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**"SPECTRAL ANALYSIS IN MACHINERY HEALTH MONITORING"**

**TURBO MECHANICS SUB-COMMITTEE**
**ASSOCIATE COMMITTEE ON PROPULSION**

**held in Calgary, September 1978**

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# A COMPARISON OF THE TURBULENT CHARACTERISTICS OF CUMULUS CLOUDS MEASURED NEAR YELLOWKNIFE AND THUNDER BAY

by

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## ABSTRACT

While serving as the seeding aircraft in a rainfall enhancement research program, the NAE T-33 atmospheric research aircraft made turbulence measurements in the tops of towering cumulus clouds near Yellowknife, N.W.T. and Thunder Bay, Ontario. Since the T-33 penetrations all tended to occur at roughly the same stage of each cloud's lifetime, and at about the same height below cloud top, the data collected afford the opportunity to compare the dynamical characteristics of cumuli measured over forested lakeland within 350 km of each location.

Data from 28 penetrations of 15 clouds at Yellowknife are matched with an equal number of gust records collected in 18 Thunder Bay clouds. Included among these clouds are 21 of the total of 25 seeded with silver iodide during this experiment. Comparisons of the RMS and peak gust velocities, spectra, turbulent energy dissipation rates, and aircraft vertical accelerations all indicate that on the average the tops of cumulus clouds in the Thunder Bay area were more turbulent than their counterparts at Yellowknife.

## 1.0 INTRODUCTION

Since 1974 the Flight Research Laboratory of the National Aeronautical Establishment (NAE) and the Cloud Physics Research Division of the Atmospheric Environment Service (AES) have co-operated in a rainfall enhancement research project to determine if cumulus clouds could be modified to produce precipitation for forest fire suppression. Silver iodide seeding experiments were conducted out of Yellowknife, N.W.T. in 1975 and 1976 and out of Thunder Bay, Ontario in 1977 and 1978. In addition to data collected in 25 clouds seeded with silver iodide, the natural microphysical and dynamical characteristics of a total of 126 summer cumulus clouds have been documented (Refs. 1 to 10).

Three NAE aircraft were used in most of these seeding experiments. The Twin Otter served as the command aircraft and measured the microphysical properties of the individual clouds before and after seeding. In addition to an array of AES cloud physics instrumentation that included four Particle Measuring Systems (PMS) particle spectrometers, it carried an NAE instrumentation package to record aircraft position and motion, cloud dynamical data, and meteorological state parameters such as temperature, dew point, and winds. The Beech 18 aircraft was used to observe cloud base conditions and to make quantitative assessments of rainfall rates using a PMS precipitation particle spectrometer. Silver iodide seeding was accomplished with the T-33 atmospheric research aircraft (Fig. 1) fitted with wing-mounted pods to carry end-burning flares. The seeding procedure usually required an along-wind penetration of the cloud and then a crosswind seeding run 300 to 600 m below cloud top. Primarily instrumented for turbulence research, the T-33 measured in-cloud gust velocities on each penetration as well as position, doppler winds, and several meteorological parameters. After seeding, it was circled about the cloud top to monitor and film subsequent changes in the cloud's structure.

With the completion of two summers of seeding trials at Yellowknife and two at Thunder Bay, it is probable that experiments to stimulate rainfall for forestry purposes have been concluded, and that future operations will address different problems in the cloud physics field. It is an appropriate time, therefore, to review the data collected to date, in particular to compare the Yellowknife data with that from Thunder Bay, since two almost equal samples of clouds have been studied. Throughout this co-operative project, the AES and the NAE have naturally tended to divide the analysis and reporting of data into their own fields of expertise, with the AES concentrating on the cloud microphysics and the NAE recreating flight tracks and analyzing the dynamical characteristics of the clouds. In this report, it is the turbulent characteristics of clouds near Yellowknife and Thunder Bay that will be compared, utilizing RMS and peak gust velocities, turbulent energy dissipation rates, and power spectra.

## 2.0 THE DATA SET OF CLOUDS STUDIED

The comparison of the turbulent characteristics of cumulus clouds at Yellowknife with those of Thunder Bay was originally undertaken in an attempt to improve the understanding of the dramatically different results of seeding trials at the two locations. In the four field experiments a total of 25 clouds were seeded with silver iodide, 16 near Yellowknife and nine in the Thunder Bay area. Approximately 40 percent of Yellowknife cumuli rained after seeding. Twin Otter measurements before and after seeding indicate that a seeding effect, i.e. the production of ice crystals or precipitation embryos, occurred in about 60 percent of the treated clouds. Those that did not produce precipitation had lifetimes of less than 20 minutes. At Thunder Bay, of the nine clouds seeded with silver iodide, rainfall occurred beneath only one, and this was possibly from an adjacent unseeded turret. Seeding effects were measured in approximately 40 percent of the clouds on subsequent penetrations by the Twin Otter. Thunder Bay clouds were found to be deeper, wetter, with a lower natural background concentration of large particles than Yellowknife clouds, all tending to make them more 'seedable'. However, for the limited sample studied, it appears that the lifetimes of Thunder Bay clouds were so short that cloud seeding could not be effective.

When studying clouds from two different geographical areas, care must be exercised in forming the basis for comparison, for the very nature of clouds makes them difficult entities to compare. In both the Yellowknife and Thunder Bay experiments, cumulus clouds selected as possible seeding candidates had to meet the following criteria:

- a depth greater than 1.5 km
- cloud top temperature between $-7$ and $-20^\circ$C
- a top with a solid and growing appearance
- a cloud top relatively isolated from its neighbours
- no rain visible within 15 km of the centre of the cloud.

All measurements were made in summer cumulus clouds within the period July 2 to July 25 at Yellowknife and June 24 to July 12 at Thunder Bay. Clouds forming this data set were located over forested lakeland within 200 n miles (370 km) of either Yellowknife (62°28′N, 114°26′W) or Thunder Bay (48°22′N, 89°19′W). None of the clouds was over either Great Slave Lake or Lake Superior when initially penetrated. Operational techniques at each locale were essentially the same. After cloud selection, the Twin Otter made one or two penetrations followed by the along-wind and crosswind seeding (or mock seeding) run by the T-33. In some cases one of these runs was eliminated to save time prior to seeding. After the T-33 passes were completed, the Twin Otter continued its series of penetrations at about 300 m below cloud top, usually until the cloud dissipated.

