

THE STATE OF THE ART OF CONVENTIONAL  
FLOW VISUALIZATION TECHNIQUES  
FOR WIND TUNNEL TESTING

by

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CONVENTIONAL WIND TUNNEL  
'FLOW VISUALIZATION TECHNIQUES'

- 1) SURFACE-FLOW METHODS
- 2) TRACERS
- 3) OPTICAL METHODS

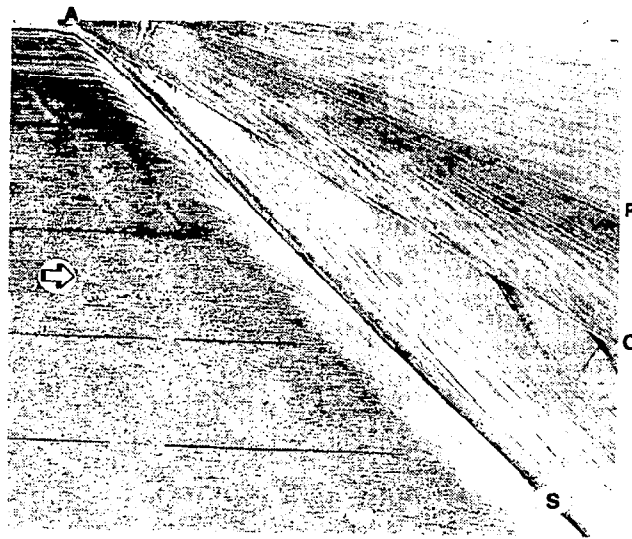
PHOTOGRAPHY AND VIDEOGRAPHY

SURFACE-FLOW METHODS

- 1) LIQUID FILMS
  - OIL + FLUORESCENT DYE, UV LIGHTING
  - RENEWABLE FILM VIA POROUS DISPENSER IN MODEL
  - VOLATILE CARRIER FLUID: DRY TRACE
  - CRYOGENIC: LIQUID PROPANE + PIGMENT
  - COLORED OIL DOTS
  - OIL FILM INTERFEROMETRY YIELDS  $C_f$
- 2) REACTIVE SURFACE TREATMENTS
  - REACTIVE GAS INJECTION
  - REVERSIBLE DYE
- 3) TRANSITION & HEAT TRANSFER DETECTORS
  - EVAPORATION
  - SUBLIMATION
  - LIQUID CRYSTALS
  - PHASE-CHANGE PAINTS
  - IR THERMOGRAPHY
- 4) TUFTS
  - FLUORESCENT MINI-TUFTS
  - CRYOGENIC SUITABILITY

## KEROSENE-LAMPBLACK SURFACE STREAK TRACES

A mixture of kerosene and lampblack has been useful for many years in producing dry traces of surface flow patterns, which are not disturbed when the wind is stopped. Rather than photographing these patterns, a novel method of preserving them is to press 8"-wide "Scotch Magic Transparent Tape" onto the model and actually peel the pattern off. The result is a full-scale, highly-detailed trace from which quantitative measurements can be made of surface streak features and angles. This example is from a series of 3D shock/turbulent boundary layer experiments done by the author.

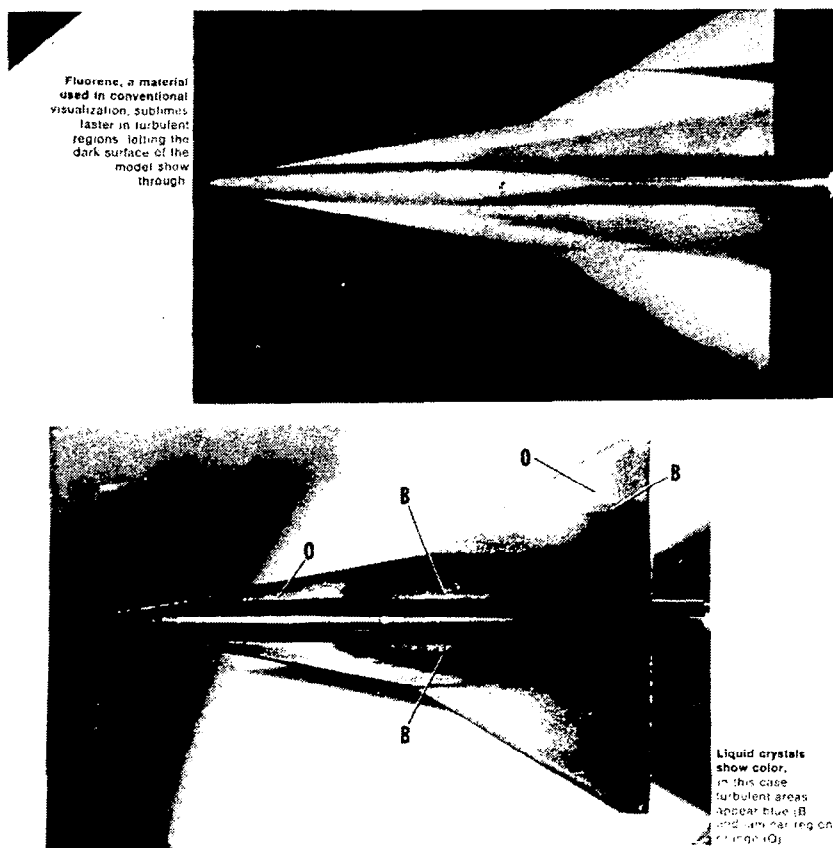


Kerosene-Lampblack Surface Streak Trace  
for  $\lambda = 60^\circ$ ; A = apex, C = corner,  
R = reattachment, S = separation.

