SURFACE FLOW VISUALIZATION
USING INDICATORS

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Surface flow visualization using indicators in the cryogenic wind tunnel will remain as important an experimental procedure as the conventional "oil flow" methods, but with the extreme testing environment will require a fresh look at materials and procedures to accommodate the new test conditions. In a sense, these new conditions are welcome, as they provide an opportunity to identify new materials and reactions to provide better surface flow visualization opportunities.

Figure 1 summarizes several potential liquid and gaseous indicators that can be identified from a cursory examination of material tables, but their particular suitability can only be determined after actual trials in the test environment. These particular materials illustrate the various requirements an indicator must fulfill. Foremost among the requirements is that the indicator must exist in the proper state at the test condition. Keeping in mind that the test conditions can span the entire operating envelope of the NTF, it is probably too much to expect one material to be used over the entire range. Several different indicators must be selected.

Equally important are the requirements that the indicator must respond properly to the flow phenomenon of interest and must be observable. Boundary layer transition is the most important phenomenon for which flow visualization indicators may be employed and probably the most difficult application. Identification of surface flow direction and separation is a more easily achieved application, and is still sufficiently important to justify the development effort required.

The visibility of a particular indicator will depend on utilizing various optical or chemical reactions. For example, liquid nitrogen may be visible on a model surface by specular reflections from the liquid-gas interface or by atomic emissions excited by tuneable laser illumination. The hydrocarbons such as propane and pentane will readily dissolve various fluorescent dyes and thus can be easily observed with ultraviolet illumination.

Gaseous indicators are probably more difficult to utilize, but because of their diversity, may present unusual and useful opportunities. Presumably they can be observed directly by resonant emissions, but other reactions can also be expected. For example, oxygen can quench the fluorescence of other materials so that one can imagine the model surface coated with a fluorescent paint which will produce a visible emission which is inhibited where the concentration of oxygen in the boundary layer is sufficiently high. Ozone has the property of strongly absorbing ultraviolet radiation and so can conceivably be used to cast a shadow on a fluorescent surface by blocking the ultraviolet excitation. At higher temperatures ammonia can be used in conjunction with pH indicators incorporated into a paint system to produce visible stains in regions of high concentration such as in Figure 2. In this example ammonia is dispensed from pressure orifices in the model surface.

Other factors that must be considered in selecting an indicator include handling safety, toxicity, potential for contamination of the tunnel, and cost.

Delivery of the indicator to the model surface is a major consideration, if not impediment, in any flow visualization system. It can be readily appreciated that a wind-on dispensing system is necessary for practical utilization of flow visualization indicators in the NTF. Not only would a one-shot pre-run application of indicator to the model surface be prohibitively expensive for routine use in the NTF, but most indicators would not even exist in the proper state at the application temperature and pressure.

Of the possible flow visualization indicator delivery systems, as summarized in Figure 3, the retractable spray bar approach is probably the least attractive. It has the advantage of being independent of the model, but it would require a complex facility installation. Its greatest disadvantage, however, may be the very inefficient delivery of indicator to the model surface which implies that large quantities of material are needed and hence the tunnel contamination may be very serious.

An onboard-model dispenser comprised of an array of orifices in the surface could be considered a conventional system, but this approach suffers several serious difficulties. The supply pressure drop of the indicator through an orifice of practical size is relatively small compared to typical aerodynamic pressure gradients across the model surface. Therefore, in order to maintain uniform delivery over the entire wing span, for example, a multiple manifold system is usually required. This complicates the installation of the system in the model and requires a complex control system. Figure 4 shows the narrow nature of liquid indicator plumes dispensed from orifices.

A delivery system comprised of a continuous strip of porous metal inset flush with the model surface offers many advantages. In particular, it is possible to achieve uniform dispensing over an entire wingspan with a single manifold at conveniently high supply pressures (on the order of 1000 psi) so there is little potential for interaction with model surface pressures. Figure 5 shows the typical appearance of an indicator dispensed from a relatively nonuniform porous strip. The model surface can be very smooth and thus presents less of a disturbance to the flow than individual orifices.

The greatest difficulty with this approach to date has been model fabrication. The porous metal has usually been in the form of sintered stock cut into strips and inset into a carefully machined groove in the model to achieve a close-fitting mechanical attachment. This has been relatively easy for conventional, 2-D models, but will be much more difficult for cryogenic, 3-D models.