For a number of reasons, the data used in this study are restricted to only a fraction of the total collected during the four seeding experiments. First of all, because of limited time and funds for digital computation, a complete turbulence analysis was done for penetrations in only 41 of the total of 126 clouds studied in this project. Clouds selected for this analysis included all those in which the T-33 flew seeding or mock seeding runs (control cases), and as well as those natural untreated clouds in which interesting microphysical data were measured. Secondly, the data set used in this paper is further restricted to that measured by the T-33, for its instrumentation was specifically designed for turbulence research and is capable of measuring the three orthogonal components of the true gust velocity. The Twin Otter is not as yet fitted with vanes to record angles of attack and sideslip, so lateral gusts cannot be measured and vertical gusts are computed using an approximate technique that is only accurate over a limited wavelength range (Ref. 3). Thirdly, for a meaningful comparison of cloud data, penetrations have to be made at roughly the same relative position in each cloud at about the same stage of the cloud's lifetime. This can be accomplished by using only data from T-33 penetrations near the normal seeding altitude (300 - 600 m below cloud top) recorded near the time of normal seeding operations, usually five to 10 minutes after cloud selection. It must be emphasized that all of the clouds in this study can be considered as natural cumuli. Although many of the turbulence records were made during seeding runs, none was recorded *after* seeding, when the dynamical characteristics of the clouds might have been altered by the seeding agent.

When these restrictions are applied to all the T-33 records, data from 28 penetrations of 15 different clouds at Yellowknife can be matched with an equal number of penetrations of 18 Thunder Bay cumulus clouds. Included among these clouds are 21 of the total of 25 seeded with silver iodide during the experiment. Table 1 identifies the flight dates and run numbers for the data used in this paper and summarizes the computed turbulence parameters for each cloud penetration. The indicated references can be consulted for further details of these runs, including flight descriptions, flight track plots, and time histories of the gust velocities and other parameters.

## 3.0 DATA PROCESSING AND EXAMPLES

True gust velocities are calculated by subtracting the aircraft transient inertial velocities, as measured by accelerometers, rate gyros, and a doppler radar, from the air motion relative to the aircraft measured by the primary sensors on the nose gust boom. The resulting gust components are then resolved into earth-fixed axes aligned with the mean wind direction, as computed from true airspeed, heading, and doppler data. Filtering of the three orthogonal gust components provides time histories describing the air motion independent of the characteristics of the aircraft over a wavelength range from approximately 15 to 2500 m for a typical true airspeed of 140 $ms^{-1}$.

For a cloud penetration, the true gust velocity time histories are computed over a period of nearly straight flight from a few seconds prior to cloud entry to a few seconds after exit. The in-cloud portions of the time histories are then extracted automatically using the signal from either the event marker pressed in cloud by the navigator or the Johnson-Williams liquid water sensor. Peak and RMS values are computed for the three components of the true gust velocity and the aircraft vertical acceleration. Spectra of the gust traces are calculated in both aircraft- and earth-fixed axes. To estimate the von Karman scale lengths, the basic principle is to fit the computed spectrum of each gust component with the appropriate von Karman expression (Ref. 11). This is accomplished by equating the integrated experimental gust spectrum to the von Karman spectrum integrated over the same frequency band. This latter is easily integrable and solely a function of scale length when a frequency band is selected above the knee, i.e. on the straight line part of the spectrum. A similar technique is employed to calculate the rate of dissipation of turbulent kinetic energy (Ref. 2). The Kolmogorov law may be written as $\Phi(k) = \alpha\epsilon^{2/3}k^{-5/3}$, where $\Phi$ is the power spectral density, k is wave number, $\alpha$ is a constant, and $\epsilon$ is the rate at which energy is dissipated in the cascade of energy from larger to smaller eddies in the inertial subrange. The dissipation rates listed in Table 1 were computed by integrating both sides of the above expression over a portion of the inertial subrange, using the spectrum of the longitudinal gust component and $\alpha$ set to 0.16.

The type of data generated during these cloud penetrations can best be illustrated with examples. Figure 2 shows time histories for the penetration of Cloud 831 at Thunder Bay (Run 103-2 in Table 1). The traces represent the event marker, liquid water content, the three components of true gust velocity in wind axes, static temperature, and a running value for dissipation rate. This last parameter is computed by the method described above, but at 1 second intervals using a 2 second wide window of data bracketing each point. Figure 3 depicts the plan and elevation views of the resultant total gust vectors in aircraft axes. Each tick on the vectors represents 1 $ms^{-1}$. On this run the T-33 encountered the largest gusts measured in any cloud to date in this program. The penetration was made at an altitude of 4590 m about 30° off a direct into-wind heading. The top of the cloud was growing and reached 5760 m about 4 minutes after the T-33 run. The vector plot shows downdrafts on entry into the downwind quadrant of the cloud, followed by an area of strong updrafts 650 m wide centred just upwind of the mid-cloud position, with smaller downdrafts just inside the upwind wall of the cloud. The peak vertical gust component measured near the cloud centre was a record 12.5 $ms^{-1}$, which when combined with the longitudinal and lateral components produced a gust vector of over 15 $ms^{-1}$. The RMS of the longitudinal and vertical gust velocities within cloud (5.17 and 5.35 $ms^{-1}$ respectively) were both record levels for this program as was the turbulent energy dissipation rate of 1199 $cm^2 s^{-3}$.

Figure 4 illustrates the elevation views of gust vectors measured in the tops of clouds at three different stages of development. The accompanying event marker trace defines the in-cloud period by an increased signal level. The upper vector plot is from Run 93-2 made about 600 m below cloud top during the period of strong vertical development. Rarely in this program has a penetration produced such an excellent example of a strong relatively smooth updraft in the centre of a cloud with corresponding overturning and downflow at the edges. The middle illustration comes from a penetration of an active cloud (Run 101-1) about 1 to 2 minutes after it had reached its peak height about 600 m above the flight level. The turbulent mixture of gusts in almost all directions is typical of a large fraction of the penetration data collected in this program and appears to be indicative of the end of the growth phase of the cloud. The final plot of Figure 4 shows strong downdrafts in Cloud 830 which was clearly dissipating. The lifetime of this cloud was very short, and although it reached a peak of 5900 m just prior to this run, the cloud had disappeared 5 minutes later.

## 4.0 THE COMPARISON OF YELLOWKNIFE AND THUNDER BAY CUMULUS CLOUDS

The distributions of RMS gust velocities from Table 1 are presented in Figure 5 for Yellowknife and Thunder Bay clouds. It is evident that, of the clouds penetrated by the T-33, those at Thunder Bay tended to have the higher turbulence levels. The Thunder Bay distributions are also more skewed than those of Yellowknife, a consequence of the very high RMS levels experienced on a few of the penetrations, particularly in the longitudinal and vertical components. At Yellowknife none of the measured RMS levels in any component of gust velocity was greater than 3.0 $ms^{-1}$; at Thunder Bay, in the vertical component alone, this level was exceeded on 21 percent of the penetrations. Put in other terms, penetrations in which $\sigma_\omega$ exceeded 3 $ms^{-1}$ occurred in 6 clouds at Thunder Bay, representing fully 1/3 of those in this study. The skewness is reflected in the significant differences between the median and mean values for the Thunder Bay distributions. Therefore, when comparing Thunder Bay and Yellowknife distributions, greater differences are observed when mean values are used rather than medians. Another observation from these data is that for the clouds of both locales, average RMS levels for the vertical component significantly exceed those of the longitudinal and lateral components, which are more evenly matched.

