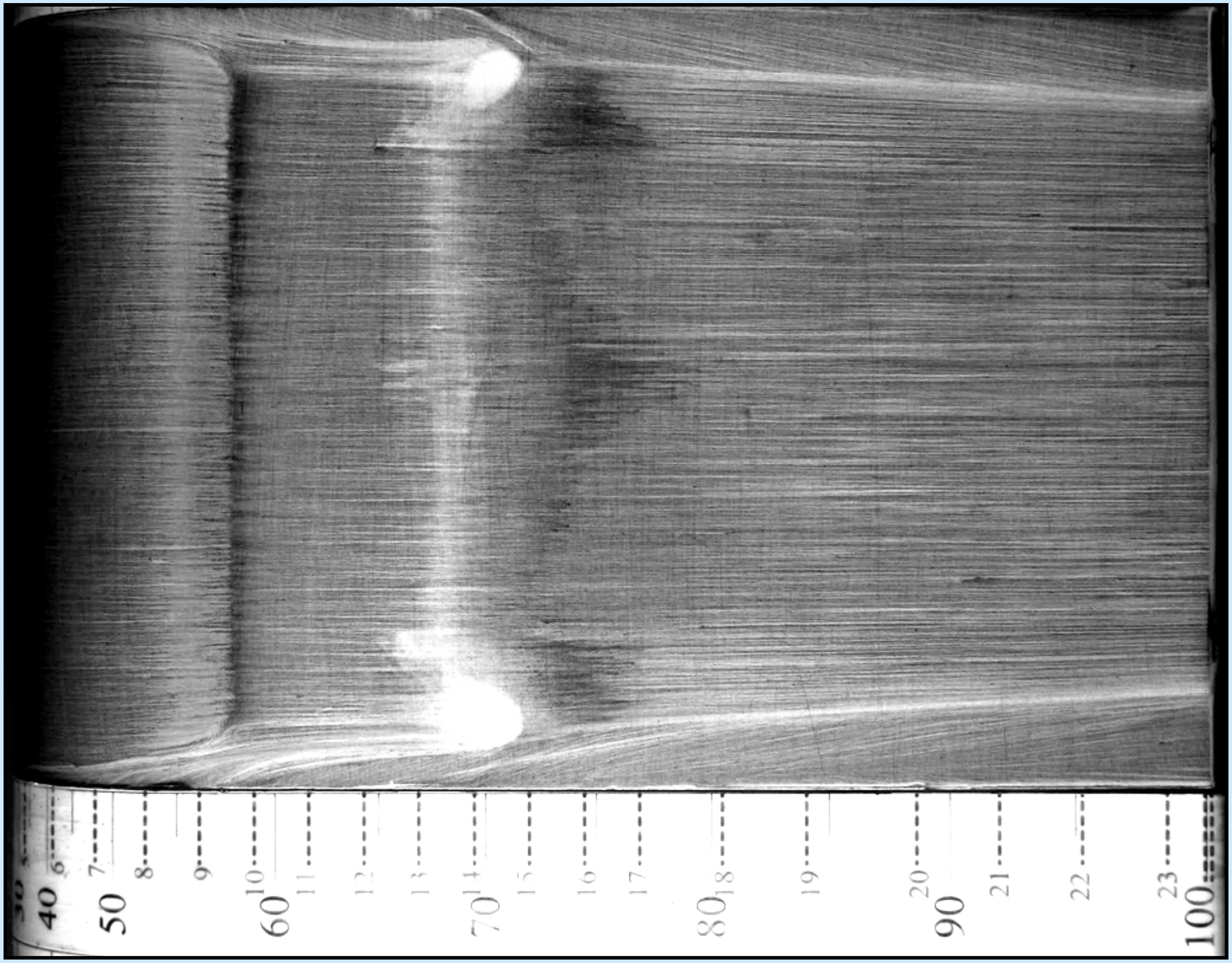
Under the influence of strong favorable pressure gradients on the blade's suction surface streamwise vortices were observed that persisted to the trailing edge.



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Flow Visualization on a Circular Cylinder

Surface flow visualization on the circular cylinder was undertaken at Mach 0.5 and the streamwise vortices occupied the forward portion of the cylinder to the 83^{o} azimuth. The geometry is identical to that considered by Kestin and Wood but the Mach number regime is very different. At an inlet Mach number of 0.5 the circular cylinder flow has become critical and is in a regime where shocks are formed intermittently on alternating surfaces - uncharted territory for considering the streamwise vorticity! The Kestin and Wood analysis was not intended to cope with this and any agreement in the prediction is fortuitous.

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Flow visualization on a Circular Cylinder at Mach 0.5

Ackerman
Turb. Level 0.4%

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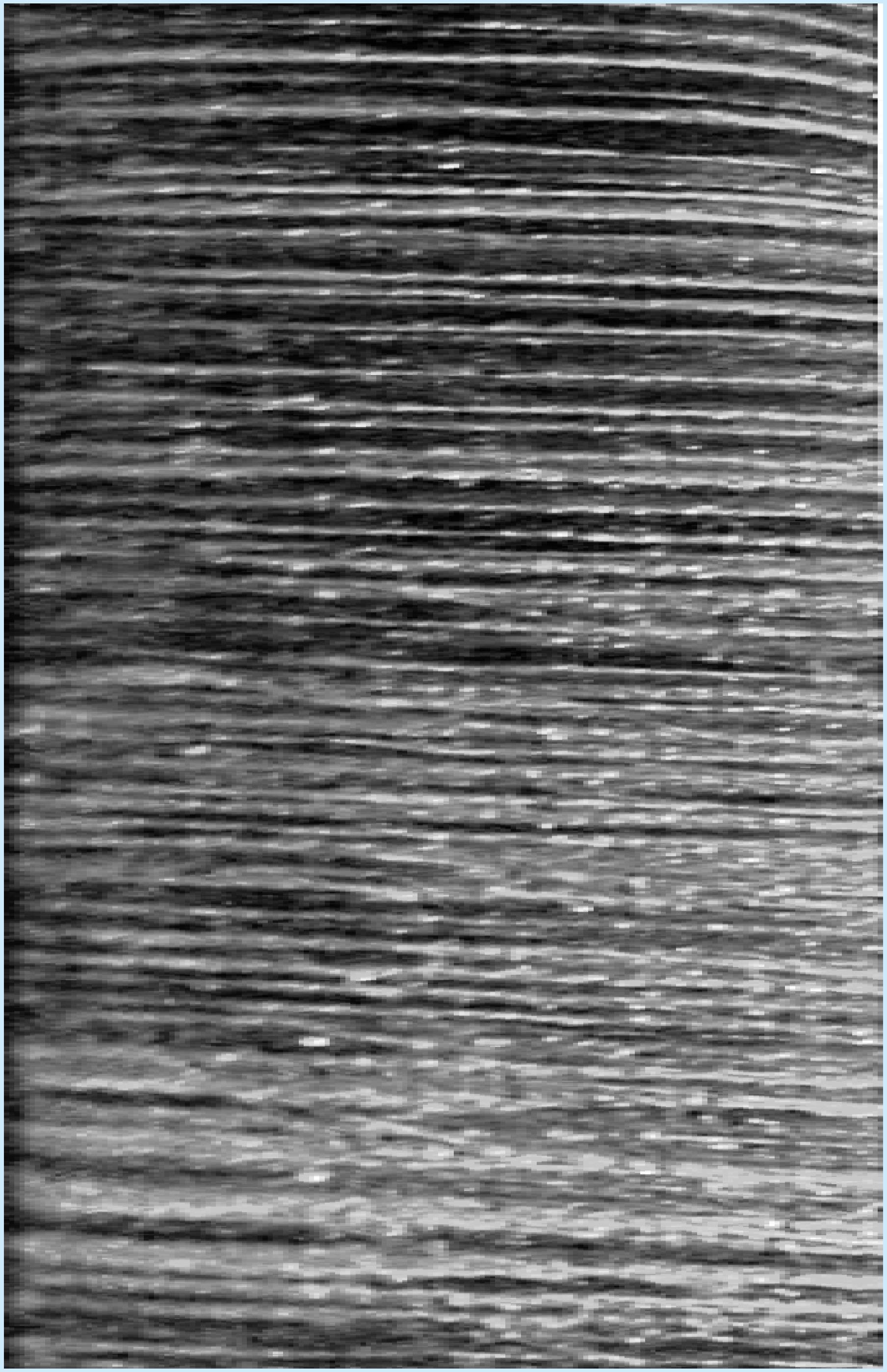
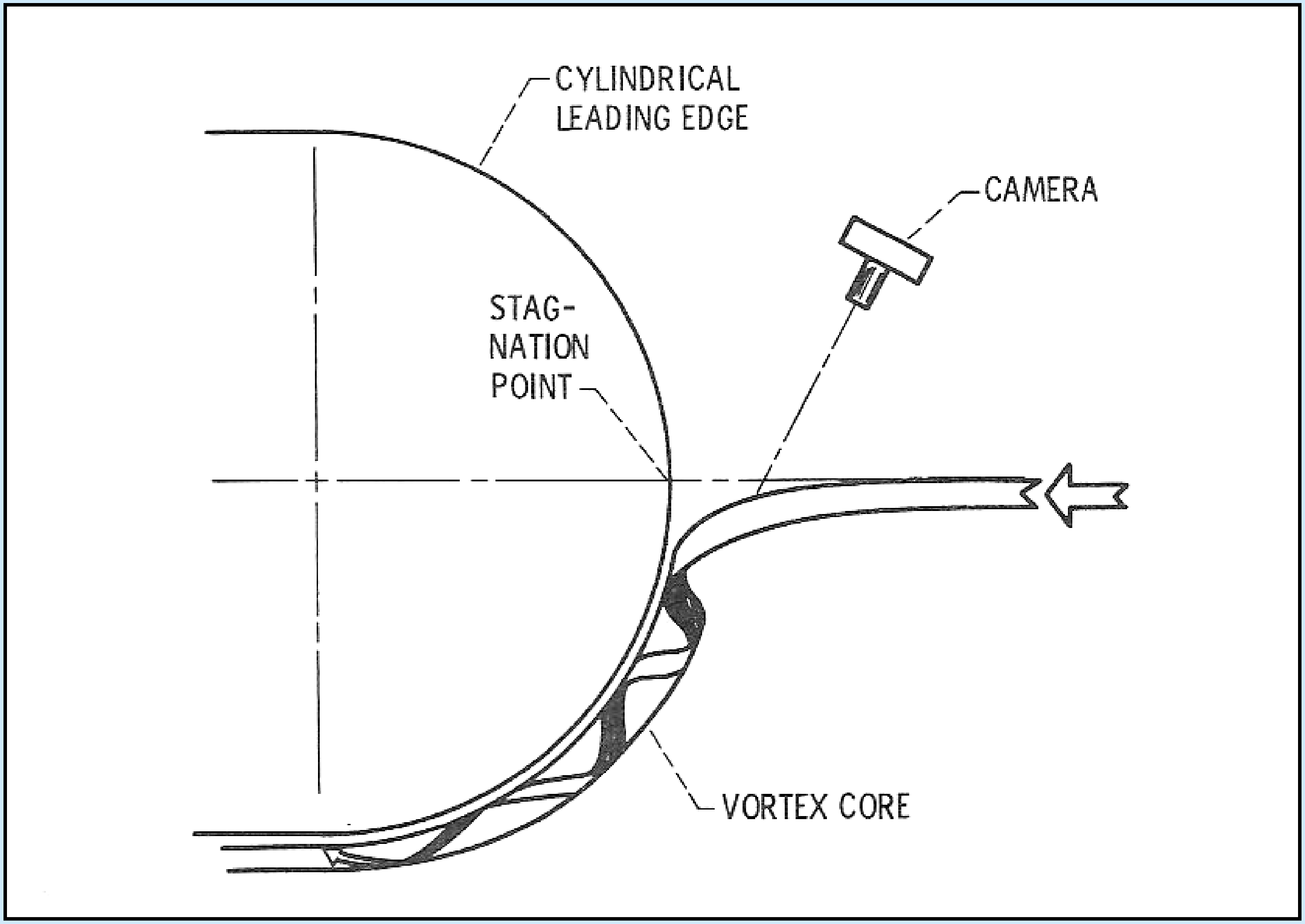