A new method of fabricating a porous dispenser suitable for a 3-D, cryogenic model has been developed at the Boeing Aerodynamic Laboratory as reported here and is depicted in Figure 6. With this new method, a single spanwise slot is machined into the wing leading edge, but it need not be very straight nor of constant dimension. The sides of the slot should be widely spread and a narrow groove located in the bottom. The slot is then filled by a flame spray process which involves blowing semi-molten powdered metal from a high temperature gun. Figure 7 shows the appearance of the flame spray application before finishing.

Depending on the details of the material used, preparation of the model surface, and the particular application process, a very secure attachment of the porous material to the model can be achieved. The flame spray material is finished to the final model contour as if it were solid metal with a very smooth surface finish. Depending on the final finishing and porosity of the material, an electro-chemical etch of the surface may be required to open the pores a controlled amount for uniform dispensing of the indicator.

Experience with this process on small specimens has been very encouraging, but several important questions remain to be answered, as summarized in Figure 8. The major structural problem may be the effect of repeated temperature cycles on the porous material attachment. Thermal stressing of small samples by alternate submersion in liquid nitrogen and hot water has so far shown no adverse effects. Another question which must await wind tunnel trials is the durability against erosion by wind-borne matter.

A final question which deserves careful study is a definition of surface roughness requirements. Even though these porous metal surfaces feel smooth to the fingertip, it is clear that they tend to have relatively large pores below the surface which would doubtless be perceived by conventional roughness inspection methods as similar to roughness features that protrude above a mean surface. It is unlikely, however, that the aerodynamic flow will react to such surface features similarly. It is probably not possible to resolve this question without actual wind tunnel trials, but conventional , and somewhat arbitrary, model surface roughness specifications should not be applied too rigorously and prematurely.

Clearly there are great potential benefits in developing surface flow visualization methods for cryogenic wind tunnel testing and there are many potential materials and reactions that deserve thorough study. Even though there appear to be a few practical techniques close at hand, the potential for even greater surface flow visualization productivity ought to justify a long term and complete development effort.

- * Candidate Flow Visualization Indicators

LIQUID		
	M.P.(K)	B.P.(K)
NITROGEN	63	77
PROPANE	83	229
FREON-12	118	278
ACETONE	179	329
PENTANE	143	309

GASEOUS	
	B.P.(K)(1 ATM)
OXYGEN	90
OZONE	161
CARBON MONOXIDE	81
NITRIC OXIDE	120
AMMONIA	240

* Pre-run application of indicator is impractical
  - access to model for one-shot flow vis involves great expense.
  - physical properties of most indicators are incompatible with standard temperature and pressure.

* Cryogenic surface flow visualization using indicators requires wind-on dispensing system.

Figure 1.- Cryogenic surface flow visualization using indicators.