This point is more readily demonstrated in Figure 6, where the in-cloud RMS of the vertical fluctuation ($\sigma_\omega$) is plotted against the RMS of horizontal gusts ($\sigma_h$) for each penetration at both experimental locations. The vertical component $\sigma_\omega$ exceeds $\sigma_h$ in 85 percent of the cases, with most of the points lying between the $\sigma_\omega = \sigma_h$ and $\sigma_\omega = 2\sigma_h$ lines. The median $\sigma_\omega/\sigma_h$ ratio was 1.22 for Yellowknife and 1.30 for Thunder Bay. Figure 6 also demonstrates the greater range of turbulence experienced in clouds at Thunder Bay than at Yellowknife.

The median values for the von Karman scale lengths for the 28 Thunder Bay cases are 105, 104, and 171 m for the longitudinal (along wind), lateral, and vertical components respectively. The corresponding values from the Yellowknife data are 96, 103, and 141 m. In both cases the scale of the vertical turbulent fluctuations within cloud is significantly greater than those of the horizontal components. This is not surprising since it is the vertical component that is initially fed the energy produced from the latent heat released through condensation of water vapour in the cloud. The median longitudinal and lateral scale lengths from the Thunder Bay data are comparable with those measured at Yellowknife, but the vertical component is some 20 percent greater. This observation, as well as the increased $\sigma_\omega/\sigma_h$ ratio for Thunder Bay clouds, may be a reflection of the greater depth of clouds at Thunder Bay or their higher liquid water contents. In the deeper clouds proportionally more of the energy appears to be in the vertical component. The greater depth of the clouds at Thunder Bay is a consequence of the higher freezing level there during the summer months. This can be seen by comparing penetration altitudes and temperatures listed in Table 1. At Yellowknife the median temperature was measured as $-8°C$ at the median penetration altitude of 4020 m (13,200 ft.). At Thunder Bay, during essentially the same period of the year, the median penetration altitude was nearly 600 m higher at 4610 m (15,100 ft.), but the corresponding temperature was warmer, registering $-6°C$.

The distributions of peak upward and downward vertical gust velocities encountered in each cloud top penetration are illustrated in Figure 7. The histogram of the peak upward velocities is more skewed than that for the down gusts, particularly in the case of the Thunder Bay data. Five of the 18 clouds from the Thunder Bay data set had peak upward gusts exceeding 8 $ms^{-1}$, i.e. greater than any cloud at Yellowknife. Incidentally, the gust vectors from the two clouds with the largest peak vertical velocity components are illustrated in Figures 3 and 4. The vertical velocity time history was also averaged over the in-cloud period for each penetration and found to be small (generally less than 1.0 $ms^{-1}$, and sometimes negative), although in most cases the cloud was sustaining itself. A principal observation from these penetrations at the potential seeding level, is that at these altitudes the cloud structure is quite turbulent and cannot be represented as a simple smooth updraft. Although there are notable updrafts to be seen in these clouds, they usually do not extend over the whole cloud width, but are instead relatively narrow in extent and often separated by sharp downdrafts. Usually the peak downdraft within the cloud occurs near its edge. The majority of clouds penetrated on this study had turbulence profiles resembling that of the middle illustration of Figure 4, which appears to be representative of a cloud that has grown to near its maximum height.

Figure 8 presents the turbulent energy dissipation rates ($\epsilon$) near cloud top calculated from the spectra of the longitudinal component of turbulence in aircraft axes. The dissipation rate is an important parameter for estimating the rate of dispersion of nucleating material within a cloud. The diameter d of a plume expanding from an axis formed by the passage of a burning flare can be estimated using the expression $d^2 = \epsilon t^3$ (Ref. 4), where t in seconds is less than 1000. To disperse seeding agent across the diameter of a 1 km wide cloud, for example, would require about 8 minutes for a dissipation rate of 100 $cm^2s^{-3}$ (light-moderate turbulence), but only 3½ minutes for $\epsilon = 1000\ cm^2s^{-3}$ (moderate-heavy turbulence). The higher dissipation rates evident in Figure 8 for the cumuli of Thunder Bay are another manifestation of their generally greater turbulence levels. The median values of $\epsilon$ were measured as 288 $cm^2s^{-3}$ for Thunder Bay clouds and 165 $cm^2s^{-3}$ for those of Yellowknife. For the example 1 km wide cloud, the silver iodide would be dispersed by turbulence across it about 1 minute faster using the dissipation rate representative of Thunder Bay cloud tops.

Average normalized spectra for the three orthogonal components of turbulence within cloud have been plotted for the Yellowknife and Thunder Bay data (Fig. 9). Prior to computing the overall averages for each location, individual spectra from each penetration were smoothed by averaging spectral estimates over some 23 equal logarithmic wavelength intervals. For both presentations in Figure 9 the spectrum of the vertical component clearly has a larger scale length, for there is relatively more energy at long wavelengths and less at the shorter wavelengths than for the other two components. The resultant von Karman scale length of the vertical component exceeds the mean of the horizontal components by 40 and 60 percent for Yellowknife and Thunder Bay respectively. The spectra of all three gust components approximate the $-5/3$ power law for wavelengths up to about 400 m. A previously-published analysis of the Yellowknife data (Ref. 7) indicated a possible steeper slope of approximately $-1.85$ for the vertical component in the wavelength range 70 to 400 m. It was postulated that this was a result of the latent heat released through condensation producing turbulent eddies which fell preferentially into this wavelength range. The Thunder Bay data do not appear to support a similar observation.

One reason for recording the turbulence levels experienced in this cloud seeding experiment is the consideration of aircraft and aircrew safety during cloud penetrations. The absolute value of the peak vertical acceleration increment and the RMS computed over the in-cloud period are listed in

Table 1 for each run. From recommendations of the International Civil Aviation Organization, frequent gust-induced acceleration increments of 0.5 to 1.0 G are considered as moderate turbulence, with accelerations greater than 1.0 G designating severe turbulence. This level was exceeded in the T-33 in six clouds at Thunder Bay, but in only one at Yellowknife. However, a person's judgement of the severity of turbulence is a function of not only the incremental acceleration level but also the duration of exposure to these accelerations. Figure 10 relates RMS accelerations and exposure time to crew tolerance of turbulence (Ref. 12). RMS vertical accelerations have been plotted versus time in cloud for all the T-33 penetrations at Thunder Bay and Yellowknife listed in Table 1. Even the most turbulent case (Run 103-2, Figure 3) only reaches the 'decreased proficiency' threshold and still falls well within the tolerable range. This tends to confirm the impression of the flight crews that turbulence levels within the clouds studied in this experiment have been light to moderate with none that would be designated as severe.

## 5.0 CONCLUSIONS

One of the principal results of this experiment has been the observation that significant differences can be found in the dynamical and microphysical characteristics of the same type of cumulus cloud from two areas of the country. Other researchers in this field are arriving at similar conclusions, leading to suggestions that data from experiments such as this be documented in a kind of cloud atlas, defining by geographical area the characteristics of clouds important to workers in weather modification.