Circular Cylinder

VanFossen and Simoneau

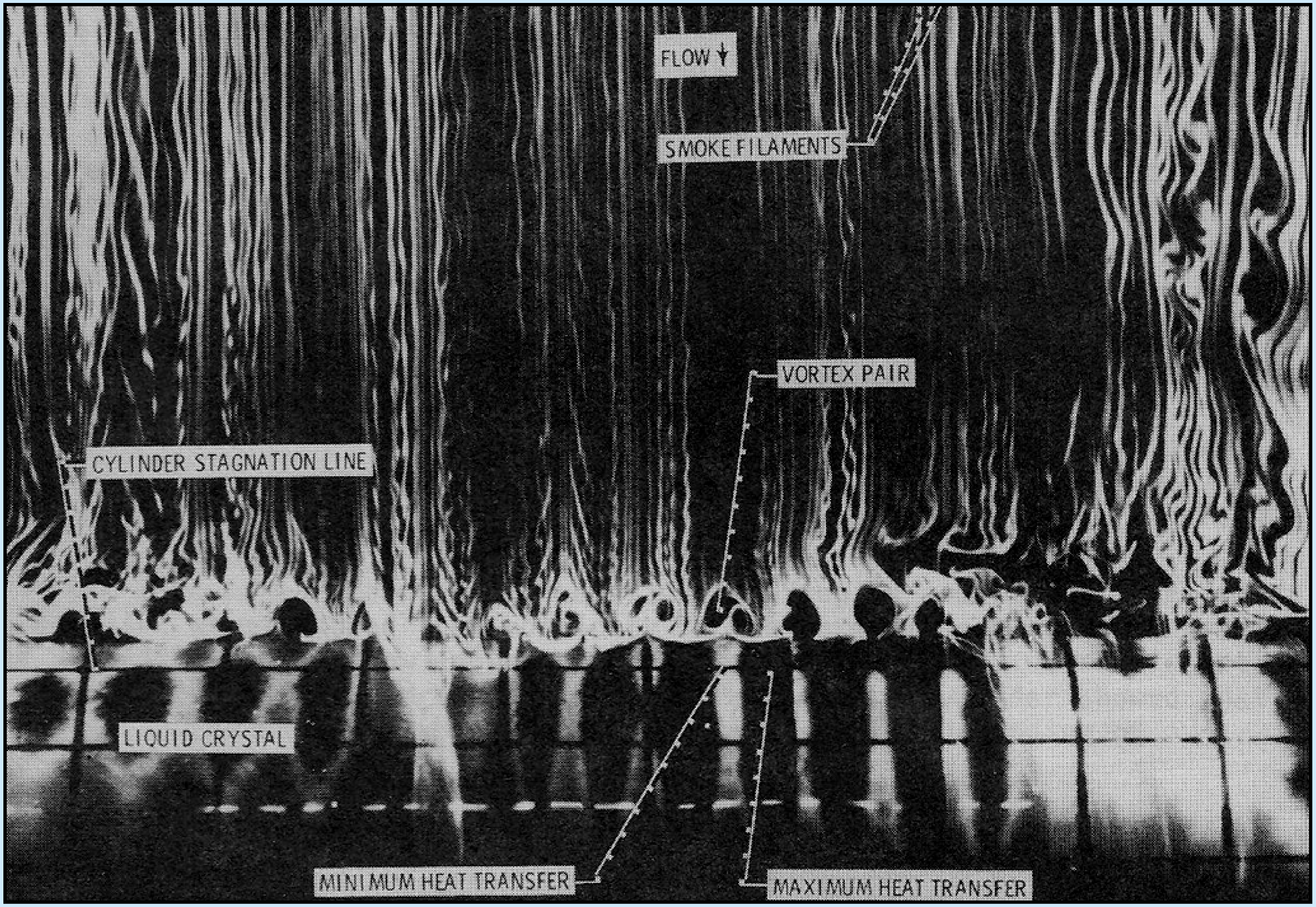
Turb. Level < 0.5 %



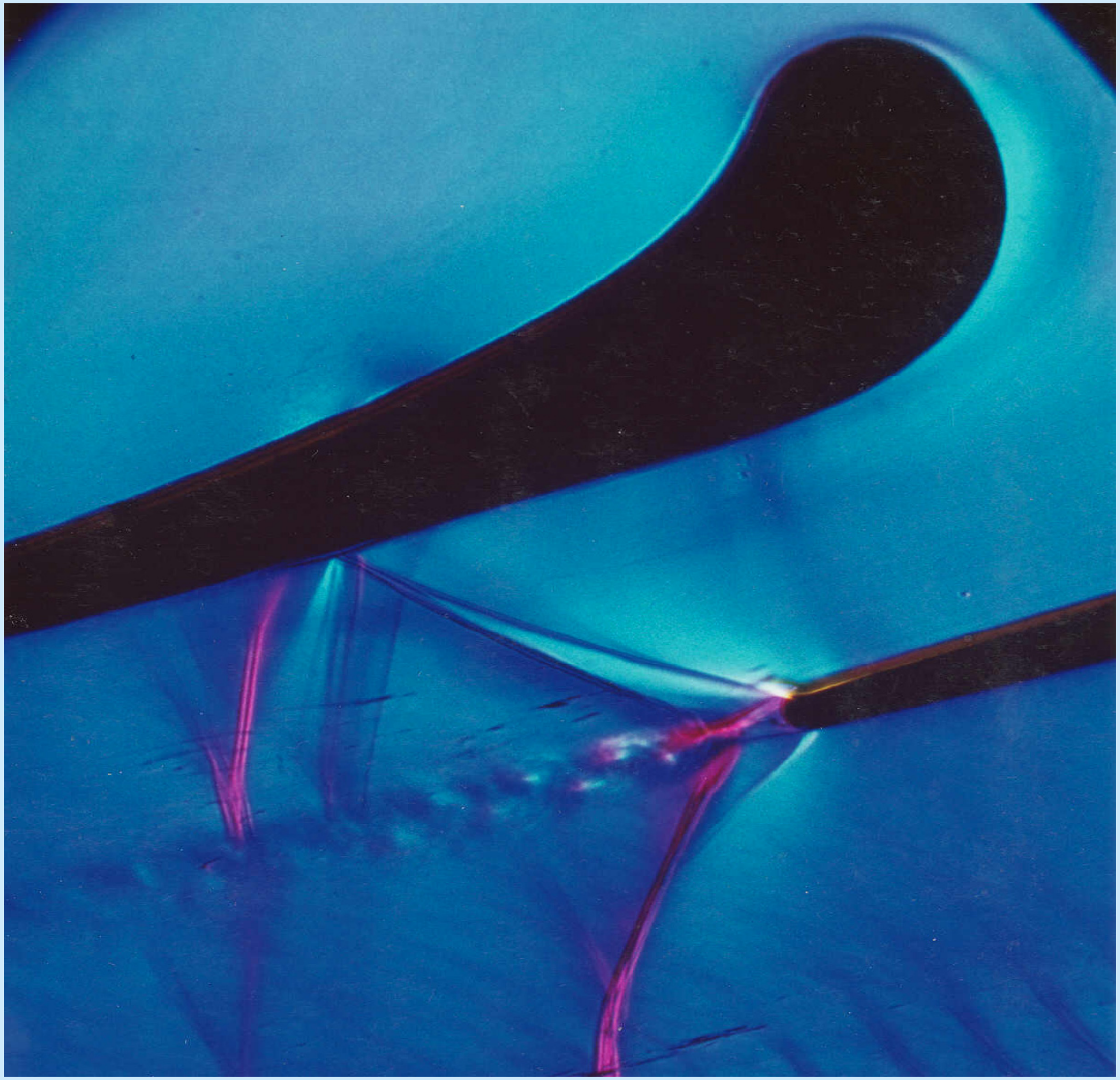
Circular Cylinder

VanFossen and Simoneau

Turb. Level < 0.5 %



Schlieren View of Vortex Shedding at $M_e = 1.16$