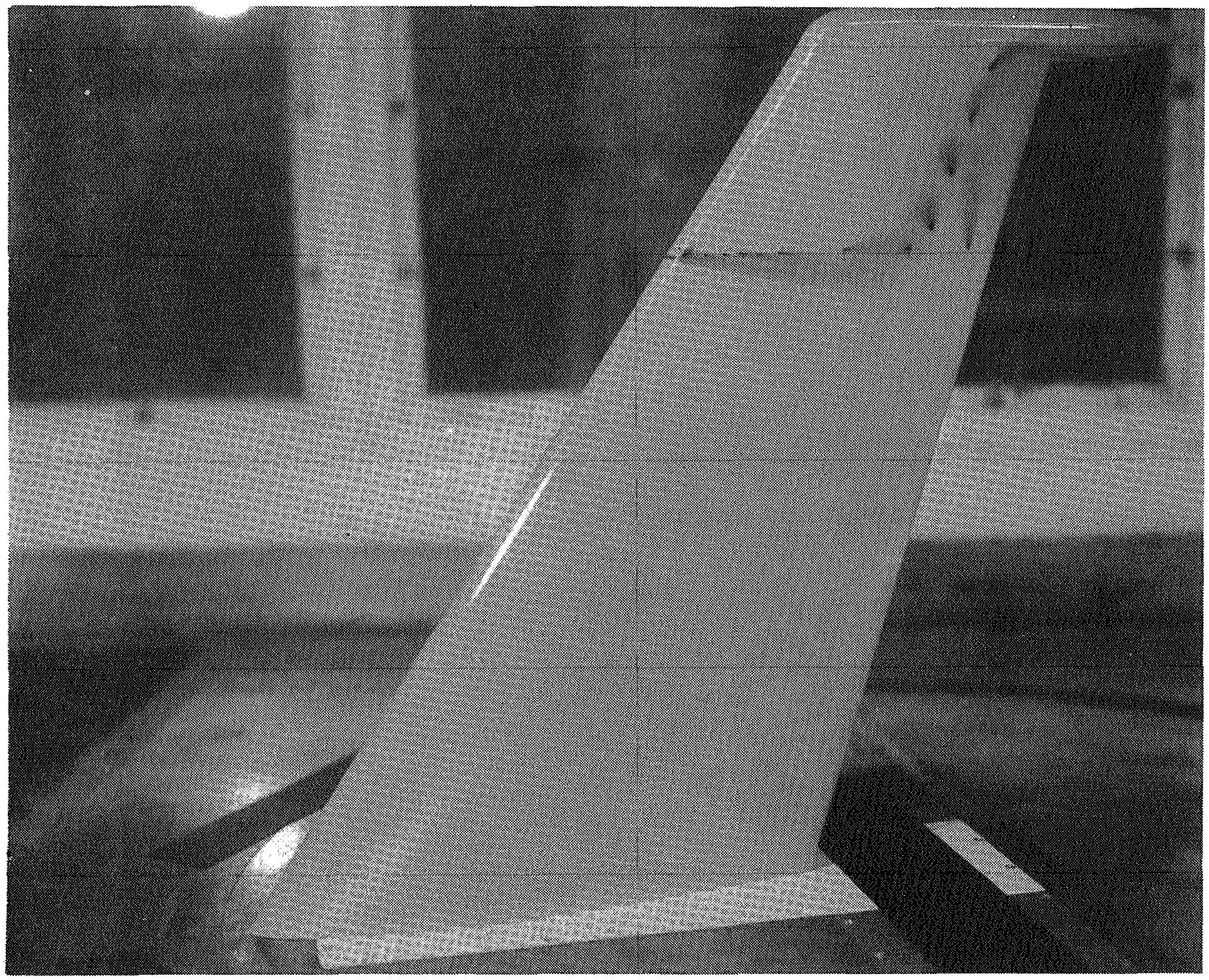

Figure 2.- Example of flow visualization using ammonia gas indicator.

* Retractable Spray Bar
  + Independent of model
  – Requires elaborate facility modification
  – Disturbs flow while dispensing
  – Large quantities of indicator——contaminates tunnel
* Orifice Arrays in Model
  + Present state–of–the–art baseline method
  + Simple concept
  – Complicated multiple manifolds
  – Small pressure drop——interacts with model pressures
  – Orifice size disturbs boundary layer
* Porous Surface
  + Uniform distribution from single manifold
  + High supply pressure (0~1000 psi)
  + Smooth surface
  – Difficult to install sintered strips in 3–D model
  – Easily plugged by non–soluble pigments

Figure 3.- Cryogenic surface flow visualization dispenser systems.