Source: Settles, G. S. and Teng, H. Y., AIAA Paper 82-0229,  
Jan. 1982.

## SUBLIMATION AND LIQUID CRYSTALS FOR TRANSITION DETECTION

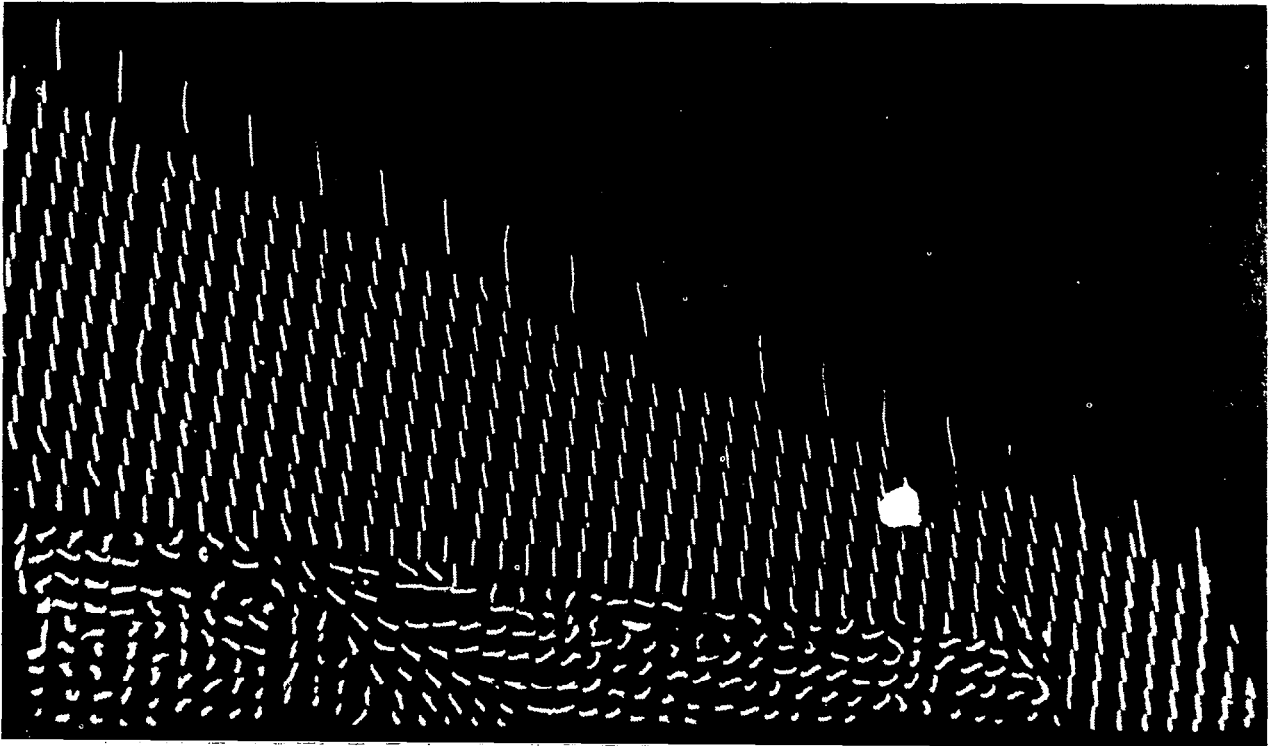
Liquid crystals are by far the most optically active substances available. They respond with a perceived color change to minute differences in temperature. Thus, as in this example, they have been proved useful for detecting the temperature change at transition. Liquid crystals have some advantages over traditional sublimation techniques in that the transition pattern is displayed with color contrast and is able to indicate changes due to, say, a change in model attitude during a single wind tunnel run.



Source: Klein, E. J., "Liquid Crystals in Aerodynamic Testing," Astronautics & Aeronautics, July 1968, pp. 70-73.

## FLUORESCENT MINI-TUFTS

Fluorescent mini-tufts are a recent advance in the state-of-the-art of tuft visualization for flow near a solid surface. Extremely thin fluorescent nylon monofilament is glued to the model surface in short lengths according to a regular grid pattern. Under UV lighting these mini-tufts can be photographed despite their small size. The results, as in this example, give a graphic indication of surface flow angles and separation. Further, the inventor of this technique (J. P. Crowder of Boeing) has shown by rigorous tests that the mini-tufts do not produce a significant disturbance to the flow.



Source: Crowder, J. P., Astronautics & Aeronautics, Nov. 1980, pp. 54-56.

## TRACERS

### 1) SMOKE

- SMOKE-WIRE TECHNIQUE
- SMOKE FILAMENTS AT HIGH SPEEDS

### 2) "VAPOR SCREEN"

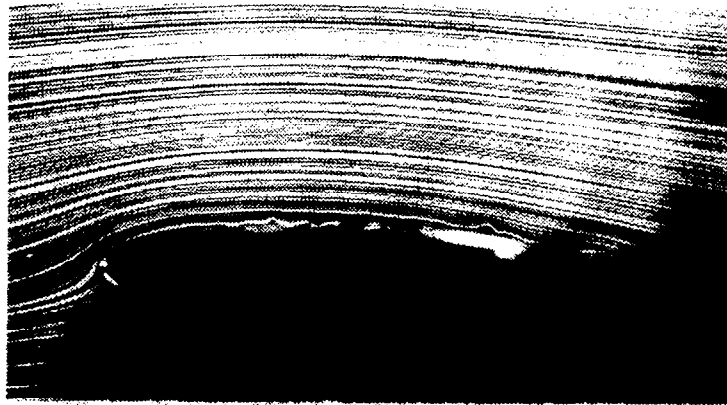
- GLOBAL SEEDING W/LASER LIGHT SHEET
- LOCAL SEEDING W/LASER OR STROBE
- CRYOGENIC: LIQUID HE YIELDS  $N_2$  "FOG"?