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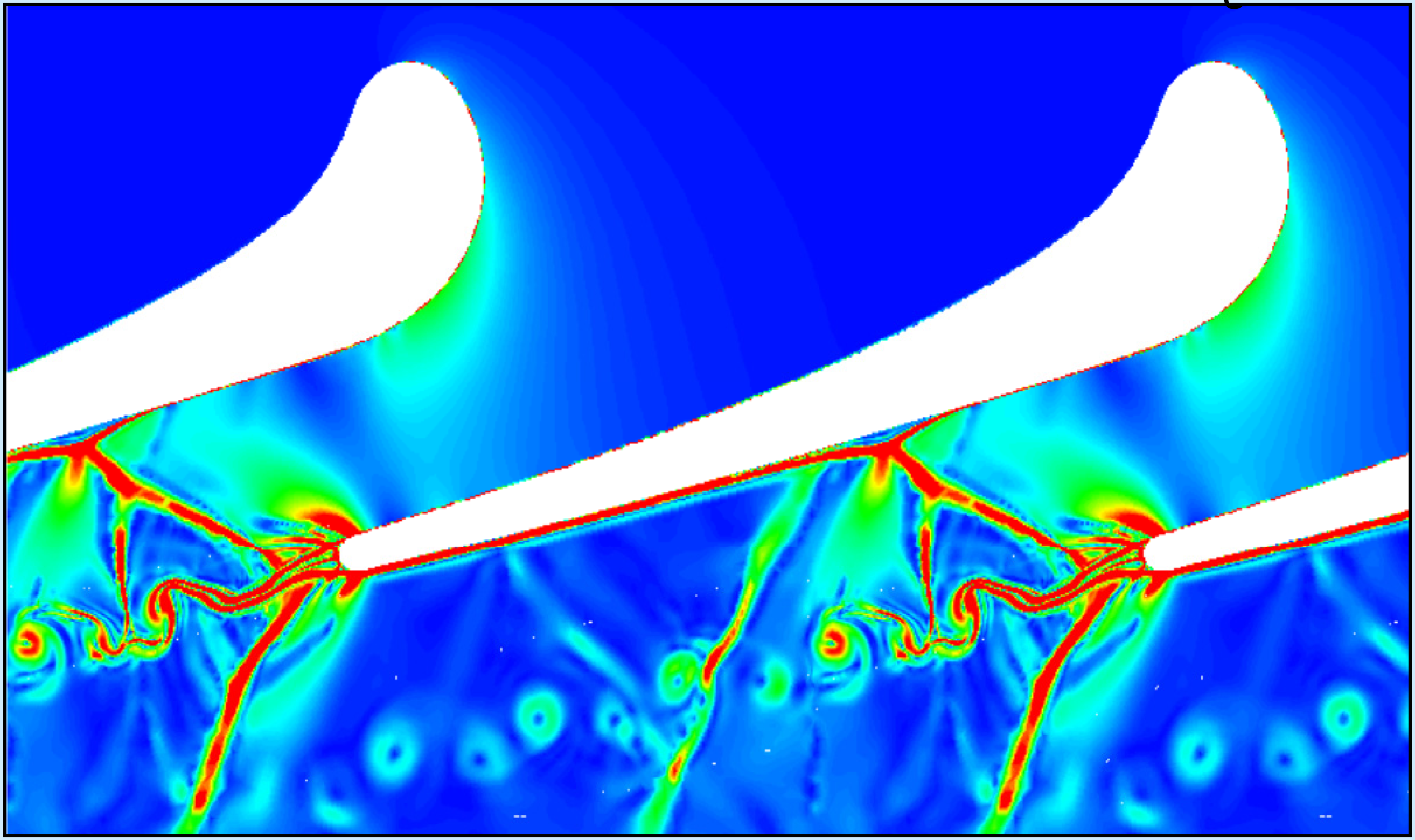
Instantaneous CFD of Vortex Shedding / Shock Interaction at M_e =1.16



Experimental and Inviscid CFD

Isentropic Mach Number Distribution

Mach 0.8 and 1.16

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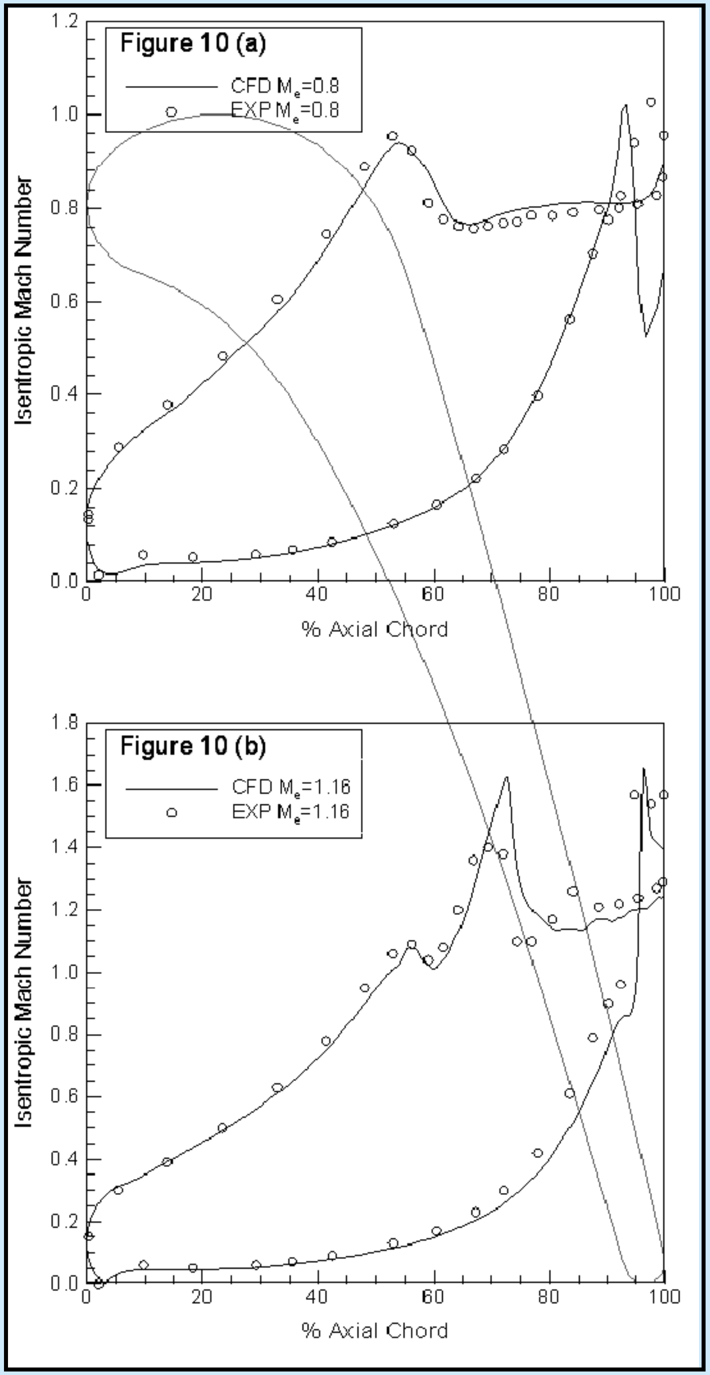