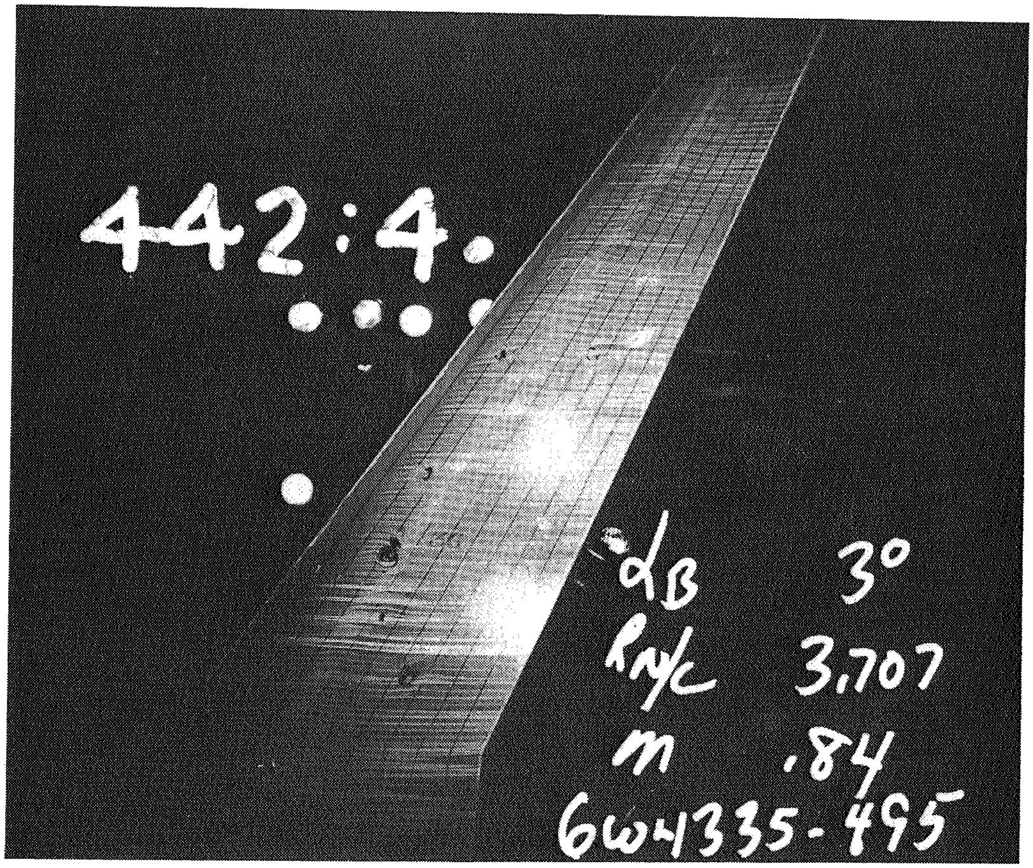

Figure 4.- Example of liquid indicator dispensed from orifices.

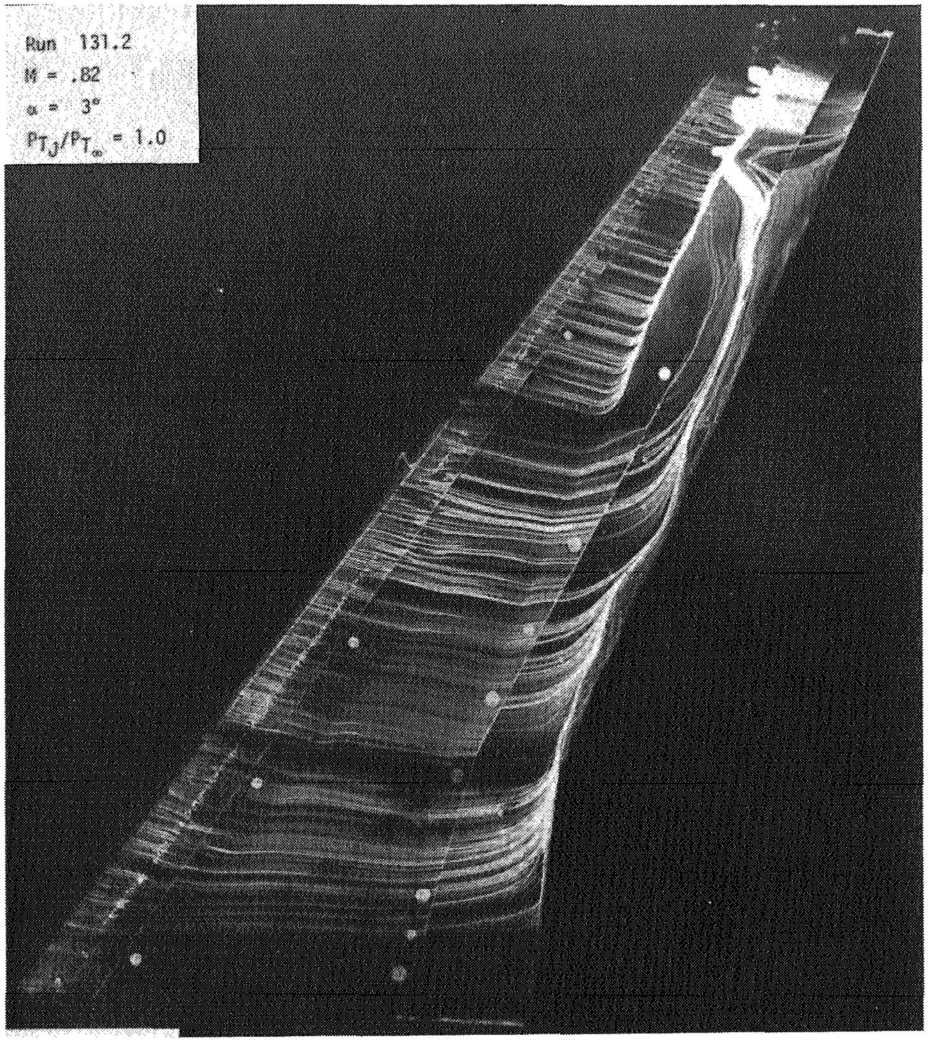

Figure 5.- Example of liquid indicator dispensed from porous strip.