For this paper, 33 towering cumulus clouds were studied that met certain well-defined criteria, and the gust records used were further restricted to those collected on 56 T-33 cloud top penetrations at roughly the same stage in each cloud's development. Comparisons of the RMS and peak gust velocities, turbulent energy dissipation rates, and aircraft vertical accelerations all indicated that cumulus clouds in the Thunder Bay area were more turbulent than their counterparts at Yellowknife.

## 6.0 ACKNOWLEDGEMENTS

The data used for this paper were collected during participation in a rainfall enhancement research program done at the request of and in co-operation with the Cloud Physics Research Division of the Atmospheric Environment Service. The author expresses his gratitude to Dr. G.A. Isaac for preparing the summary of seeding statistics presented in this paper.

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TABLE 1

TURBULENCE DATA SUMMARY — T-33 CLOUD TOP PENETRATIONS — YELLOWKNIFE

| Date | Cloud # | Cloud Seeded? | Ref. (a) | Cloud (b) Top Height | Cloud Base Height | Flt-Run | Penetration Altitude | Temp | Time In Cloud | RMS Gusts $U_{ge}$ | RMS Gusts $V_{ge}$ | RMS Gusts $W_{ge}$ | Peak Gusts Up | Peak Gusts Down | ε (c) | RMS $A_z$ | Peak $\|A_z\|$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | m | m | | m | °C | s | $ms^{-1}$ | | | $ms^{-1}$ | | $cm^2 s^{-3}$ | G | |
| **1975** | | | | | | | | | | | | | | | | | |
| Jul 17 | (1) | Y | 1 | 7160 | 2740 | 16-1 | 4940 | -11 | 85.2 | 0.56 | 0.66 | 0.84 | 3.1 | -3.4 | 7 | 0.16 | 0.65 |
| | | | | | | -2 | 4910 | -10 | 64.3 | 0.68 | 0.71 | 0.80 | 2.0 | -4.1 | 9 | 0.13 | 0.52 |
| Jul 19 | (2) | Y | 1 | 4210 | 3230 | 18-1 | 3810 | - 8 | 5.6 | 0.72 | 0.61 | 1.07 | 3.1 | -1.6 | 10 | 0.21 | 0.55 |
| | | | | | | -2 | 3780 | - 8 | 4.4 | 1.01 | 0.47 | 0.80 | 1.7 | -2.6 | 26 | 0.22 | 0.50 |
| | (3) | Y | 1 | 3350 | 1550 | -3 | 3170 | - 4 | 8.4 | 1.62 | 1.91 | 1.88 | 4.8 | -2.6 | 390 | 0.33 | 0.83 |
| | | | | | | -4 | 3050 | - 3 | 4.4 | 1.85 | 0.88 | 1.56 | 4.6 | -1.9 | 283 | 0.34 | 0.90 |
| Jul 22 | (4) | Y | 1 | 3660 | 1220 | 20-1 | 3350 | - 5 | 13.3 | 1.52 | 1.56 | 2.10 | 4.4 | -6.6 | 110 | 0.31 | 1.00 |
| | | | | | | -2 | 3350 | - 6 | 25.1 | 1.45 | 1.56 | 1.60 | 3.6 | -4.9 | 110 | 0.21 | 0.58 |
| | | | | | | -3 | 3350 | - 6 | 26.6 | 1.30 | 1.92 | 1.48 | 3.4 | -5.0 | 92 | 0.23 | 0.62 |
| | (5) | N | 1 | 3700 | N/A | -5 | 3480 | - 7 | 8.5 | 2.01 | 1.26 | 2.56 | 4.4 | -7.9 | 192 | 0.22 | 0.81 |
| | (6) | Y | 1 | 3810 | 1680 | 21-1 | 3350 | - 5 | 18.3 | 1.60 | 1.65 | 2.24 | 4.9 | -7.8 | 220 | 0.30 | 0.91 |
| | | | | | | -2 | 3380 | - 5 | 6.0 | 1.60 | 1.96 | 2.31 | 5.3 | -6.5 | 250 | 0.27 | 0.82 |
| Jul 25 | (7) | Y | 1 | 3660 | 1520 | 24-1 | 3380 | - 5 | 22.3 | 1.89 | 1.37 | 2.27 | 6.6 | -6.6 | 165 | 0.27 | 0.83 |
| | | | | | | -2 | 3350 | - 5 | 21.2 | 0.95 | 1.44 | 1.36 | 4.0 | -3.0 | 48 | 0.17 | 0.56 |
| **1976** | | | | | | | | | | | | | | | | | |
| Jul 2 | (8) | Y | 3,5 | 5490 | N/A | 32-1 | 4820 | - 8 | 7.3 | 1.94 | 2.36 | 1.98 | 3.9 | -7.5 | 541 | 0.28 | 0.75 |
| | | | | | | -2 | 4820 | - 8 | 10.5 | 1.42 | 1.15 | 2.46 | 5.8 | -6.5 | 311 | 0.20 | 0.52 |
| Jul 11 | (9) | N | 3,5 | N/A | N/A | 40-1 | 4150 | - 8 | 5.7 | 0.84 | 1.20 | 0.99 | 3.6 | -2.6 | 298 | 0.13 | 0.40 |
| | (10) | Y | 3,5 | 5180 | 2000 | -2 | 4120 | - 8 | 20.5 | 1.52 | 1.30 | 2.68 | 5.6 | -6.7 | 164 | 0.21 | 0.72 |
| | | | | | | -3 | 4120 | - 8 | 7.9 | 2.26 | 2.00 | 2.27 | 7.1 | -6.2 | 992 | 0.23 | 0.69 |
| Jul 15 | (11) | Y | 3,5 | 5030 | 2130 | 42-1 | 4020 | -10 | 41.1 | 1.20 | 1.46 | 1.85 | 7.9 | -3.7 | 110 | 0.22 | 0.71 |
| | | | | | | -2 | 4020 | -10 | 15.9 | 0.92 | 0.96 | 0.86 | 3.0 | -2.1 | 103 | 0.32 | 0.86 |
| | (12) | Y | 3,5 | 5060 | 2440 | 43-1 | 4020 | - 9 | 8.8 | 2.03 | 1.03 | 1.99 | 4.0 | -3.8 | 336 | 0.24 | 0.82 |
| | | | | | | -2 | 4020 | - 9 | 15.1 | 1.47 | 1.45 | 2.50 | 5.1 | -5.9 | 191 | 0.29 | 0.67 |
| Jul 16 | (13) | Y | 3,5 | 5300 | 2230 | 44-1 | 4330 | -10 | 15.6 | 1.92 | 2.27 | 2.56 | 6.4 | -5.4 | 372 | 0.22 | 0.80 |
| | | | | | | -2 | 4330 | -10 | 16.1 | 1.61 | 1.42 | (2.86) | 7.3 | -7.0 | 213 | 0.25 | 0.69 |
| Jul 17 | (14) | N | 3,5 | N/A | N/A | 45-1 | 4180 | -11 | 29.9 | 0.87 | 0.87 | 0.99 | 3.4 | -3.3 | 54 | 0.17 | 0.53 |
| | (15) | Y | 3,5 | 4630 | 2220 | -2 | 4180 | -10 | 7.7 | 1.06 | 1.02 | 1.27 | 2.8 | -4.2 | 141 | 0.22 | 0.48 |
| | | | | | | -3 | 4120 | -10 | 7.7 | 0.91 | 1.37 | 1.16 | 4.1 | -3.0 | 162 | 0.26 | 0.79 |

(a) Refer to indicated references for more complete summaries of data, flight track plots, gust velocity time histories, etc.