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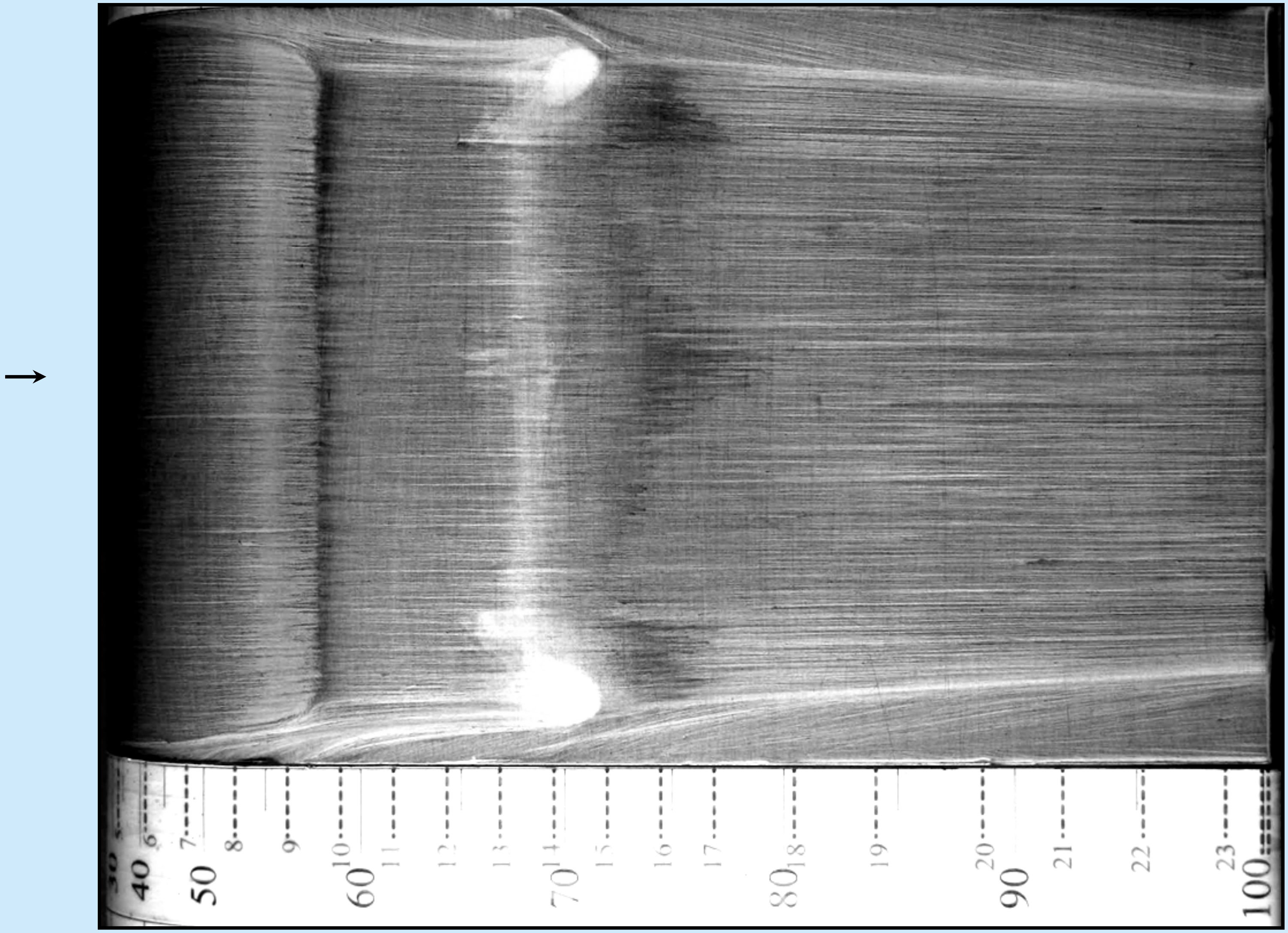
The NRC Turbine Blade

The suction surface leading edge is virtually circular; it then develops strong convex curvature becoming quite flat further downstream.

Surface flow visualization was performed at three speeds, displaying coherent streamwise vorticity extending to the trailing edge. The blade was covered with a sheet of self adhesive white vinyl; a mixture of linseed oil and powdered lampblack was applied in a very thin layer. After running for five minutes, the blade was removed and photographed.

Suction surface visualization for exit Mach number of 1.16 is shown. Large numbers on the scale represent percentage axial chord and small numbers mark static tap locations. The shock impingement and separation region is at an axial chord around 70%.

Suction Surface Flow Visualization at Mach 1.16

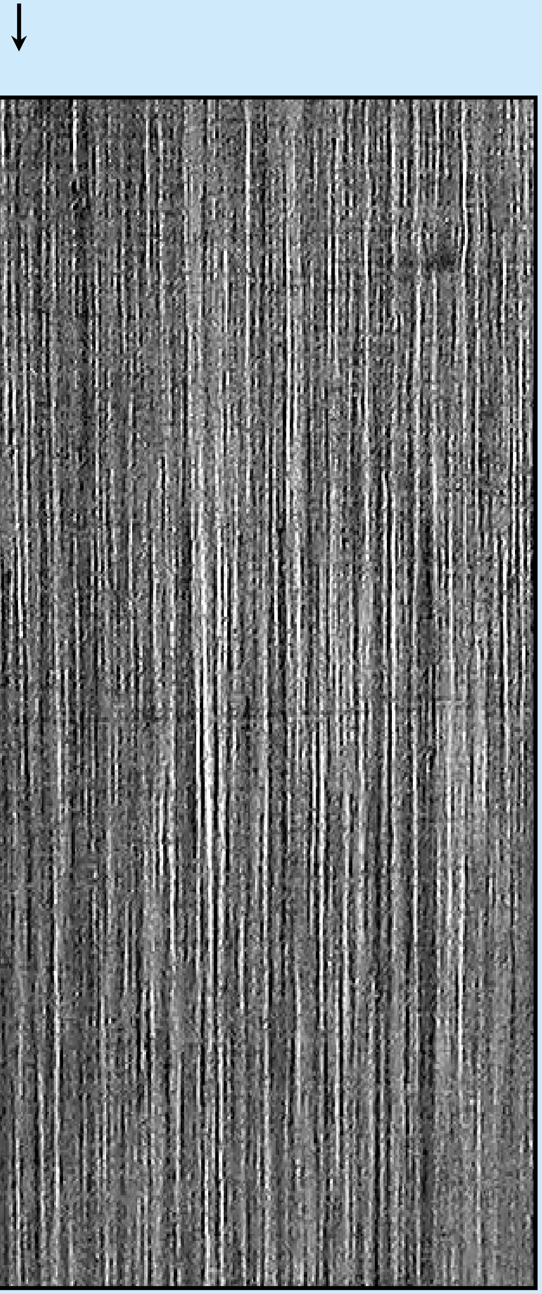


Visualization of Streamwise Vortices

at 80% to 95% axial chord on suction surface

Mahallati

(Enlarged view)



Comparisons with Kestin and Wood Theory

Measured spanwise wavelengths of the vortices are compared with the predictions of Kestin and Wood. The flow in the leading edge region determines susceptibility to organized streamwise vorticity. Rapid changes in curvature of the convex surface raise the question of what effective diameter should be applied if comparing with theory. The curvature at the 10% true chord location was most representative over a range of compressor and turbine blades and also gave the most consistent results.

Acceleration through the blade passage is strong; the inlet and discharge Mach numbers are 0.118 and 1.16 respectively. At inlet the flow dynamics should not be very different from observations in low speed flows.

Flow visualization results from blading of other researchers are also compared with the predictions of the Kestin and Wood theory.

