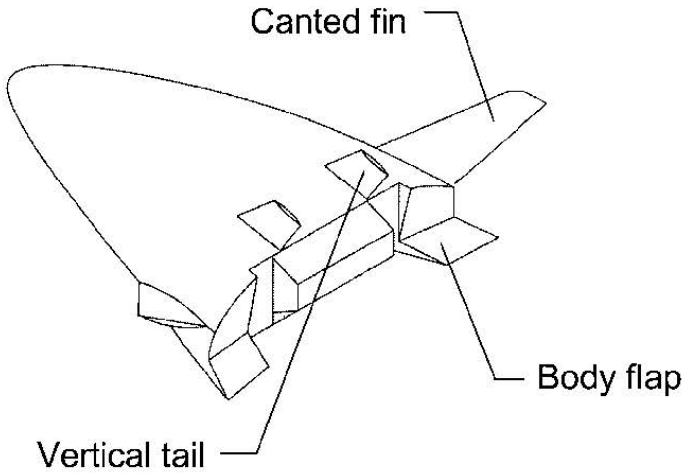
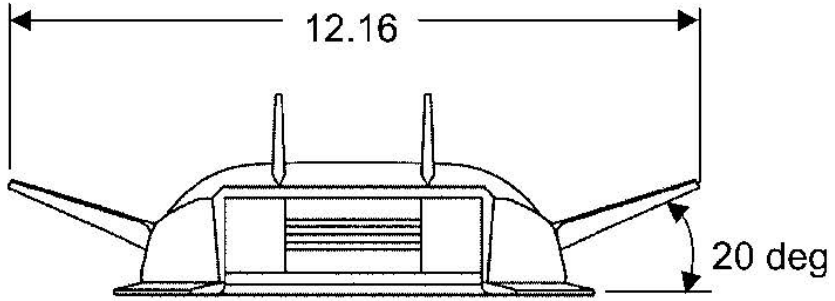
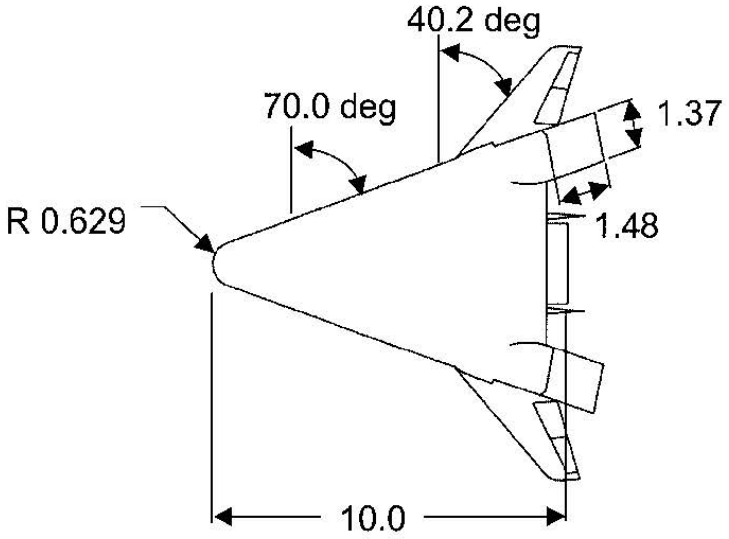
Introduction to Shock/BL Interaction Lab