### 3) OTHER METHODS

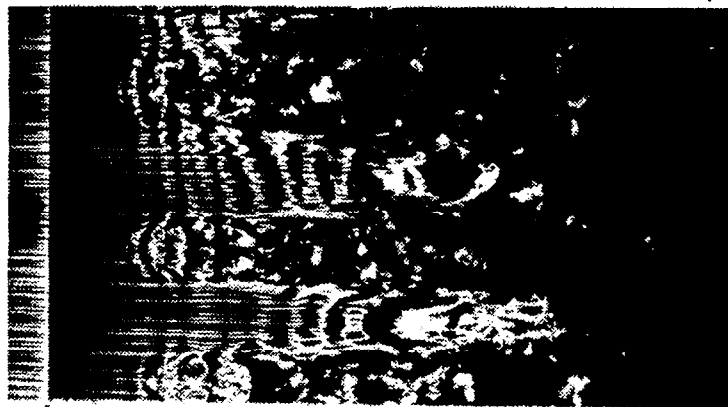
- FLUORESCENT AEROSOLS, PARTICLES, OR ATOMS
- NEUTRALLY BOUYANT BUBBLES
- SPARK TRACING
- PROBE SURVEYS + GRAPHICS

## SMOKE-WIRE TECHNIQUE

For low-speed flows the smoke-wire technique is a simple and elegant means to produce high-quality smoke filaments for flow visualization. A fine resistive wire on the order of 0.1 mm diameter is coated with oil and heated by electrical current, whereupon the oil forms beads and ejects filaments of aerosol particles. Given proper lighting and a low level of free-stream turbulence, these filaments can dramatically reveal, for example, boundary layer transition on a wing.



PROFILE VIEW



PLANFORM VIEW

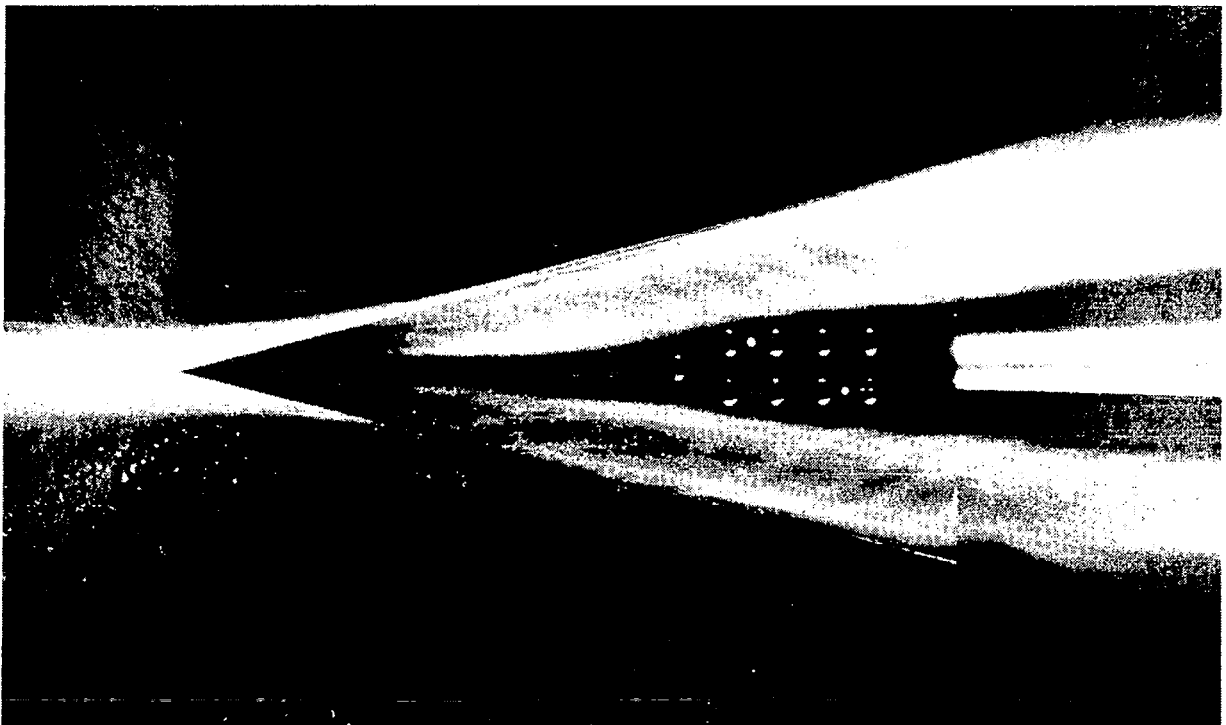
↑  
L.E.

Smoke-wire visualization for  $\alpha = 8$  deg and  $Re_c = 55,000$ .

Source: Batill, S. M. and Mueller, T. J., AIAA Journal,  
March 1981, pp. 340-345.

## HIGH-SPEED SMOKE

Recent efforts by various investigators — notably including the group at Notre Dame University — have extended the range of smoke visualization techniques to include transonic and supersonic speeds. While extra precautions may be necessary in assuming a large contraction ratio and flow smoothing, the results are quite good. This photograph, for example, clearly shows the leading-edge vortices of a delta wing at angle of attack and Mach 0.9. It was obtained by introducing a single smoke filament along the flow centerline in the wind tunnel stilling chamber.