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Streamwise Vortices on Turbine Blade Suction Surface

Benner

Turb. Level 0.3%

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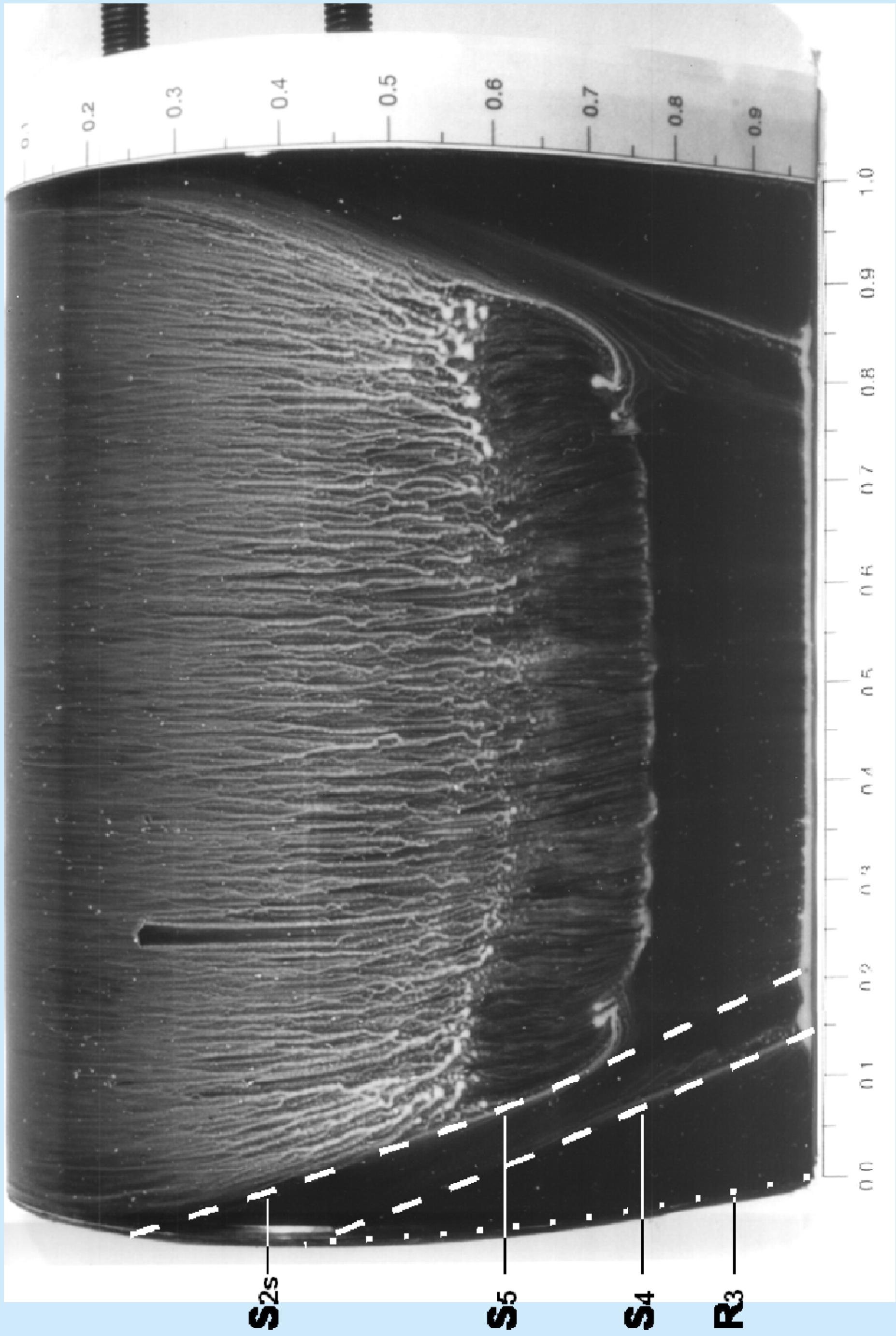

Turbine Blade

Hodson and Dominy

Turb. Level 0.5%

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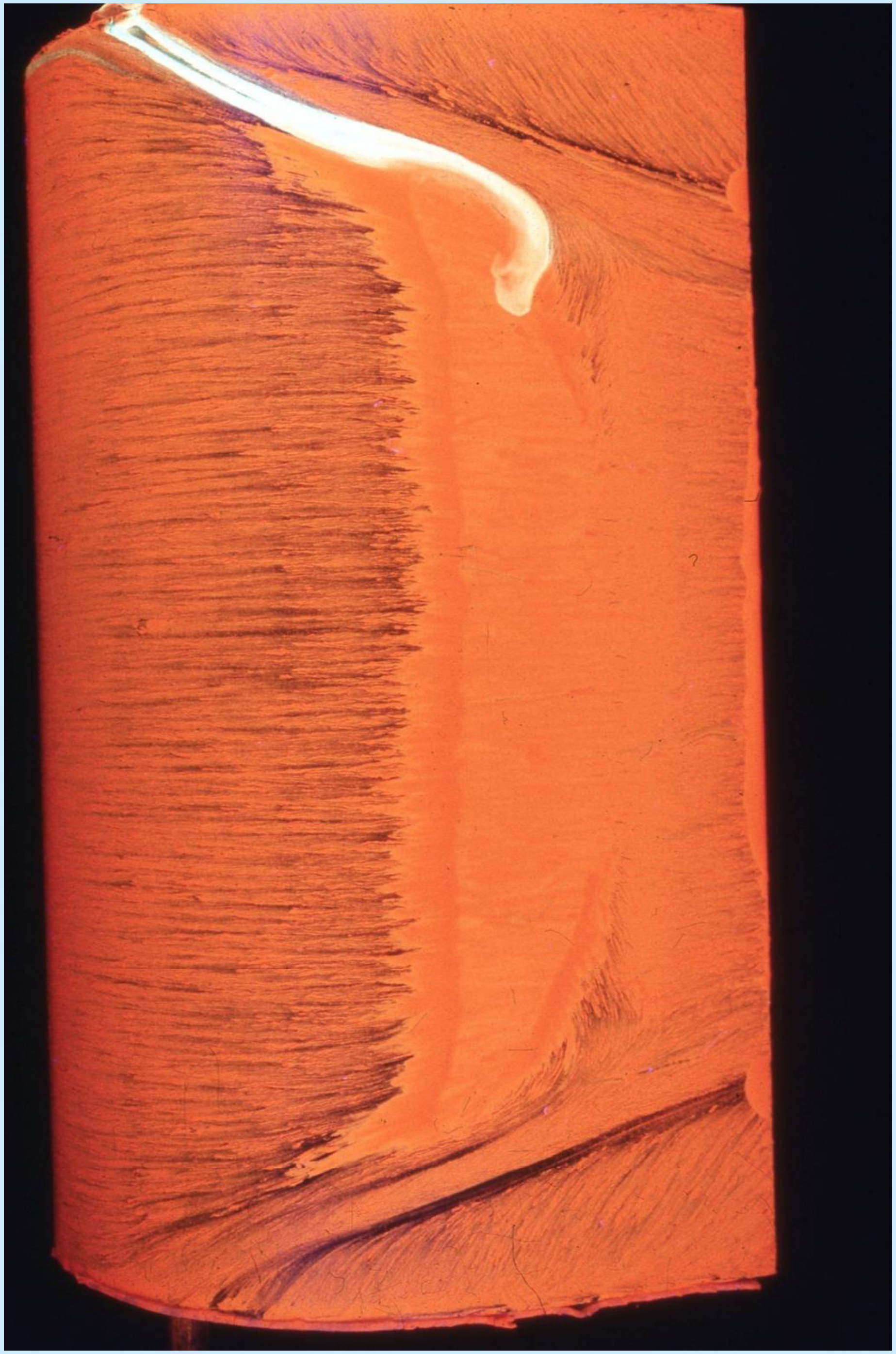