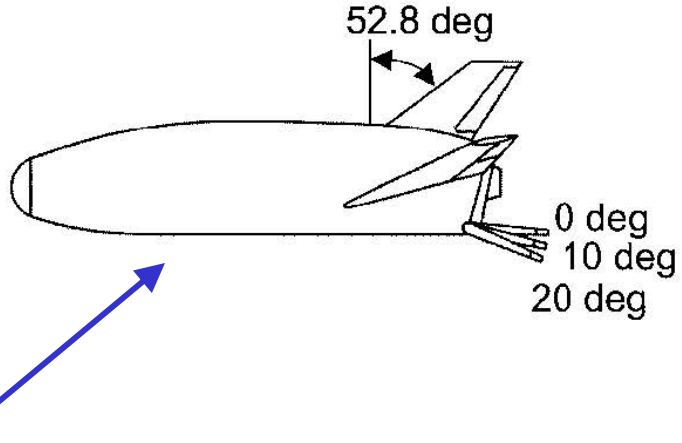
•Learn to use a small supersonic wind tunnel, pressure measurements system, schlieren, and oil-flow visualization
•“Supersonic wind tunnel” gives some information on how to run the experiment. See also papers, etc., on website
•Week 1 to focus on pressure measurements and Schlieren. Week 2, extend to flow visualization with oil flow.
•Spring 2009, replaced a PSI pressure-measurement system with 8 Kulites (time signals). Read the voltage signals using the digital scope and get the voltages quickly using the Measure function between vertical bars indicating start and end of the run. Also look at fluctuations in the Kulite signals.
•Mar. 2011-Feb. 2012, replaced Schlieren camera & modified optics to improve quality. Eliminated computer. Autotrigger Schlieren to improve productivity. Also, replaced pressure regulator so can run better at low pressures. Procured vacuum gauge to better calibrate pressure sensors.
•Ca. Jan. 2013, a new Mach-3.6 nozzle was built. However, the old compression-corner models don’t start without using vacuum. Completed a new Mach-2.0 nozzle, Jan. 2014, we will run this. Also have Mach 0.6 and old Mach 2.5. Stored in new cabinets.

The X-33 Body Flap:
One Example of a Compression Corner Flow









Flow Direction

S.P. Schneider 4-Feb-13

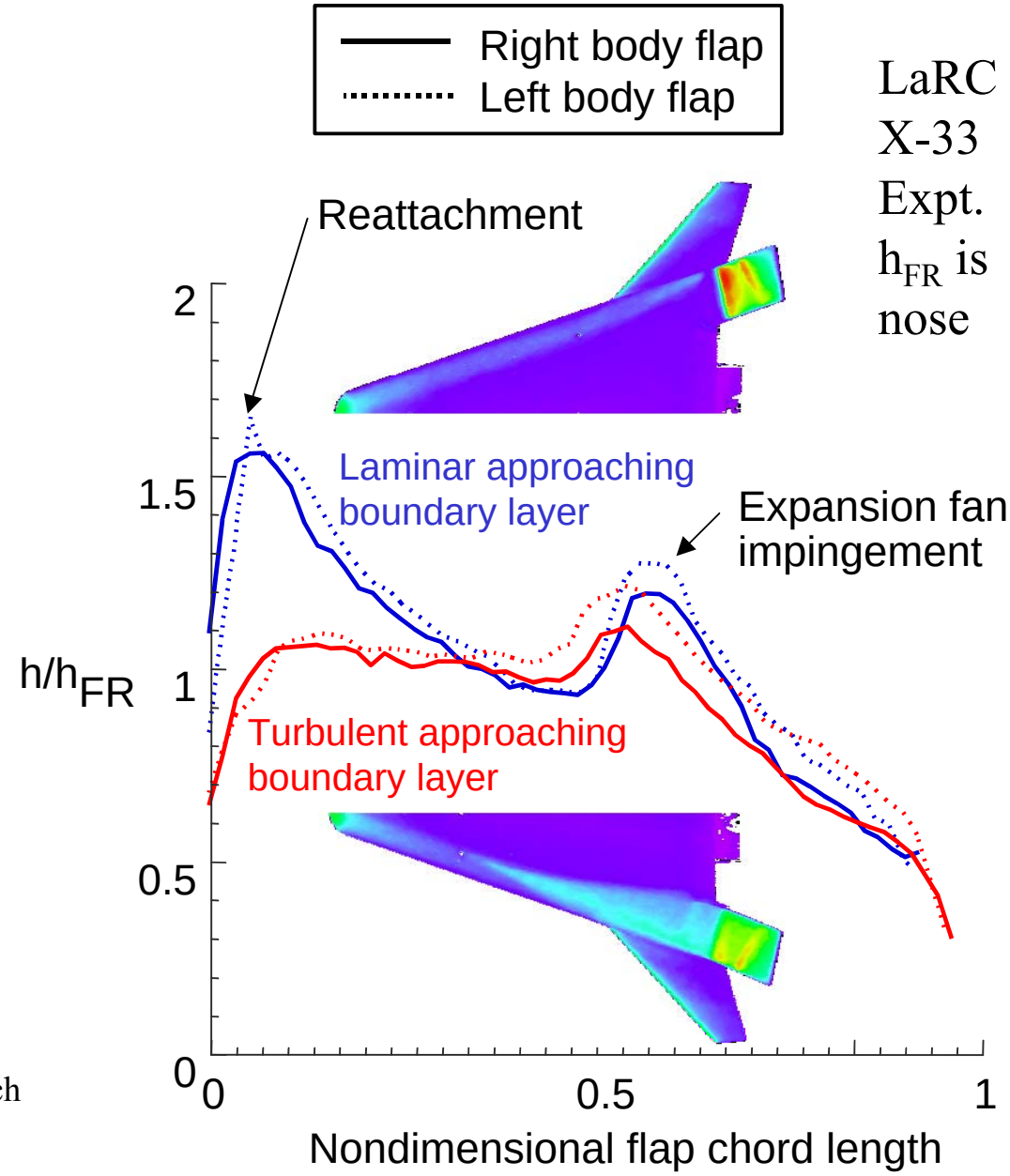
From Horvath et al., J. Spacecraft & Rockets, v. 38, no. 5, Sept. 2001, pp. 634-645