*Bild 7:  $Ma_{\infty} = 0,9$  ;  $\alpha = 18^{\circ}$*

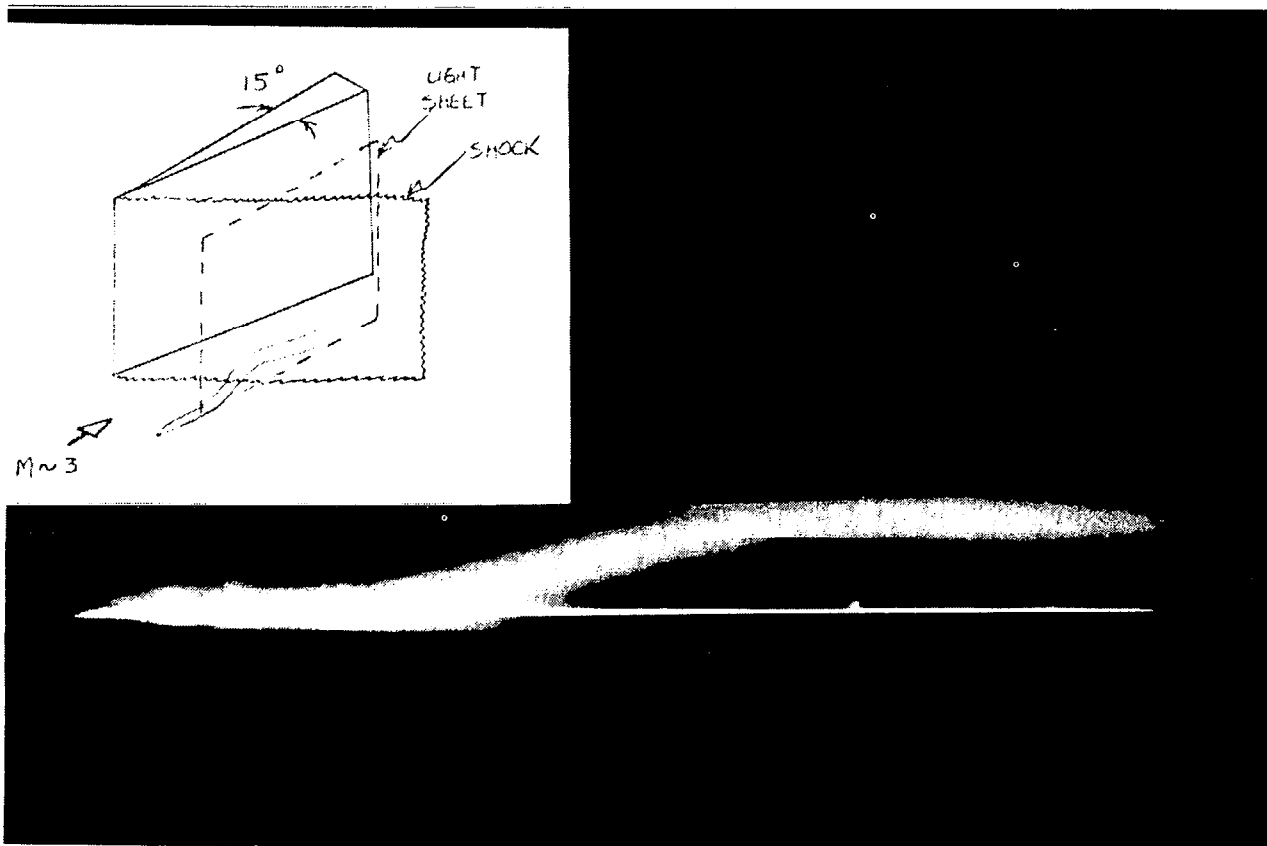
70 A 45

Source: Stahl, W., "Zur Sichtbarmachung von Strömungen um schlanke Deltaflügel bei hohen Unterschallgeschwindigkeiten," DFVLR-AVA-70-A-45, Oct. 1970.