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Compressor Blade

Streamwise Vorticity on Suction Surface

Schulz and Gallus

Turb. Level 1.2%

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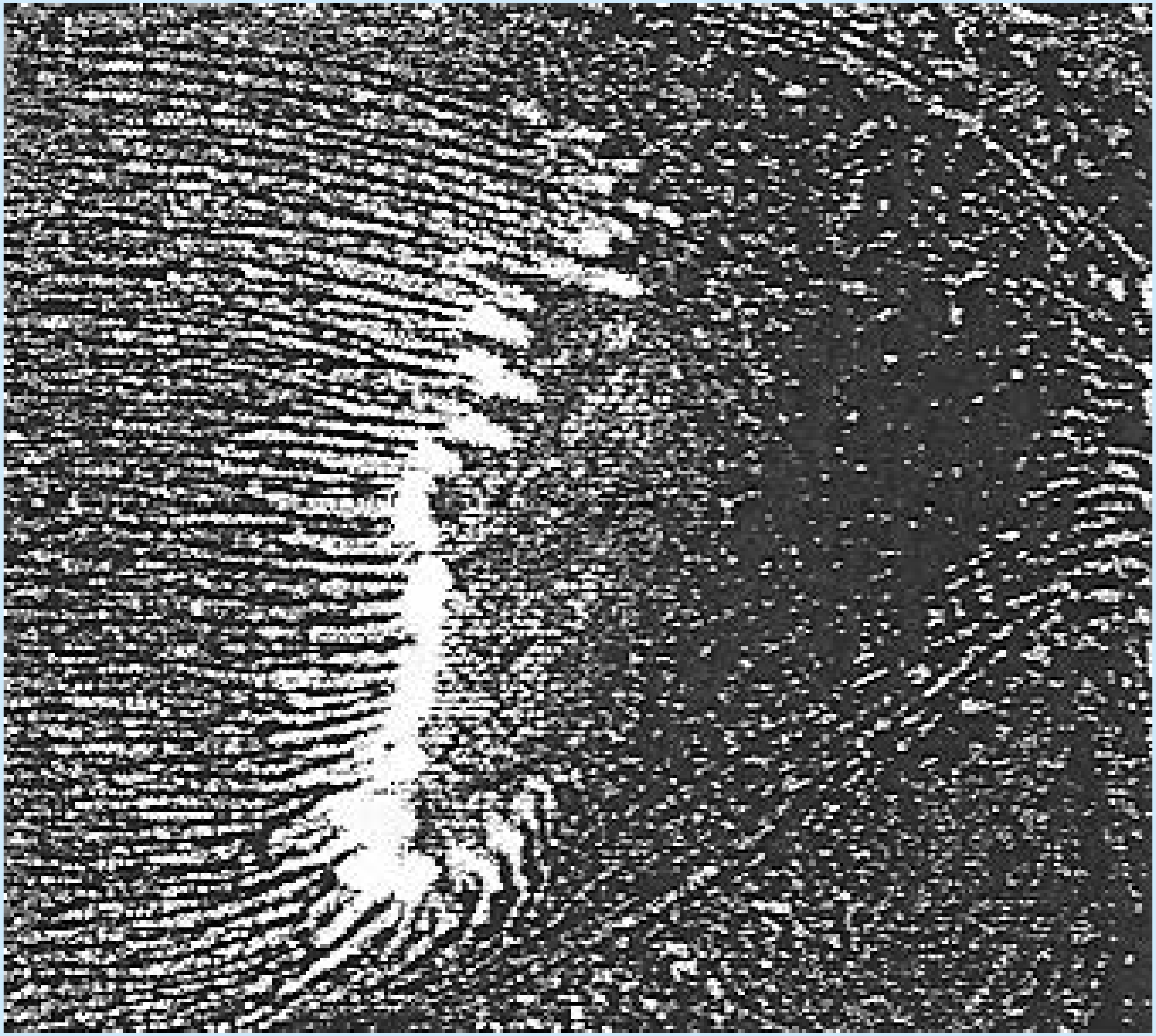

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Transonic Compressor Blade

Weber et al., Turb. Level 0.6%

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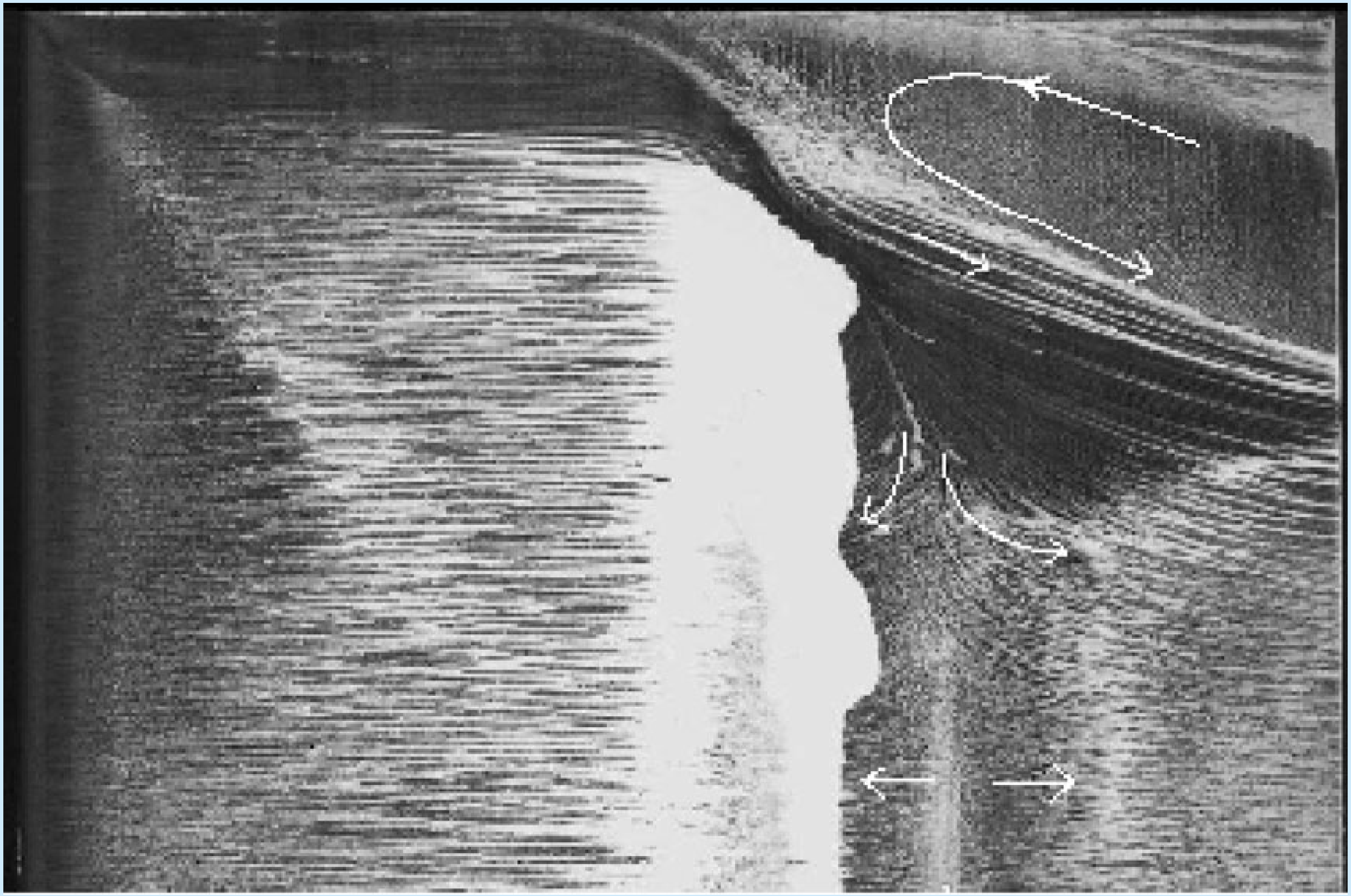
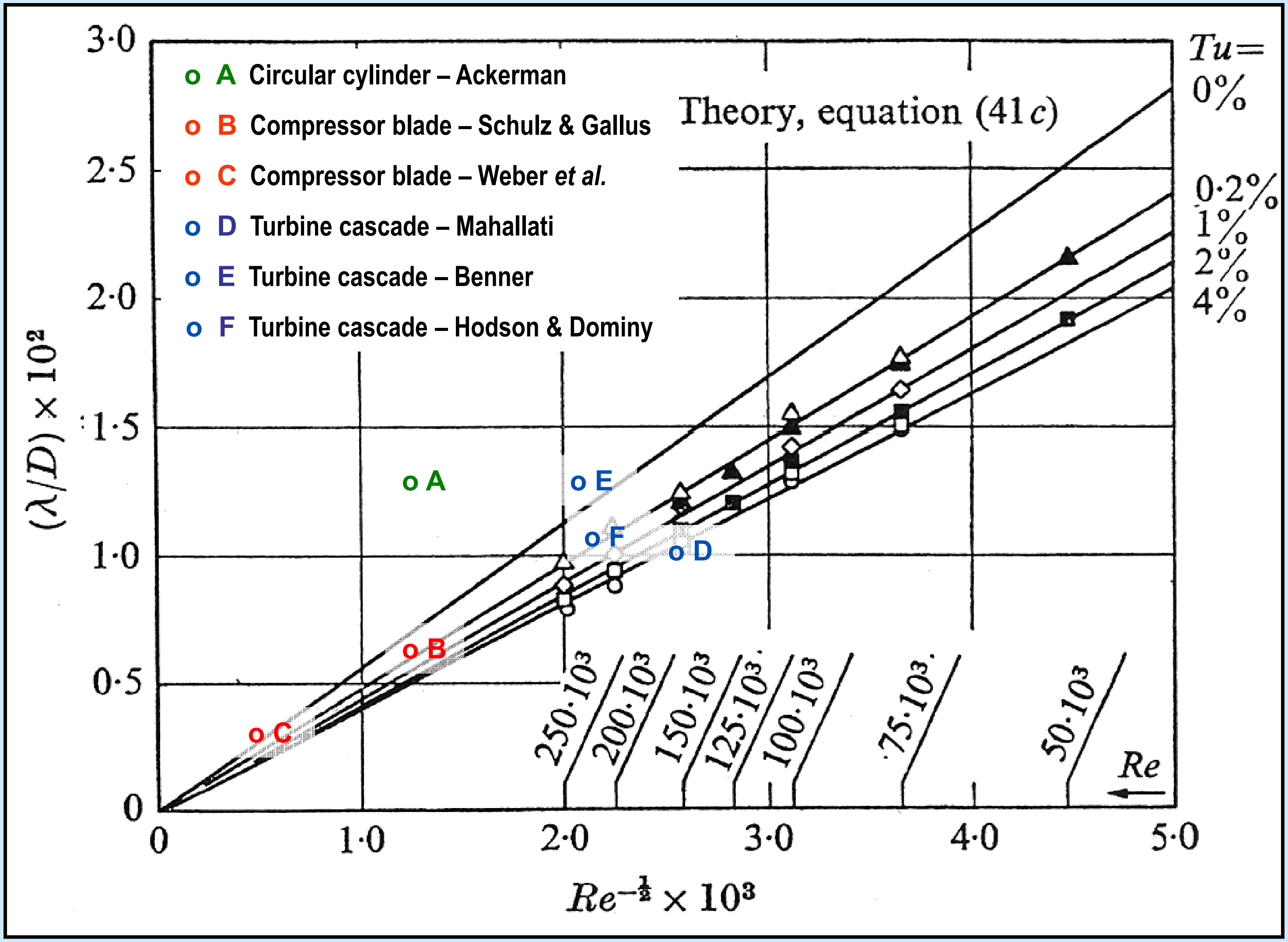