Deflected Control Surfaces with Compression-Corner Separations:

-Transitional Heating Can be 50% Larger than Turbulent Heating

-Transition Occurs at Low Reynolds Numbers

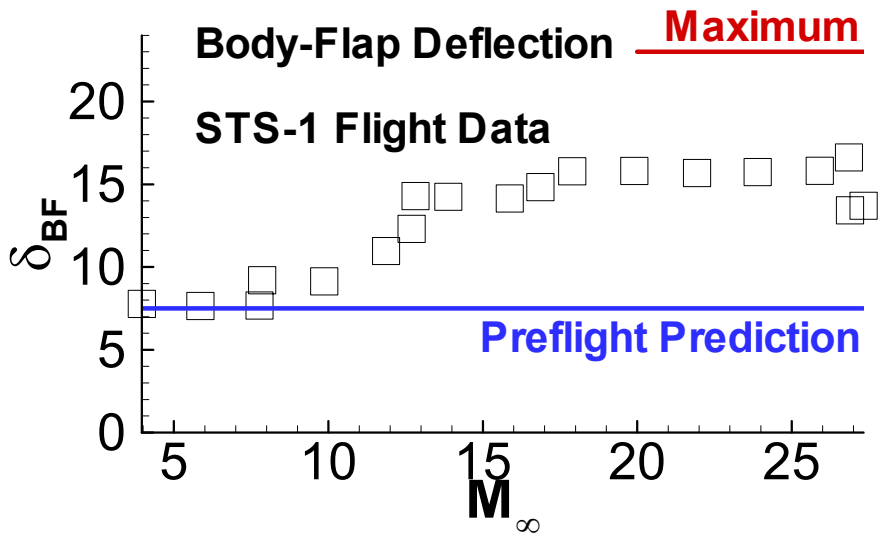
-Improved Predictions Can Reduce Control Surface TPS Requirements



Horvath et al., AIAA 99-3558, Fig. 14. Mach 6, 40-deg. AOA, Re=2E6/ft., δ_{BF}=20 deg.

Transition Also Affects RLV Controllability

- Asymmetrical transition caused Shuttle flight STS-50 to use extra RCS fuel to correct the yawing moment
- Body-flap effectiveness is dramatically affected by transition – a laminar incoming boundary layer increases corner-flow separation and reduces flap effectiveness.