## LOCALIZED VAPOR SCREEN

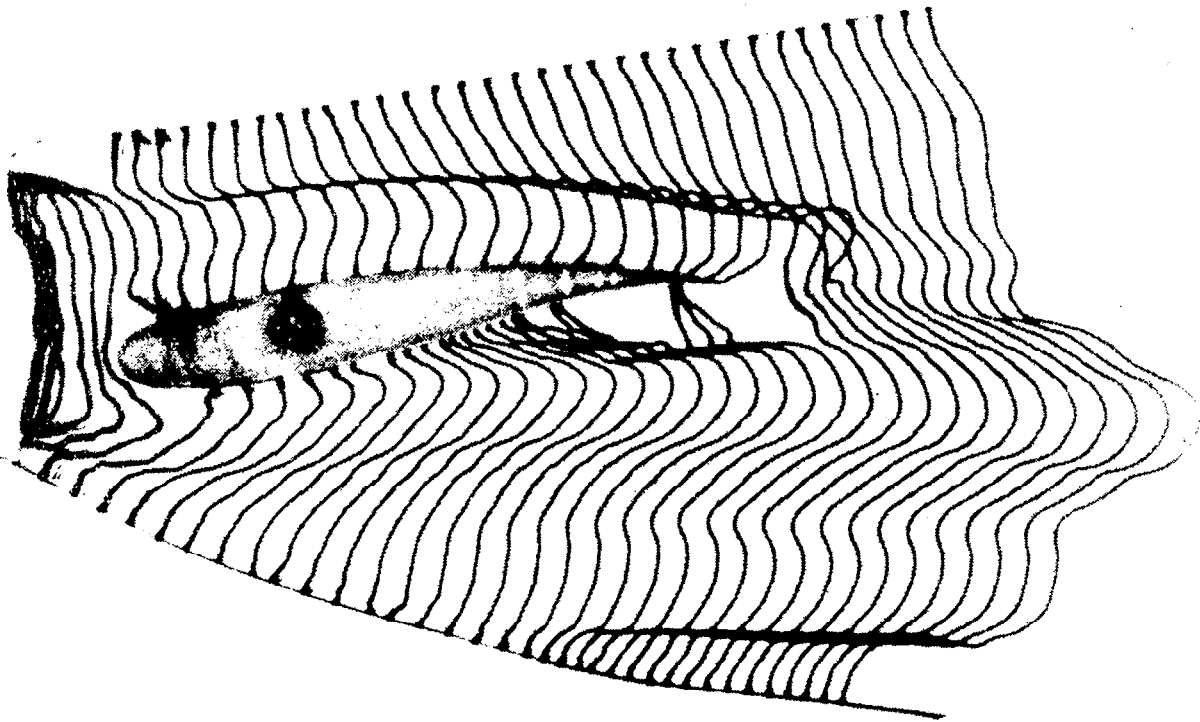
The vapor screen method can be highly useful for investigating complex flows and obtaining flowfield "cuts" which are impossible with standard optical methods. The usual vapor screen technique involves global flow seeding with an aerosol such as water fog. However, vapor screen results can also be had with localized seeding, as shown in this example. Here, a small quantity of acetone was injected through a pressure tap upstream of a 3D shock/turbulent boundary layer interaction. The acetone boiled and atomized, filling the incoming turbulent layer with fog. A streamwise light sheet was generated by spreading the beam of a 1-watt argon-ion laser with a cylindrical lens. The resulting vapor screen photo clearly shows the turbulent boundary layer lifting off the surface. (For more details of the technique, see AIAA Paper 82-0229 by Settles and Teng.)



Source: G. S. Settles and F. Lu, Princeton University.

## SPARK TRACING

Profiles of flow velocities from incompressible to supersonic speeds can be obtained by the spark tracing method. Electrical pulses at up to 250 kV and 100 kHz generate periodically luminous spark plasma trails which are convected with the flow. This example shows the flow pattern over a transonic airfoil (spark frequency: 10 kHz). The equipment is made by IMPULSPHYSIK GmbH, Hamburg FRG.



Source: Sales literature, IMPULSPHYSIK GmbH.

## OPTICAL METHODS

### 1) SHADOWGRAPH

- CONVENTIONAL PARALLEL BEAM
- CONICAL SHADOWGRAPH
- RETROREFLECTIVE MODEL SURFACE
- SPECULAR MODEL SURFACE
- WIDE-FIELD MOIRE-GRID PROJECTION

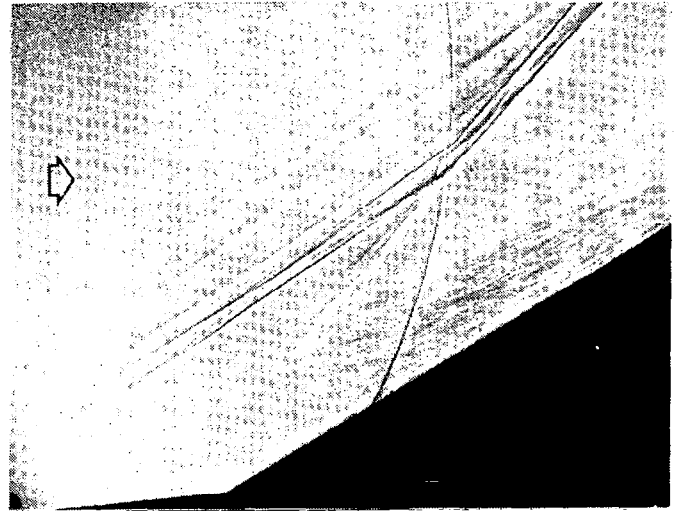
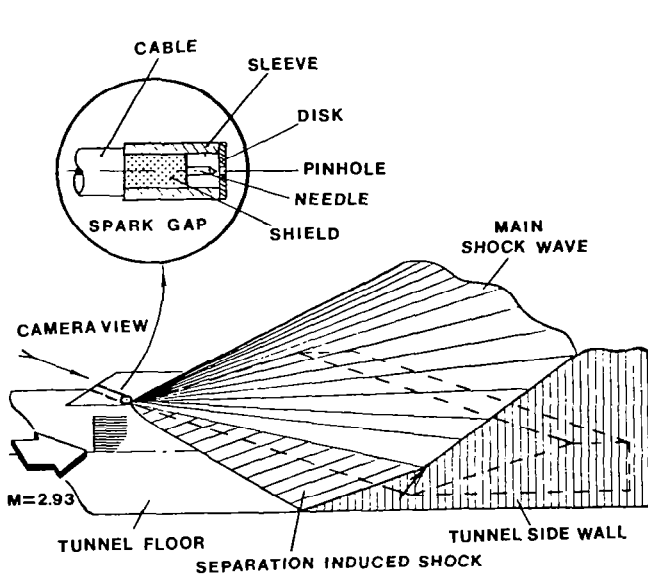
### 2) SCHLIEREN

- CONVENTIONAL PARALLEL BEAM, KNIFE-EDGE
- COLOR-CODING
- MULTIPLE-SOURCE, SHARP-FOCUSING
- STEREOSCOPIC
- SIMPLE GRID BACKGROUND
- SPECULAR MODEL SURFACE
- QUALITATIVE VS. QUANTITATIVE EVALUATION
- RELATED METHODS: PHASE CONTRAST,  
RESONANT REFRACTIVITY, LASER DEFLECTOMETRY,  
HOLOGRAPHY

### 3) INTERFEROMETER

## CONICAL SHADOWGRAPH

A variation of the traditional parallel-beam shadowgraph can be used to investigate quasi-conical flowfields. The light source (in this case a spark generated at the end of a coaxial cable inserted into the flow) is positioned near the apex of the conical flow. The shadowgram is cast upon the tunnel wall downstream, where it may be photographed.