- * Machine one continuous spanwise slot in wing leading edge

– slot need not be straight nor constant dimension
– hand finishing can be used for transition regions
– narrow part of slot serves as distribution manifold

- * Flame spray with powdered metal

– various materials (i.e. alum, nickel, s.s., etc.)
– various particle sizes––adjust for proper porosity, bonding strength, smoothness, etc.
– various processes(i.e. flame spray, plasma arc, etc.)
– various preparation steps (i.e. degrease, blast clean, masking, etc.)

- * Finish to final contour

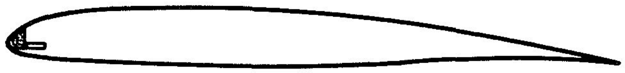

Figure 6.- New porous dispensing system for cryogenic surface flow visualization, developed by Boeing Aerodynamic Laboratory.

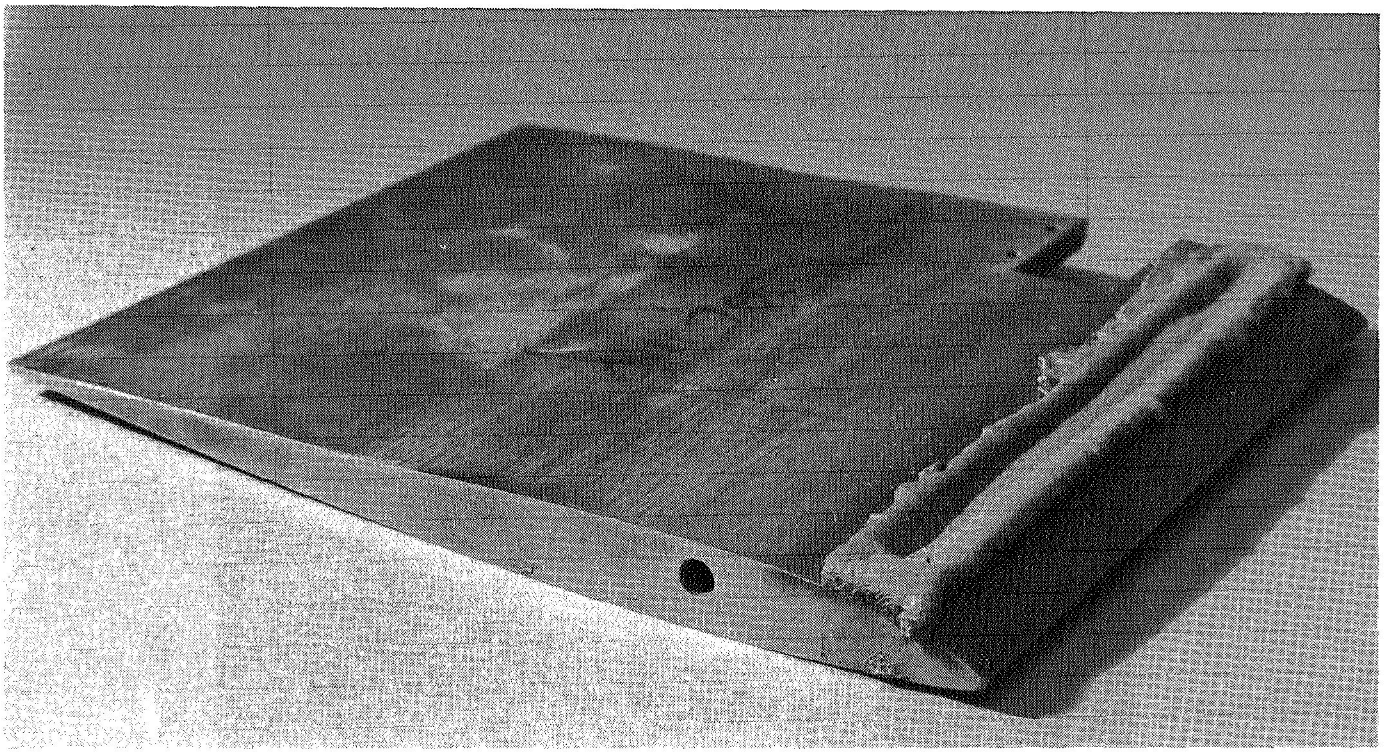

Figure 7.- Typical appearance of flame spray application.

- * Bond strength after repeated temperature cycles
- * Durability against erosion by wind—borne matter
- * "Effective Roughness" of roughness geometry, especially subsurface pits

Figure 8.- Cryogenic surface flow visualization questions to be investigated.