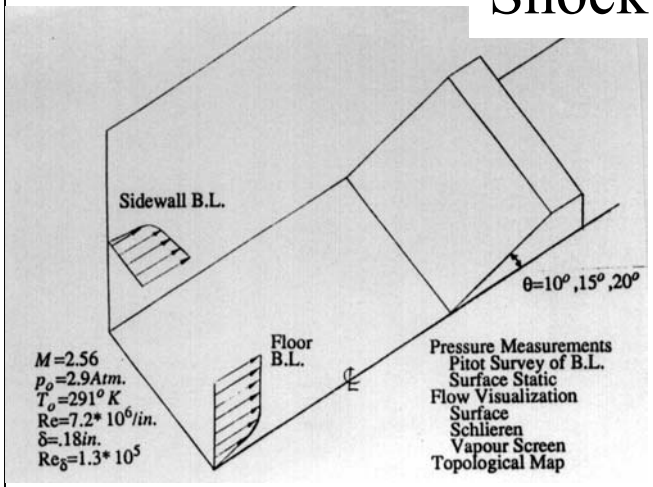


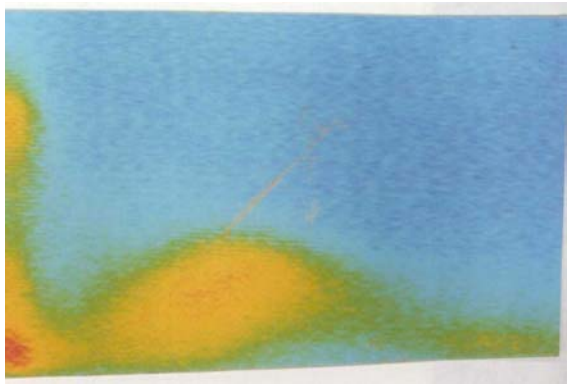
Shuttle Pitchup Anomaly.

-Mostly due to Real-Gas Effects on C_M.
-However, Body-Flap Effectiveness is also Hard to Predict, due in part to Transition