Conical Shadowgram

Sketch of Experimental Arrangement for  
Conical Shadowgraph, Showing Shock  
Wave Shape for  $\lambda = 40^\circ$ .

Source: Settles, G. S. and Teng, H. Y., AIAA Paper 82-0229, Jan. 1982.

## SCHLIEREN: COLOR-CODING

A variety of modifications (usually simple) to existing schlieren equipment can convey useful flow visualization data by color-coding the schlieren image. This example shows a 1970-vintage Shuttle Orbiter model in the NASA-Ames 6 x 6-foot supersonic tunnel. Here the color-coding serves to provide contrast between the flowfield and the model, and to combine both vertical (yellow-blue) and horizontal (red-green) knife-edge settings in a single photograph. Additionally, the color schlieren arrangement used here has sensitivity equal to that of black-and-white schlieren using the same optics. At least a dozen different color-coding schemes are available to highlight different types of information in the schlieren image. (See Settles, G. S., "Color Schlieren Optics - A Review of Techniques and Applications," in Flow Visualization II, ed. W. Merzkirch, Hemisphere Pub. Corp., 1982, pp. 749-763.

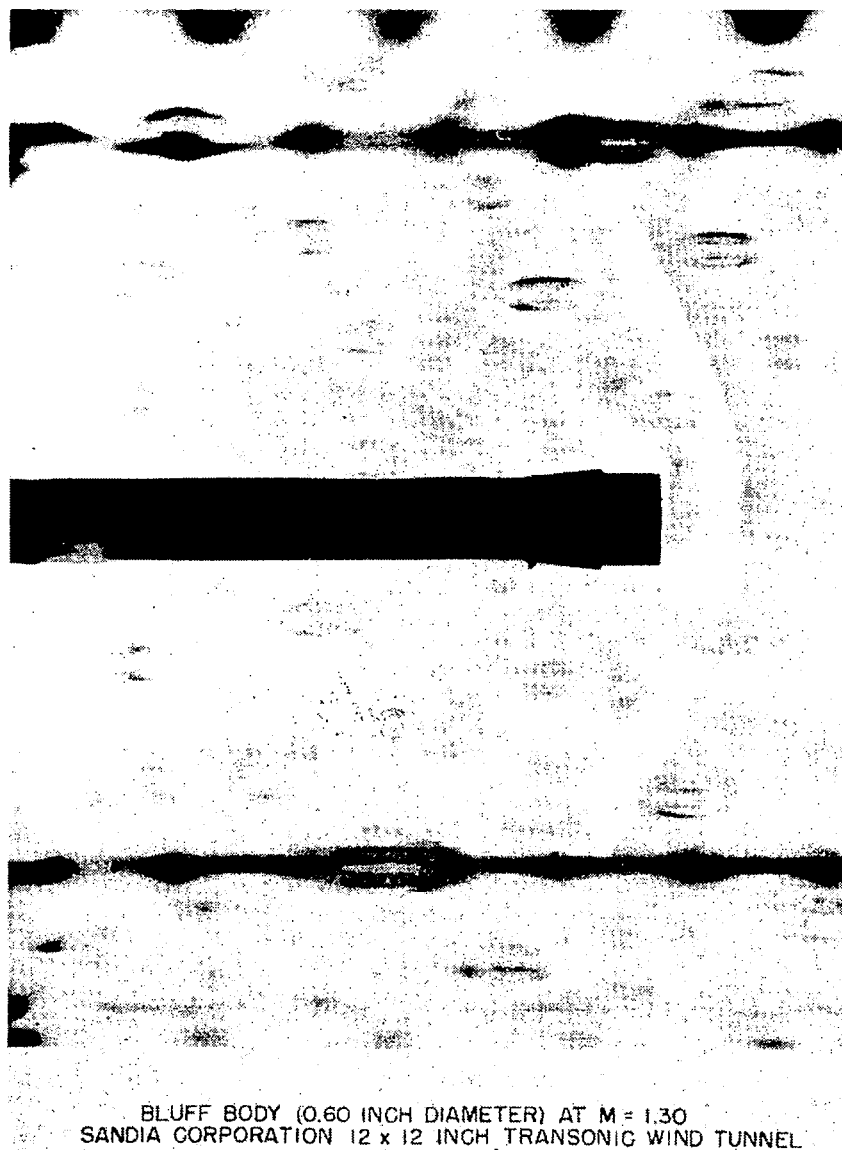


L-82-5674

Source: G. S. Settles/NASA Ames Research Center.

## MULTIPLE-SOURCE SCHLIEREN

While conventional schlieren methods generally use small single light sources, there are reasons to use multiple sources for some applications. An extended light source gives a sharp-focusing capability, allowing one to concentrate, say, on the centerline of a complex 3D flowfield. Perhaps even more important for transonic testing is the ability to configure a multiple-source schlieren system to look through slotted or perforated tunnel walls, as in this example.