(b) Maximum height cloud top attained.

(c) Turbulent energy dissipation rate.

(1) to (15) Clouds were not officially numbered in 1975 and 1976. Numbers used here denote different clouds.

( ) Data in parentheses suspected of being inaccurate.

TABLE 1

TURBULENCE DATA SUMMARY — T-33 CLOUD TOP PENETRATIONS — THUNDER BAY

| Date | Cloud # | Cloud Seeded? | Ref (a) | Cloud (b) Top Height m | Cloud Base Height m | Flt-Run | Penetration Altitude m | Temp °C | Time In Cloud s | RMS Gusts $U_{ge}$ $ms^{-1}$ | RMS Gusts $V_{ge}$ $ms^{-1}$ | RMS Gusts $W_{ge}$ $ms^{-1}$ | Peak Gusts Up $ms^{-1}$ | Peak Gusts Down $ms^{-1}$ | ε (c) $cm^2 s^{-3}$ | RMS $A_z$ G | Peak $\|A_z\|$ G |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1977 | | | | | | | | | | | | | | | | | |
| Jun 24 | 706 | Y | 6,8 | 4940 | 1580 | 52-1 | 4570 | − 6 | 3.8 | 0.89 | 1.17 | 1.76 | 1.0 | −5.9 | 526 | 0.16 | 0.46 |
| | | | | | | -2 | 4340 | − 6 | 11.0 | 0.99 | 1.07 | 1.38 | 2.8 | −4.1 | 87 | 0.17 | 0.66 |
| | 707 | N | 6,8 | 4900 | 1550 | -3 | 4180 | − 4 | 16.0 | 2.36 | 1.37 | 2.63 | 6.9 | −5.2 | 164 | 0.22 | 0.70 |
| | | | | | | -4 | 4170 | − 5 | 15.9 | 1.32 | 1.55 | 1.75 | 4.0 | −4.6 | 186 | 0.19 | 0.53 |
| Jun 26 | A | N | 6,8 | 7620 | N/A | 53-1 | 7340 | −25 | 6.9 | 2.49 | 2.56 | 3.09 | 6.3 | −5.8 | 1170 | 0.26 | 1.18 |
| | | | | | | -2 | 6770 | −20 | 8.5 | 1.14 | 1.24 | 1.56 | 5.4 | −3.4 | 134 | 0.16 | 0.38 |
| Jun 27 | 711 | Y | 6,8 | 4660 | 2280 | 55-1 | 4250 | − 3 | 7.3 | 1.33 | 0.91 | 1.48 | 2.2 | −5.9 | 205 | 0.17 | 0.50 |
| | | | | | | -2 | 4030 | − 3 | 11.4 | 0.65 | 0.91 | 0.64 | 1.6 | −2.4 | 50 | 0.17 | 0.52 |
| Jul 8 | 716 | Y | 6,8 | 5180 | 1800 | 65-1 | (4680) | − 8 | 14.3 | 1.32 | 2.57 | (2.73) | 4.6 | (−5.2) | 420 | 0.19 | 0.52 |
| | | | | | | -2 | (4470) | − 7 | 10.3 | 1.35 | 1.25 | 2.01 | 3.2 | −5.3 | 79 | 0.16 | 0.37 |
| Jul 11 | 719 | Y | 6,8 | 5850 | 1530 | 70-1 | 5080 | −10 | 14.0 | 2.87 | 2.82 | 3.49 | 7.0 | −6.9 | 978 | 0.31 | 0.97 |
| | | | | | | -2 | 5090 | −11 | 10.3 | 3.13 | 2.83 | 2.74 | 9.8 | −7.1 | 548 | 0.25 | 1.07 |
| Jul 12 | B | N | 6,8 | 4570 | 850 | 73-1 | 3870 | − 2 | 13.4 | 2.11 | 1.74 | 2.48 | 6.3 | −6.6 | 285 | 0.24 | 0.86 |
| | | | | | | -2 | 3880 | − 2 | 17.3 | (2.15) | (1.53) | 2.04 | 4.7 | −5.2 | (187) | 0.21 | 0.62 |
| | C | N | 6,8 | 5120 | 1400 | -9 | 4990 | − 9 | 11.0 | 1.25 | 1.24 | 2.02 | 4.1 | −6.0 | 165 | 0.23 | 0.56 |
| 1978 | | | | | | | | | | | | | | | | | |
| Jun 24 | 803 | N | 9 | 5490 | 1770 | 92-1 | 4590 | − 6 | 16.5 | 2.47 | 2.17 | 3.53 | 10.6 | −8.4 | 447 | 0.26 | 1.03 |
| Jun 25 | 806 | N | 9 | 5240 | 1460 | 93-1 | 4580 | − 5 | 9.7 | 1.36 | 1.84 | 1.48 | 3.9 | −8.5 | 266 | 0.25 | 0.70 |
| | | | | | | -2 | 4650 | − 6 | 7.0 | 2.33 | 1.46 | 4.42 | 9.0 | −8.4 | 467 | 0.33 | 0.90 |
| Jun 26 | 813 | Y | 9 | 5120 | 1040 | 94-1 | 4520 | − 5 | 1.5 | 1.06 | 1.35 | 1.68 | 2.8 | −4.5 | 62 | 0.21 | 0.41 |
| | | | | | | -2 | 4630 | − 6 | 6.0 | 1.77 | 1.36 | 1.60 | 2.9 | −5.3 | 291 | 0.16 | 0.47 |
| Jul 1 | 823 | Y | 9 | 5490 | N/A | 98-1 | 5170 | − 7 | 3.0 | 1.22 | 1.75 | 1.43 | 2.5 | −5.1 | 317 | 0.23 | 0.58 |
| | 824 | N | 9 | 5340 | N/A | -2 | 4660 | − 5 | 22.9 | 1.55 | 1.77 | 1.94 | 3.8 | −6.2 | 196 | 0.18 | 0.63 |
| Jul 3 | 827 | N | 9 | 5240 | 1830 | 101-1 | 4640 | − 5 | 19.2 | (2.82) | (3.23) | 3.45 | 12.4 | −7.8 | 775 | 0.33 | 1.01 |
| Jul 4 | 830 | Y | 9 | 5900 | N/ A | 103-1 | 4570 | − 6 | 6.1 | 2.26 | 1.46 | 1.92 | 5.5 | −6.9 | 346 | 0.24 | 1.06 |
| | 831 | Y | 9 | 5760 | 2040 | -2 | 4590 | − 6 | 8.8 | 5.17 | 1.94 | 5.35 | 12.5 | −8.1 | 1199 | 0.35 | 1.18 |
| Jul 6 | 836 | Y | 9 | 5550 | 2040 | 105-1 | 5040 | − 7 | 15.9 | 1.37 | 2.23 | 2.68 | 3.4 | −6.5 | 450 | 0.24 | 0.60 |
| | 839 | N | 9 | 6250 | N/A | -2 | 5600 | −10 | 12.0 | 2.06 | 1.39 | 2.14 | 3.6 | −6.1 | 272 | 0.23 | 0.65 |
| | | | | | | -3 | 5470 | − 8 | 5.6 | 1.80 | 1.97 | 2.70 | 4.0 | −6.9 | 545 | 0.24 | 0.74 |

(a) Refer to indicated references for more complete summaries of data, flight track plots, gust velocity time histories, etc.
(b) Maximum height cloud top attained.
(c) Turbulent energy dissipation rate.
( ) Data in parentheses suspected of being inaccurate.