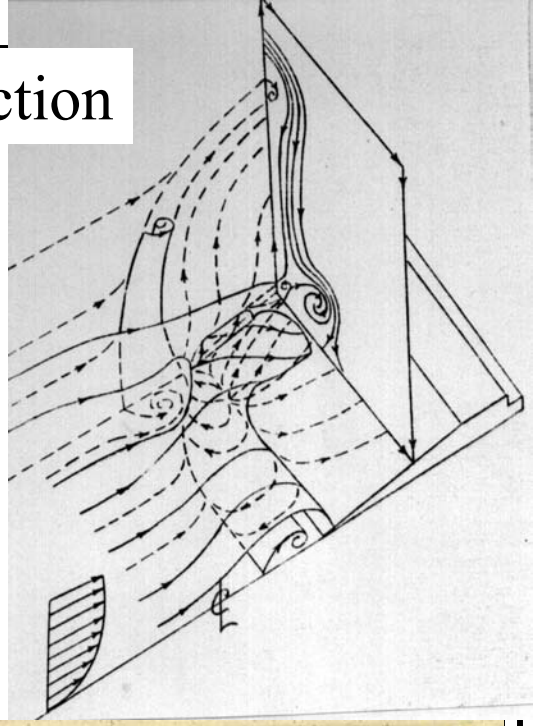
NASA CP-2283 p. 343
NASA TM-4499 p. 15

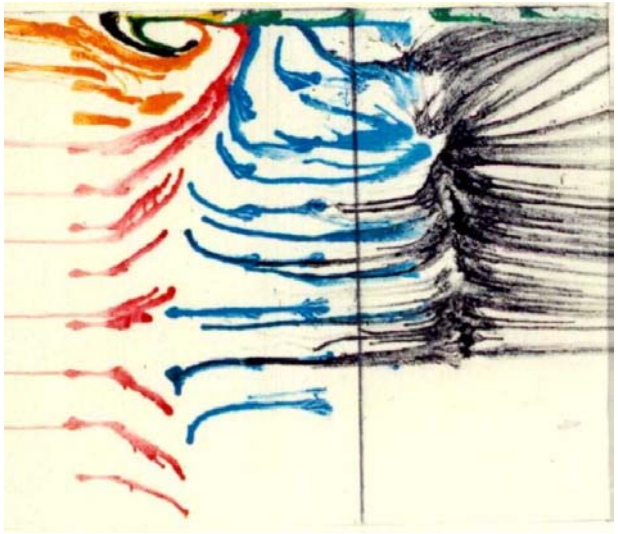
Shock Boundary Layer Interaction





Vapor Screen
Acetone



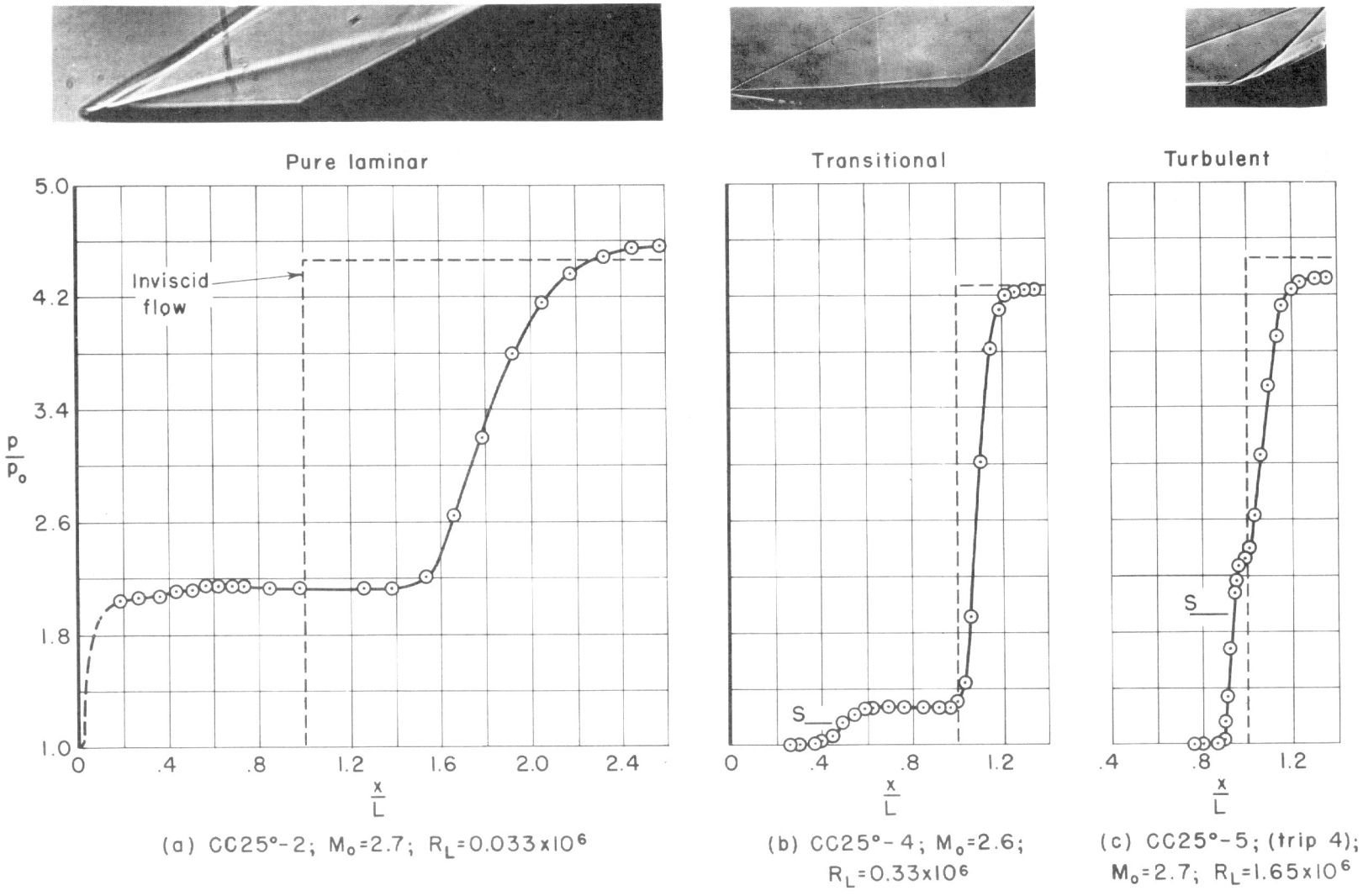


Artist Oil Paint on Floor

Oil Flow on Side Wall

Shock/BL Interaction Physics

- Compression corner critical to flaps, airbreathing forebodies, etc. Complex flow which is still not well understood.
- See classic paper by Chapman et al. for background, also see Batcho work
- Get separation in corner if angle sufficiently large
- Flowfield depends on upstream boundary-layer thickness and on laminar-turbulent transition. Boundary-layer thickness depends on Reynolds number
- Can we see separation? In pressure? (Mean or fluctuations?) Schlieren? Oil-flow? What does it look like? How do the 3 measurements of separation compare? How does separation depend on Reynolds number (total pressure)?
- Do we see transition? See any effect of it?