Measurements of Wavelength

and comparison with Kestin and Wood theory



Conclusions

- *In assessing the results please recall that the Mach number regimes and model geometries differ considerably. Selection of the radius of curvature at the 10% chord location is consistent but arbitrary, although it does seem representative for most blades and gives a good fit for the results.*

- *Measured spanwise wavelengths of the periodic vortex arrays on blading are predicted well by the Kestin and Wood theory. If this behavior is at all common it could have implications for turbine aerodynamic and blade cooling design.*

- *The outcome is to establish that organized streamwise vorticity may occur more frequently on convex surfaces, such as turbine blade suction surfaces, than hitherto appreciated. Investigations and predictions of flow behavior should be extended to encompass that possibility.*

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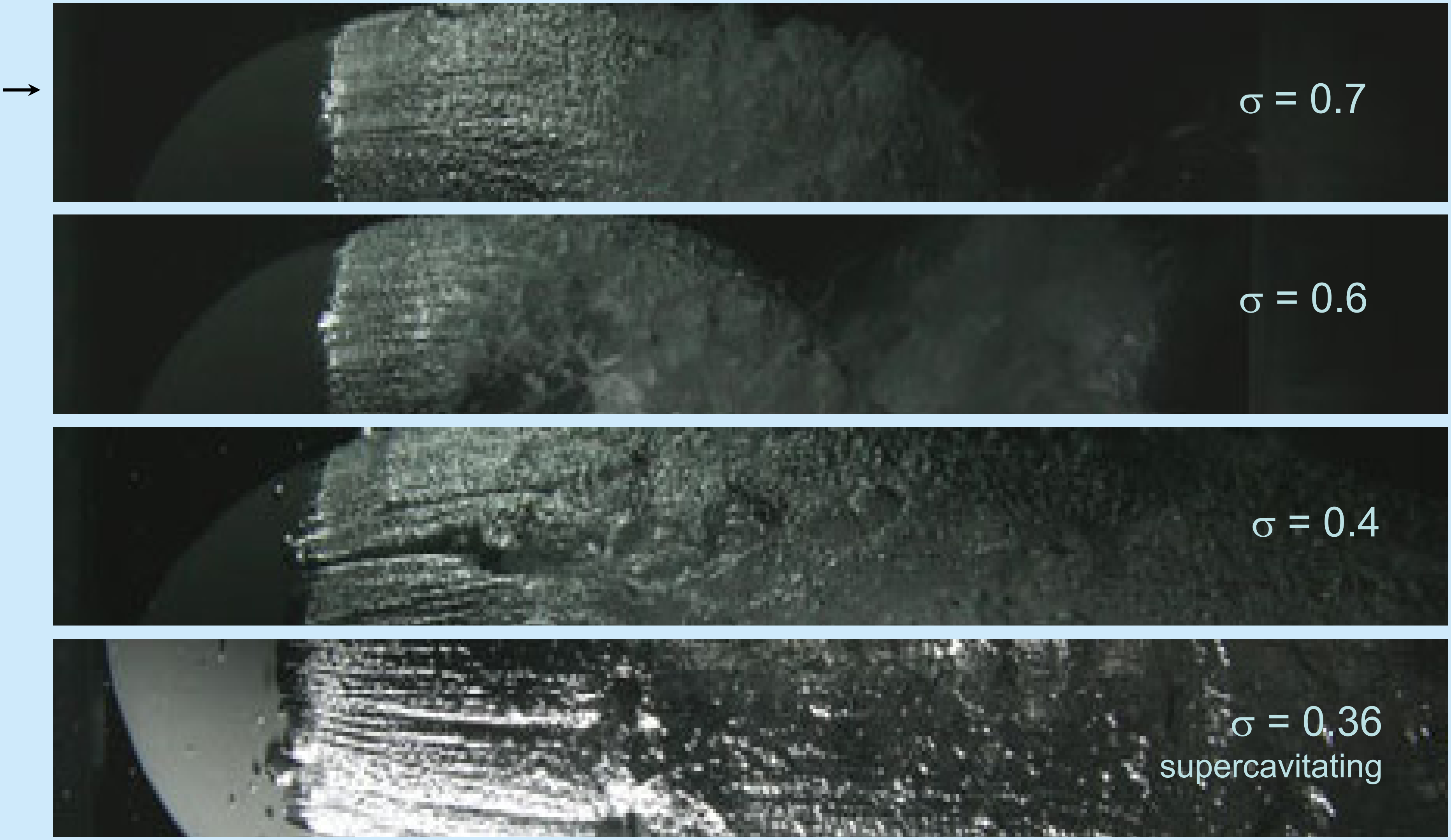
Cloud Cavitation on Sphere

Showing Streamwise Vortices - Turb. Level 0.5%

Walker et al.



Cloud Cavitation on Sphere

Streamwise Vortices and K-H Instability

Walker et al.

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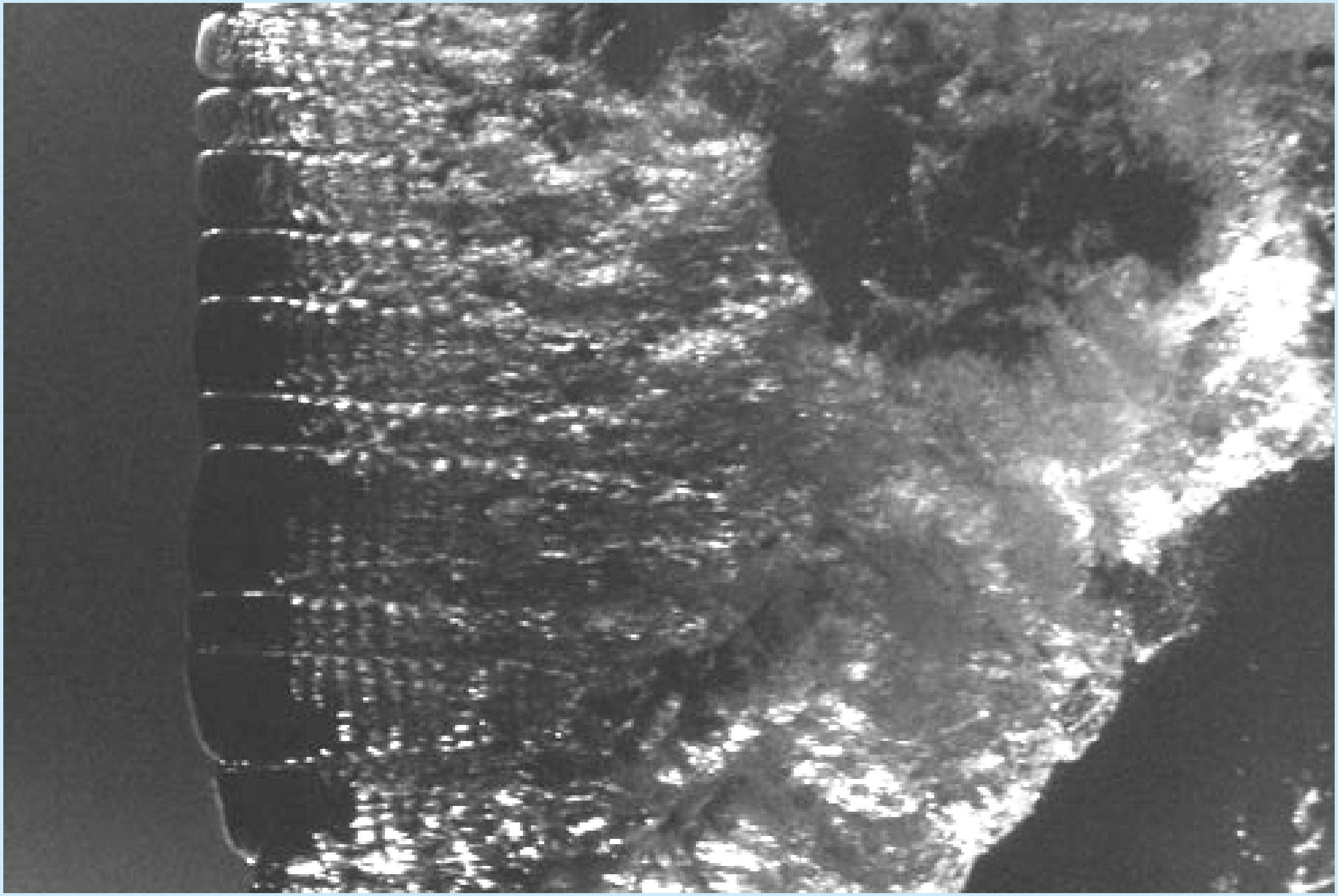