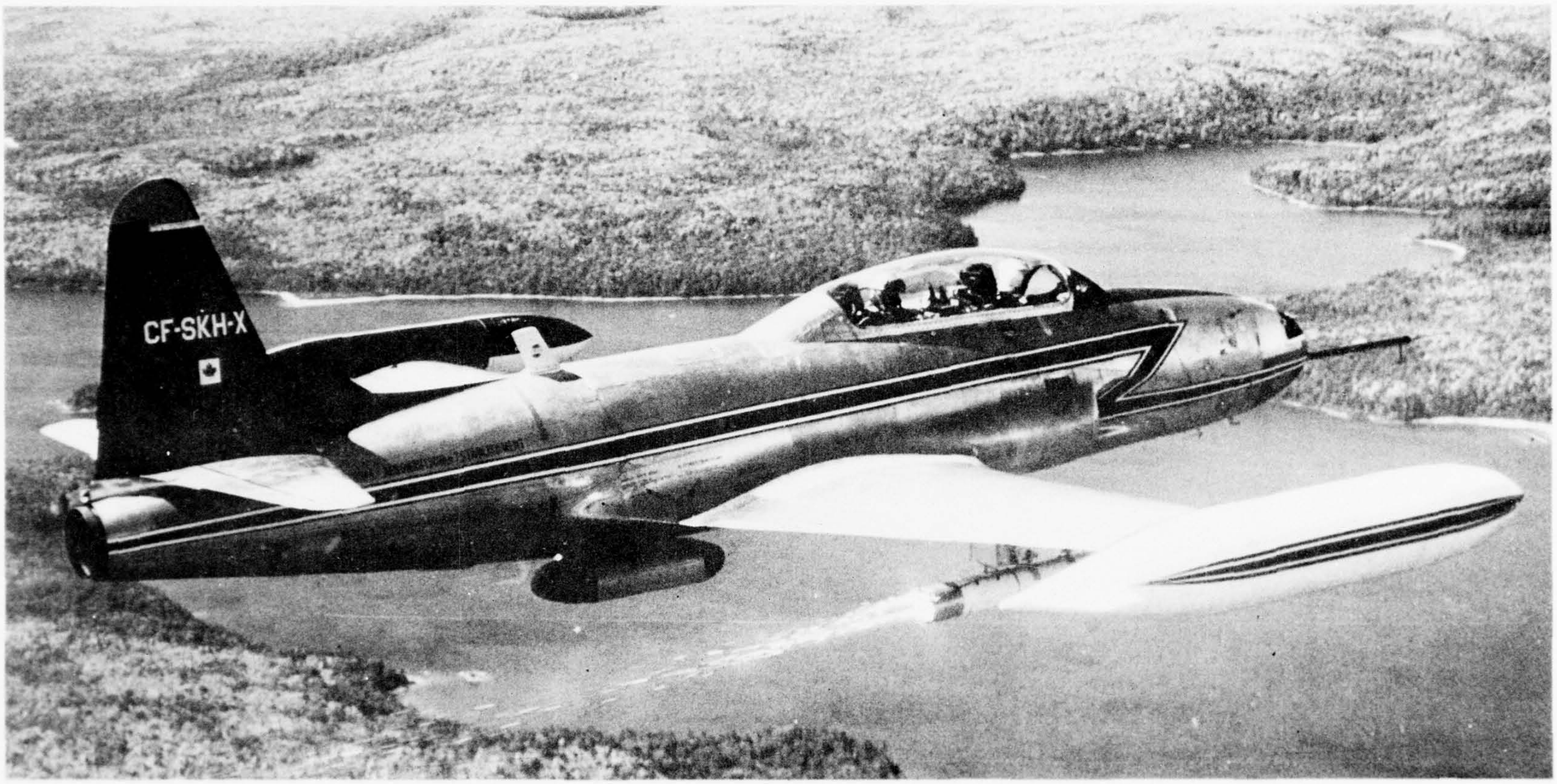


FIG. 1: NAE T-33 ATMOSPHERIC RESEARCH AIRCRAFT BURNING TWO SILVER IODIDE FLARES

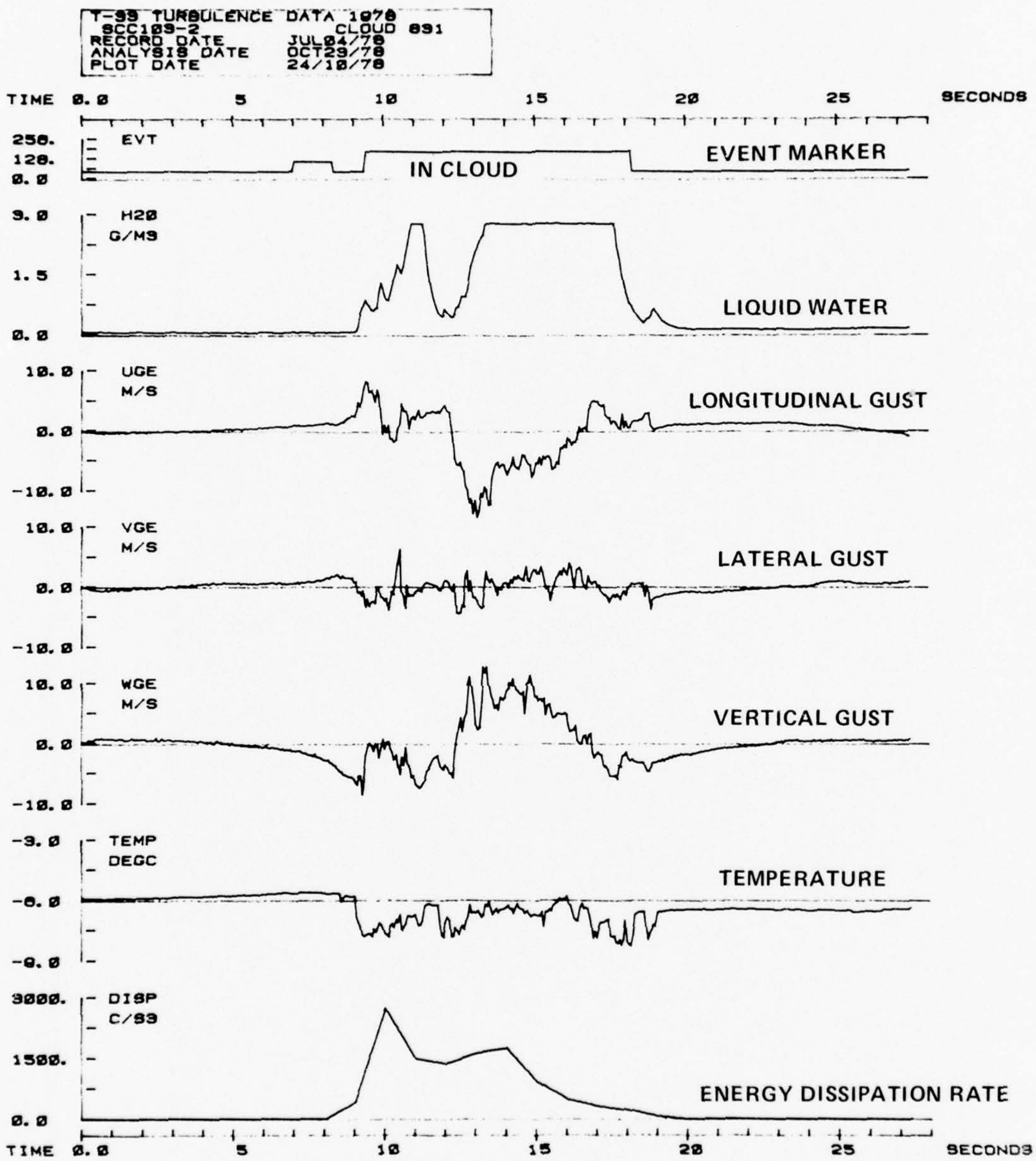


FIG. 2: TIME HISTORIES FOR THE MOST TURBULENT CLOUD PENETRATION IN EXPERIMENT