(a) CC25°-2; M_o=2.7; R_L=0.033x10⁶

(b) CC25°-4; M_o=2.6; R_L=0.33x10⁶

(c) CC25°-5; (trip 4); M_o=2.7; R_L=1.65x10⁶

Figure 14.—The three regimes for a compression corner; $M_o \approx 2.7$

From Chapman et al., NACA TN 3869, March 1957.
->There are many papers on shock/boundary-layer interaction, probably thousands. See, for example, the monograph "Shock Wave-Boundary-Layer Interactions", by Babinsky and Harvey, Cambridge Univ. Press, 2011, which contains review articles by various leading experts.

Issues with Performing the Lab

•Hardware much more expensive and less robust! Use care! Ask if uncertain!

•Use digital scope and voltmeters to read data from the pressure transducer electronics. Two scopes permit 1-sec. runs, 4 channels per scope.

•Change scope settings to look at mean or fluctuating pressures.

• Turn tunnel on, take data, turn tunnel off. Don't run tunnel longer than needed! 1-2 sec. may be enough. 30 sec. max.!

•Reference pressure measurements to vacuum, check factory calibration via a point at 1 atm (barometer on Boeing tunnel) and a point at maximum vacuum. Vac. gauge on small ref. tank is probably the most accurate. Study plumbing.

•Leave vacuum pump on, unless the noise is a problem. Valve at pump must be closed when pump is turned on or off.

Issues with Performing the Lab, 2

- Mach number fixed by nozzle geometry!
- Downstream pressure does NOT affect Reynolds number as long as it is low enough that the tunnel can start!
- With ambient exit pressure, stagnation pressure (and Re) can be varied from perhaps 30 psia to perhaps 60-70 psia (pressure drop from compressor thru regulator)
- Can run to vacuum exhaust, allows reducing stagnation pressure (and Re) to **low** values (not clear how low you can go). Trickier, and fewer runs will be possible. But pumps to 100 torr rapidly, so could run some low Re. quickly. Might get a laminar boundary layer by using vacuum exit pressure and lowering the upstream stagnation pressure.

Issues with Performing the Lab, 3

•Do easy things the first week, try harder things after you have the easy things working.

•Don’t run the vacuum exhaust until the second week.

•Oil flow experiments would foul the small pressure tap holes. Second compression-corner model is without taps, for use with the oil flow. Save oil-flow work for second week.

•Compression angle is 20 deg. Now one angle and one height, there are already more things to do than there is time for. New model is more precisely machined to fit the tunnel and avoid extraneous compression waves off the joints.

•Do not readjust the Schlieren system during this lab, except for moving the knife edge by adjusting the micrometer control knob. While adjusting a Schlieren is good experience, realigning it in case of problems takes too much time.