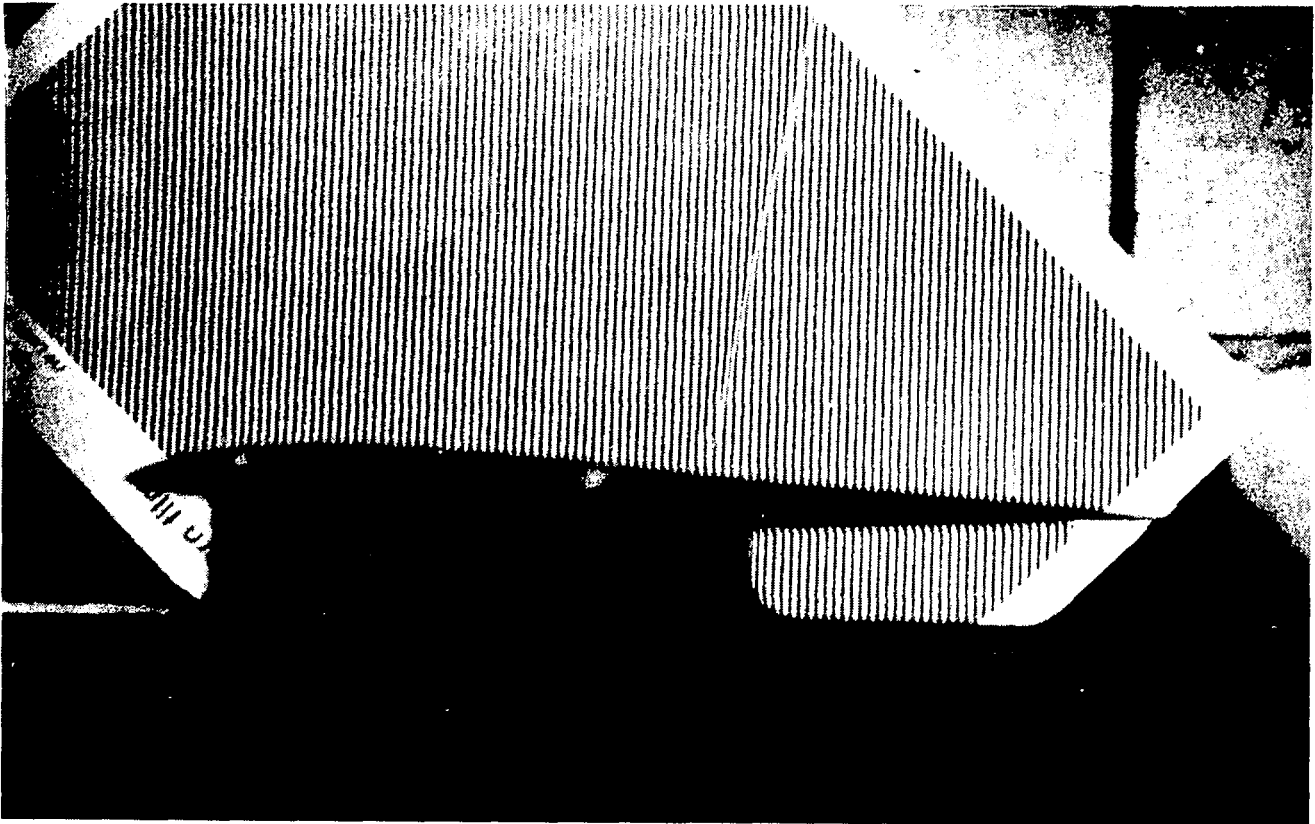


BLUFF BODY (0.60 INCH DIAMETER) AT  $M = 1.30$   
SANDIA CORPORATION 12 x 12 INCH TRANSONIC WIND TUNNEL

Source: R. C. Maydew, Sandia Corp.

## SIMPLE BACKGROUND-GRID SCHLIEREN

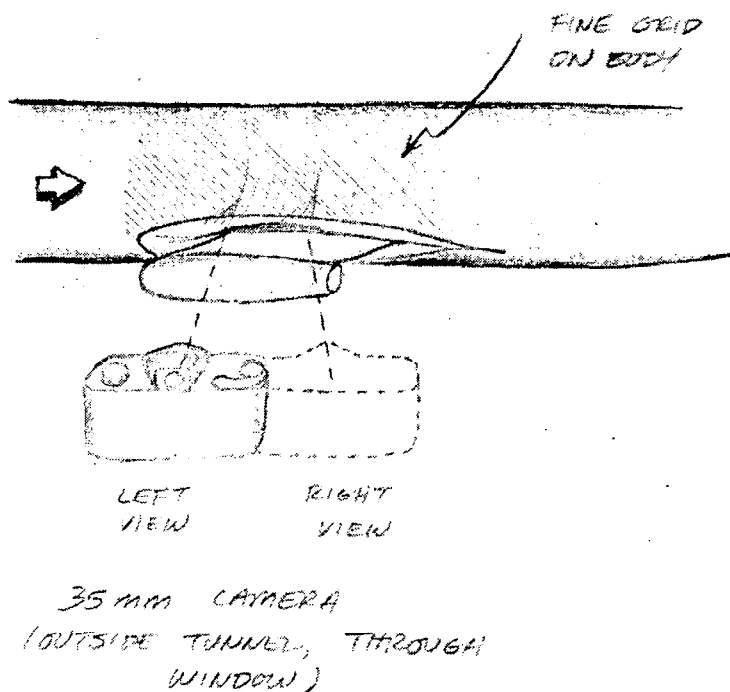
Shock wave locations and shapes can often be found by the simple expedient of viewing through the wind tunnel test section toward a background grid. This technique lacks the sensitivity of more sophisticated optical methods, but requires no equipment and is adaptable to a wide range of viewing angles and to tunnels not originally designed for flow visualization. Here, an airfoil is tested at Mach 0.8 in the Boeing Model Transonic Wind Tunnel. A sheet of ordinary drafting grid was placed a few feet in back of the test section. Stroboscopic backlighting was used to visualize the shock, which appears clearly at about 60% chord.