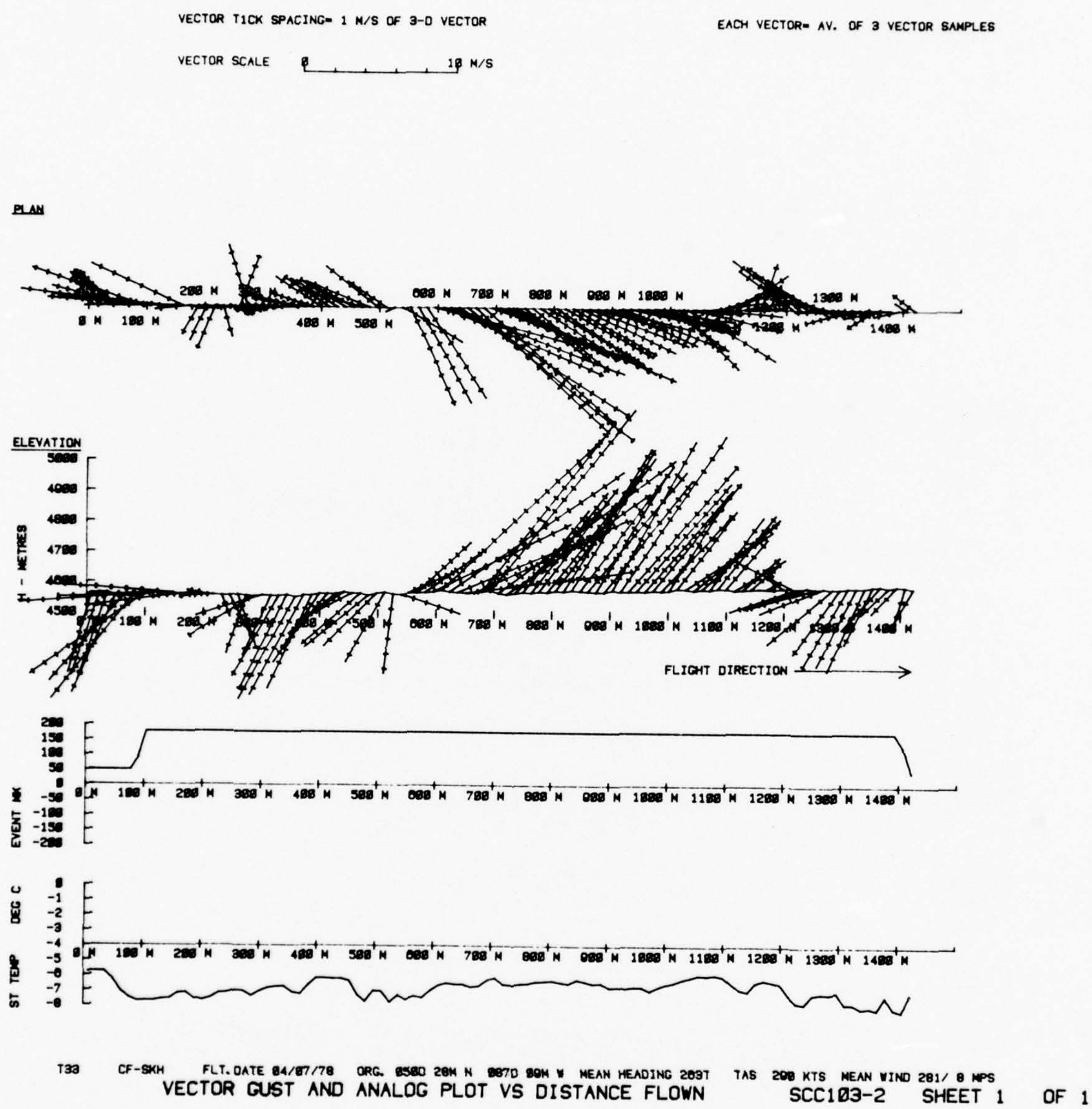


FIG. 3: GUST VECTORS COMPUTED FROM TIME HISTORIES OF FIGURE 2

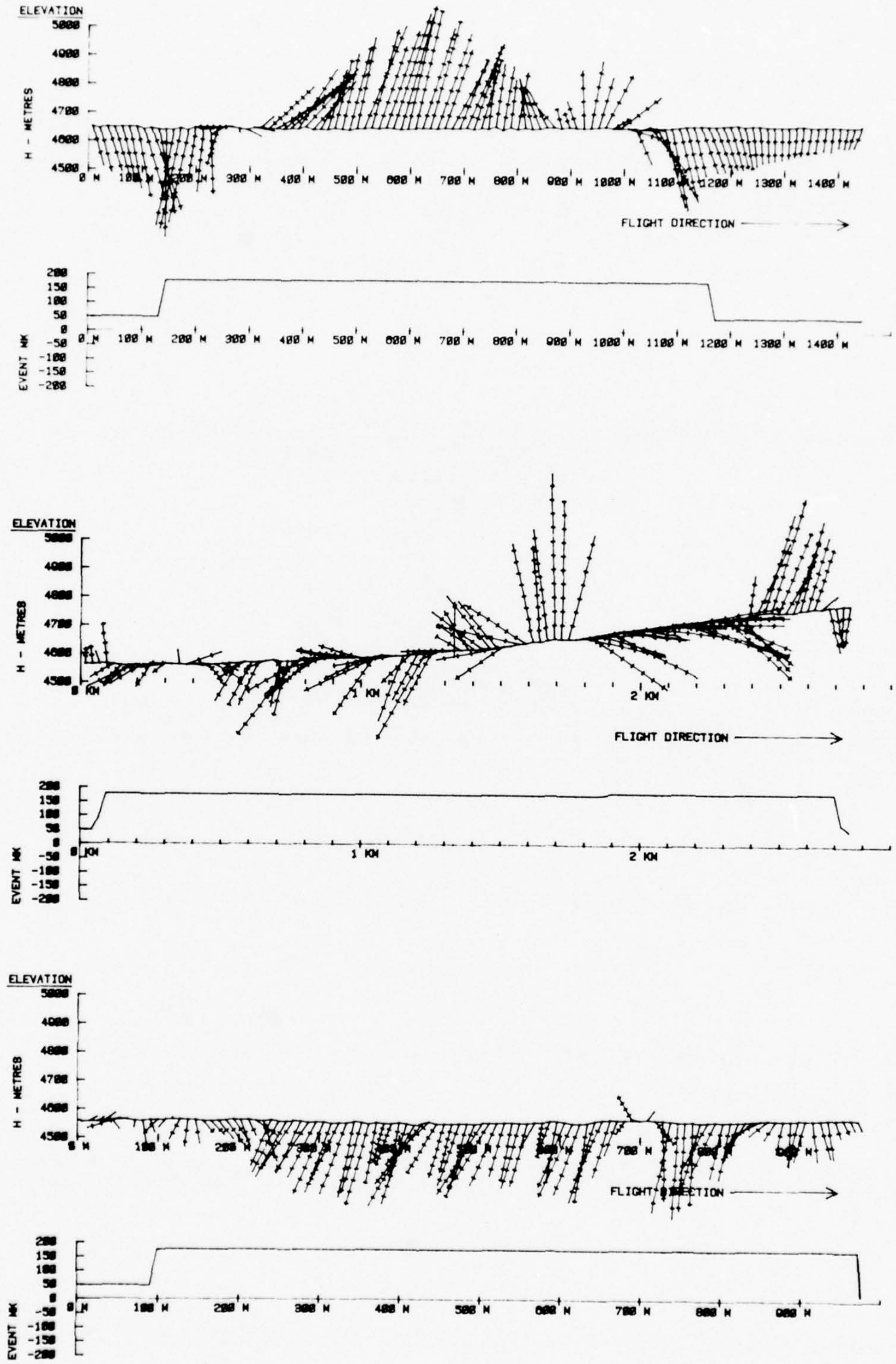


FIG. 4: GUST VECTORS MEASURED IN THE TOPS