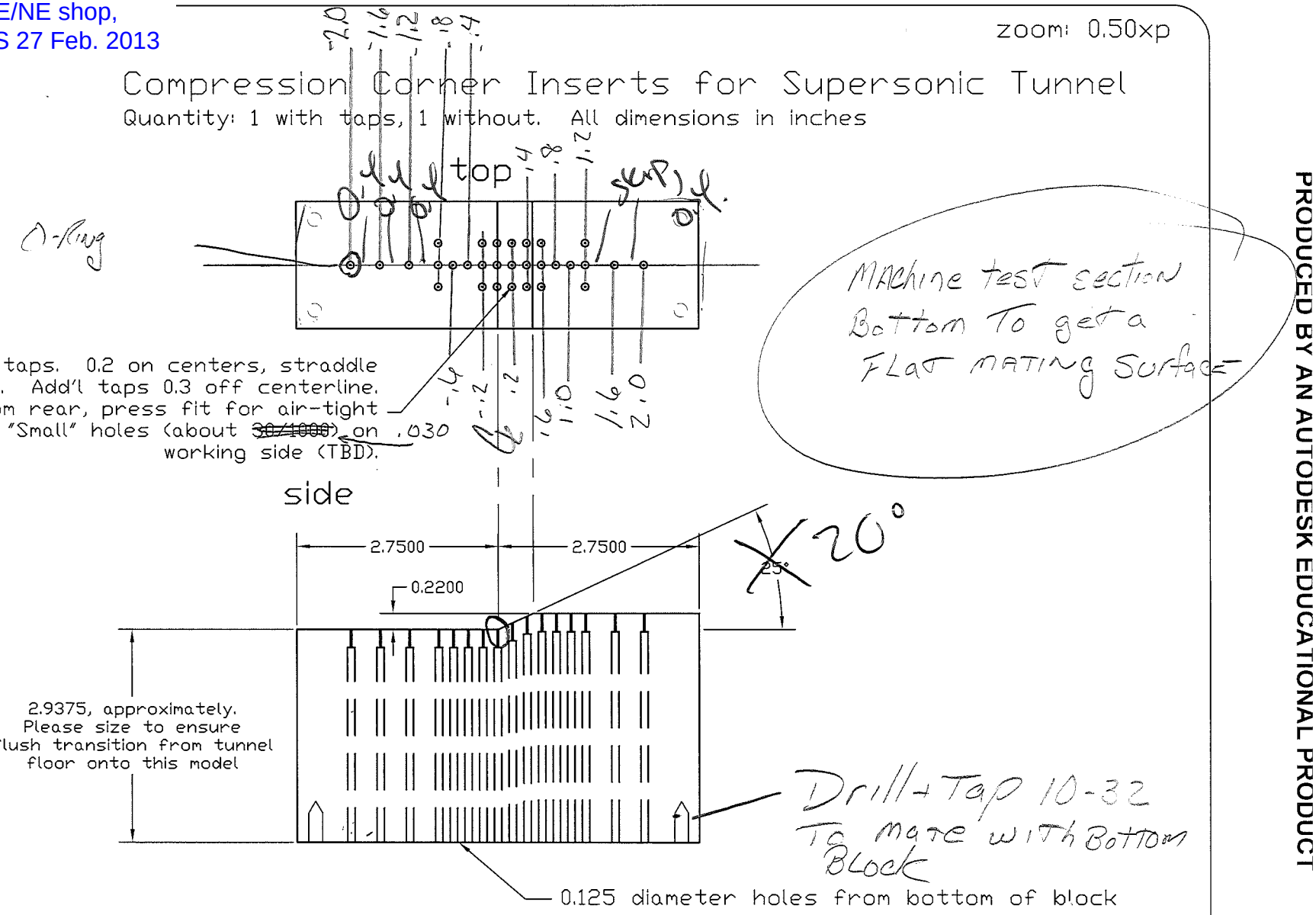
•Don’t touch the front-surface mirrors. Mirror film on front surface to avoid double reflections. Delicate!

Design was modified during fabrication. These are the drawings of the inserts, as built by Robin Snodgrass in the AAE/NE shop, ca. March 2012. SPS 27 Feb. 2013