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Turbine Blade

Hodson and Dominy

Turb. Level 0.5%

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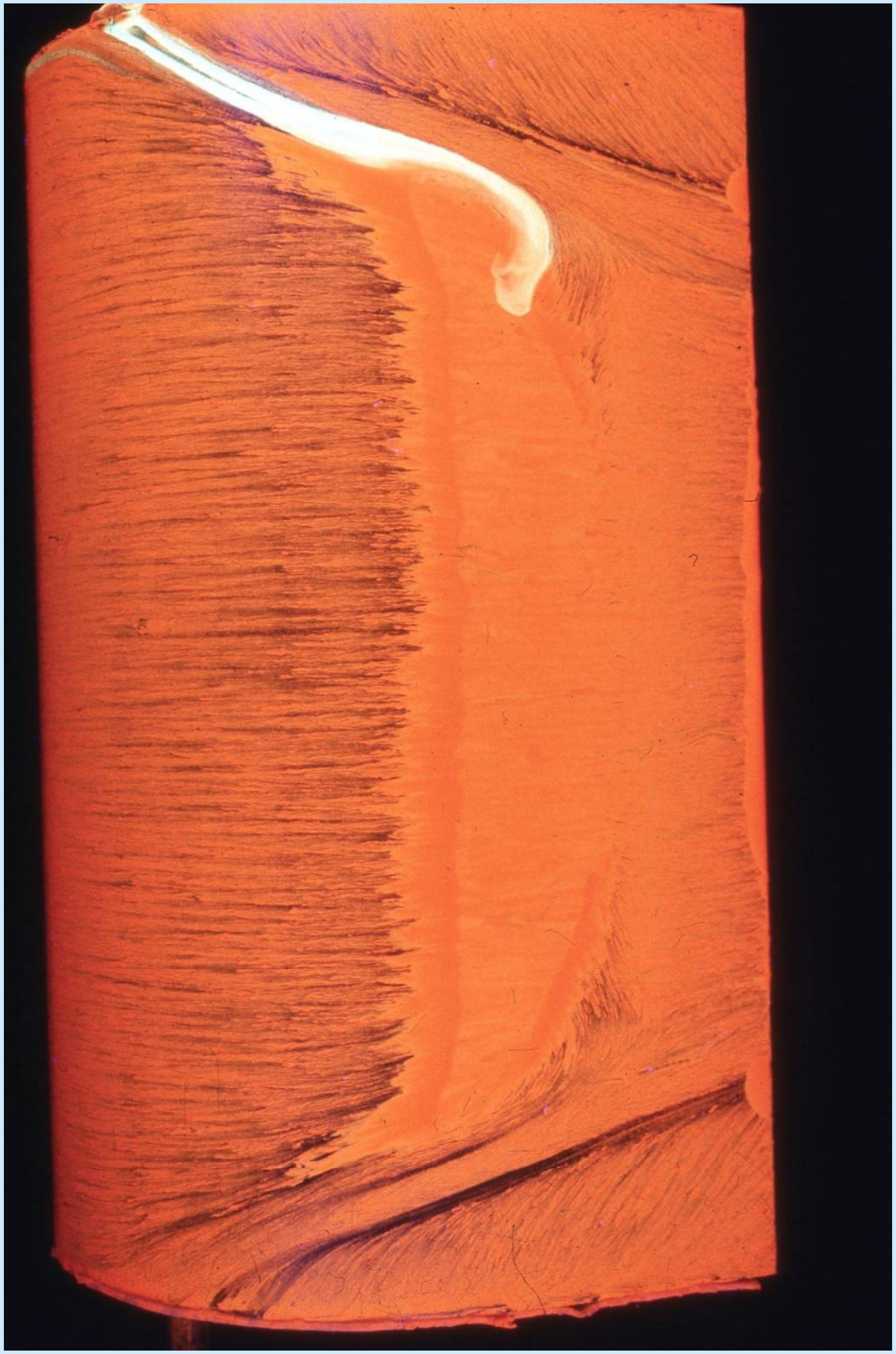

Streamwise Vortices on Turbine Blade Suction Surface

Benner

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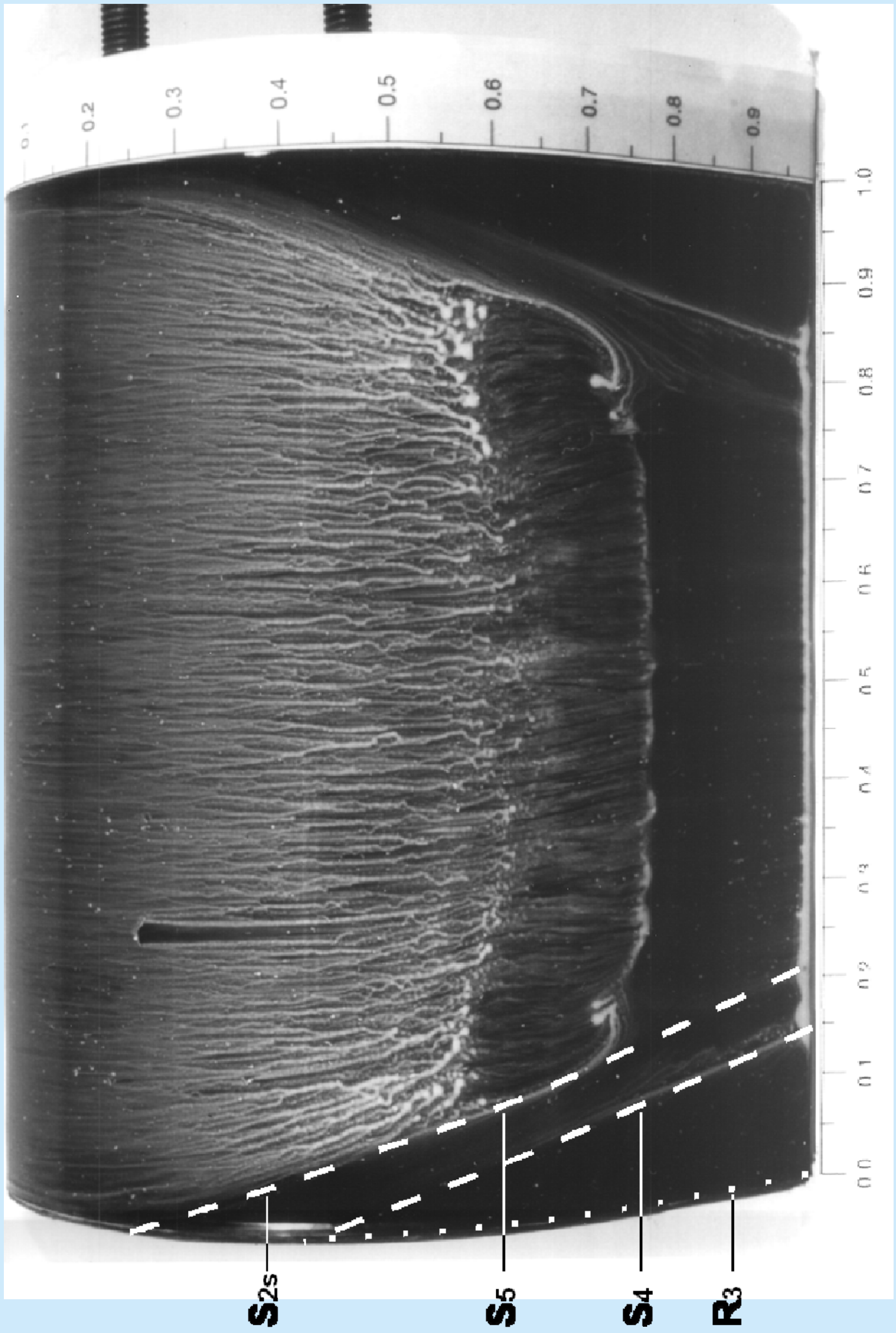

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Enlarged View of Endwall Vortex *(Mahallati)*

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