Source: G. S. Settles/Boeing Aerodynamic Laboratory, Boeing Commercial Airplane Company.

## STEREOSCOPIC SCHLIEREN

Various arrangements are possible for taking stereoscopic schlieren views of 3D flow phenomena. These methods overcome the inherent disadvantage of conventional schlieren visualizations: the integration of 3D flow information into a 2D image. The simplest stereo schlieren method involves taking stereo photos with the grid background described earlier. As shown in this sketch, the method can be used, for example, to visualize the 3D transonic shock pattern on the wing of a commercial air transport model. Such visualizations were carried out by the author and J. P. Crowder of Boeing's Aerodynamic Laboratory during 1981 tests in the Boeing Transonic Wind Tunnel.

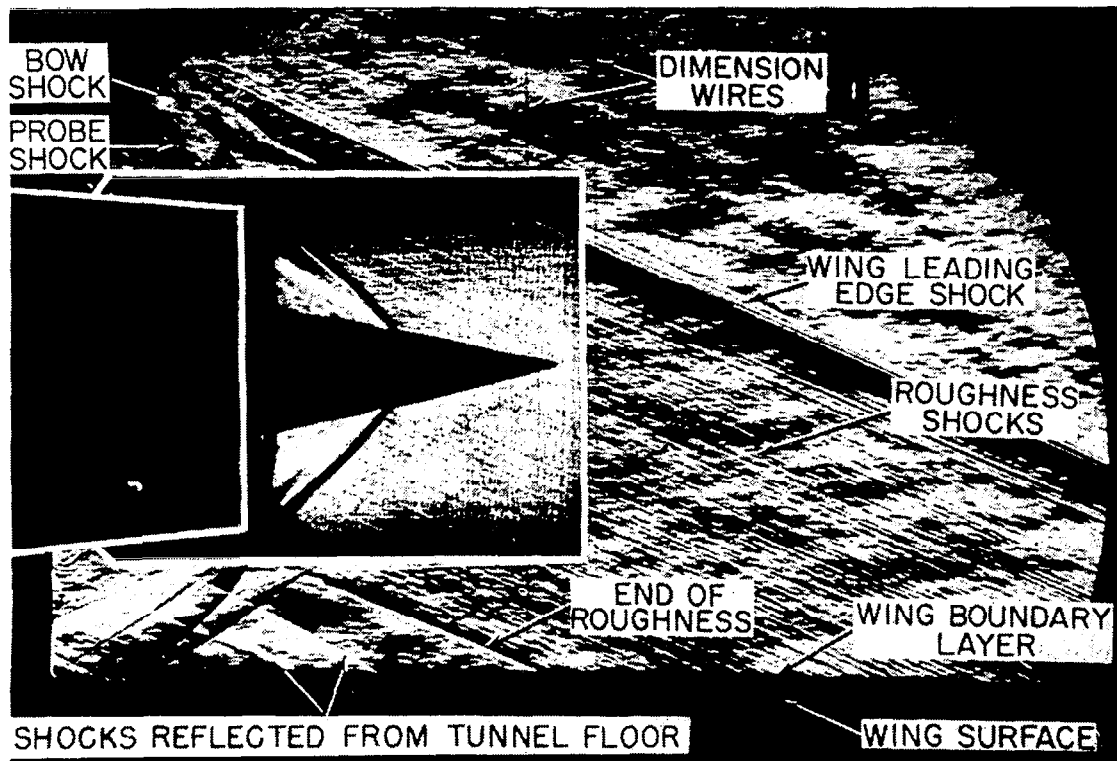


Source: G. S. Settles/Boeing Aerodynamic Laboratory, Boeing Commercial Airplane Company.



## SCHLIEREN AND SHADOWGRAPH USING REFLECTING MODEL SURFACES

Test models appear only in silhouette in most optical flow visualizations. This is a disadvantage in observing complex 3D flows, where the model may obscure important parts of the flowfield. Specular model surfaces can sometimes be used to overcome this problem by allowing one to collect the reflected light and form an image of the normally-obscured flow. In this example a reflecting splitter-plate was used to visualize an inlet shock pattern that would otherwise have been obscured. Such techniques have the potential to visualize transition on polished wings by planform schlieren or shadowgraphy. Further, in NTF the model surfaces may need to be specular for other reasons as well.



Composite shadowgraph and schlieren of the flow. Splitter plate 1; high pylon;  $\phi = 0^\circ$ ;  $\dot{m}_2/\dot{m}_1 = 0.72$ .

L-66-1003

Source: Moseley, G. W., et al., NASA TN D-3385, April 1966.

## PHOTOGRAPHY AND VIDEOGRAPHY

### 1) LIGHT SOURCES

- CONVENTIONAL, STROBOSCOPIC, & LASER

### 2) CAMERAS

- HIGH-SPEED:  $> 1$  MHz
- STANDARD VIDEO: 30 Hz
- HIGH-SPEED VIDEO: 12 kHz B&W, 200 Hz COLOR