zoom: 0.50xp

Compression Corner Inserts for Supersonic Tunnel

Quantity: 1 with taps, 1 without. All dimensions in inches



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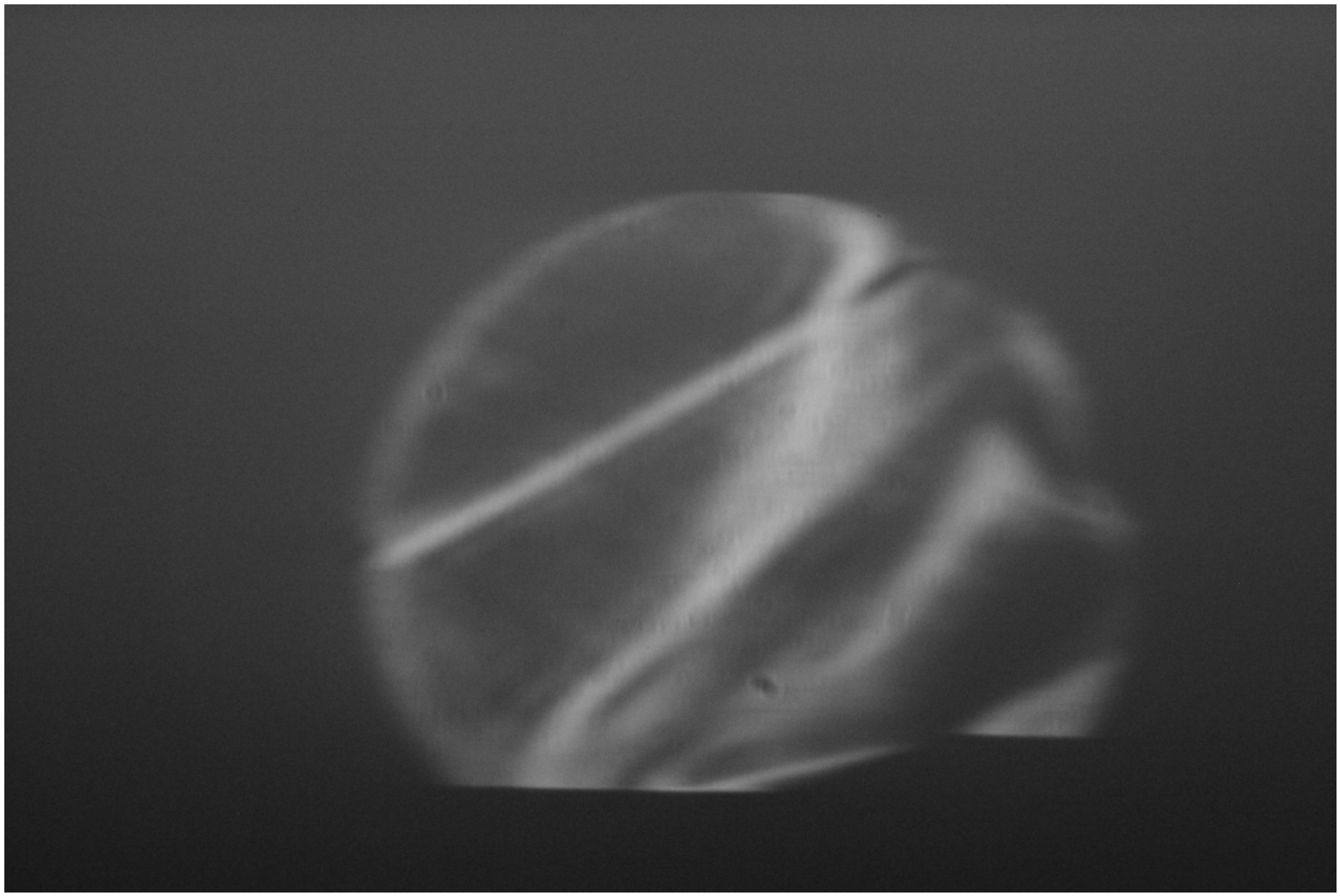
Issues with Performing the Lab, 4

- When you run the oil flow during the second week, you will foul the Schlieren windows. You will need to clean them. These are precision windows, use clean kimwipes and solvent and don't scratch them. Keep acetone away from the large plexiglas sidewalls, or it will craze the acrylic.
- The biggest part of experimental work is figuring out how to make the apparatus work. It's a bit like debugging a code.
- Develop your troubleshooting skills!
- Don't be afraid to turn things off and on, reboot them.

Schlieren of 20-deg Corner at P_0=33 psia in Mach-2 Nozzle

3-inch Schlieren quality windows

See shocks from joints and from separation bubble at corner, see expansion fan at corner also.



Screen Dump: 20-deg Corner at P_0=33 psia in Mach-2 Nozzle

Kulite pressure sensors hooked to taps on 20-deg. corner. Short runtime of a second or so now very feasible. Canon camera auto-triggers. Use Hi-Res mode and see details of pressure fluctuations