OF CUMULUS CLOUDS AT THREE STAGES OF DEVELOPMENT

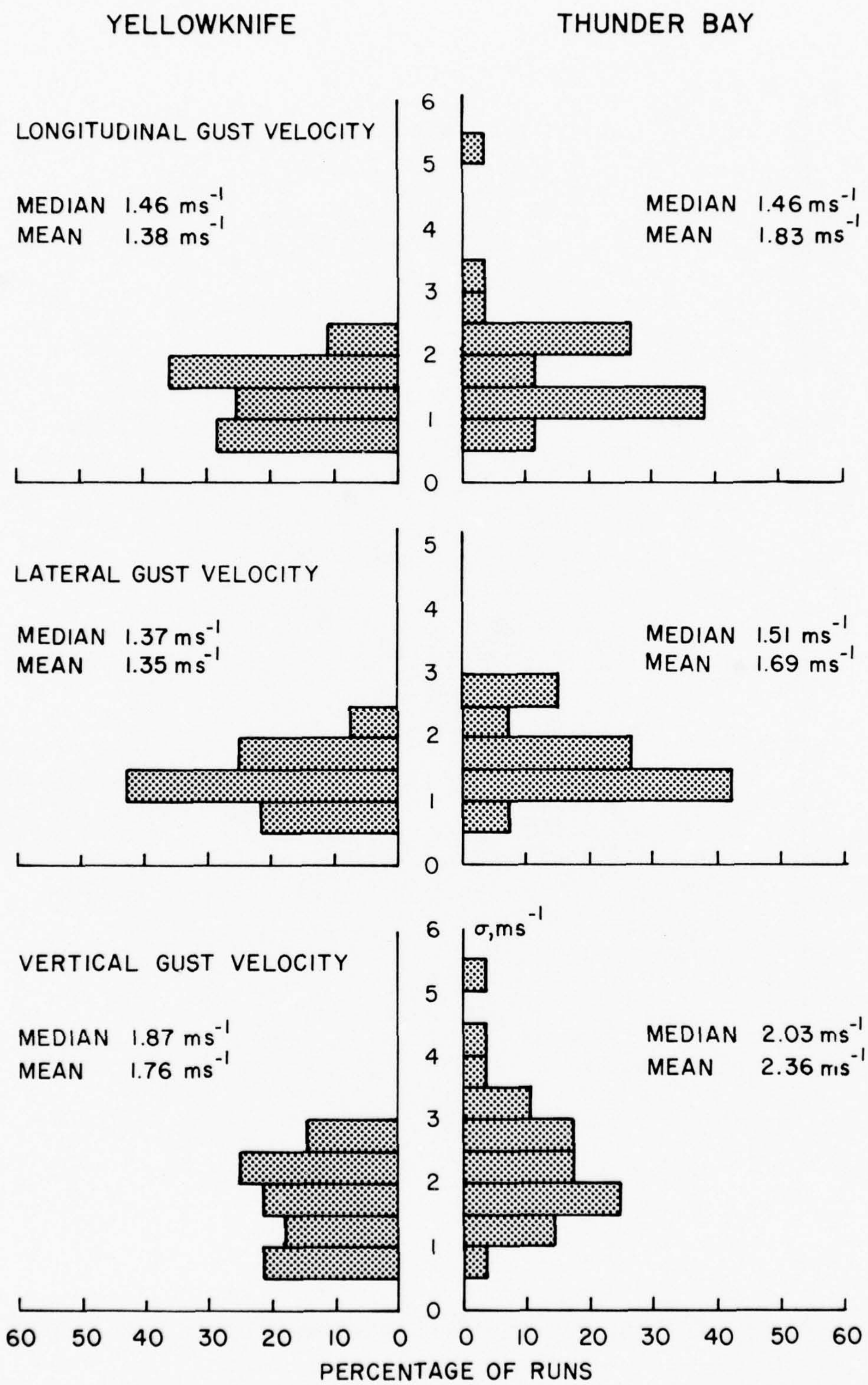


**FIG. 5: HISTOGRAMS OF T-33 RMS GUST VELOCITIES MEASURED IN CUMULUS CLOUD TOPS — YELLOWKNIFE AND THUNDER BAY DATA COMPARED**

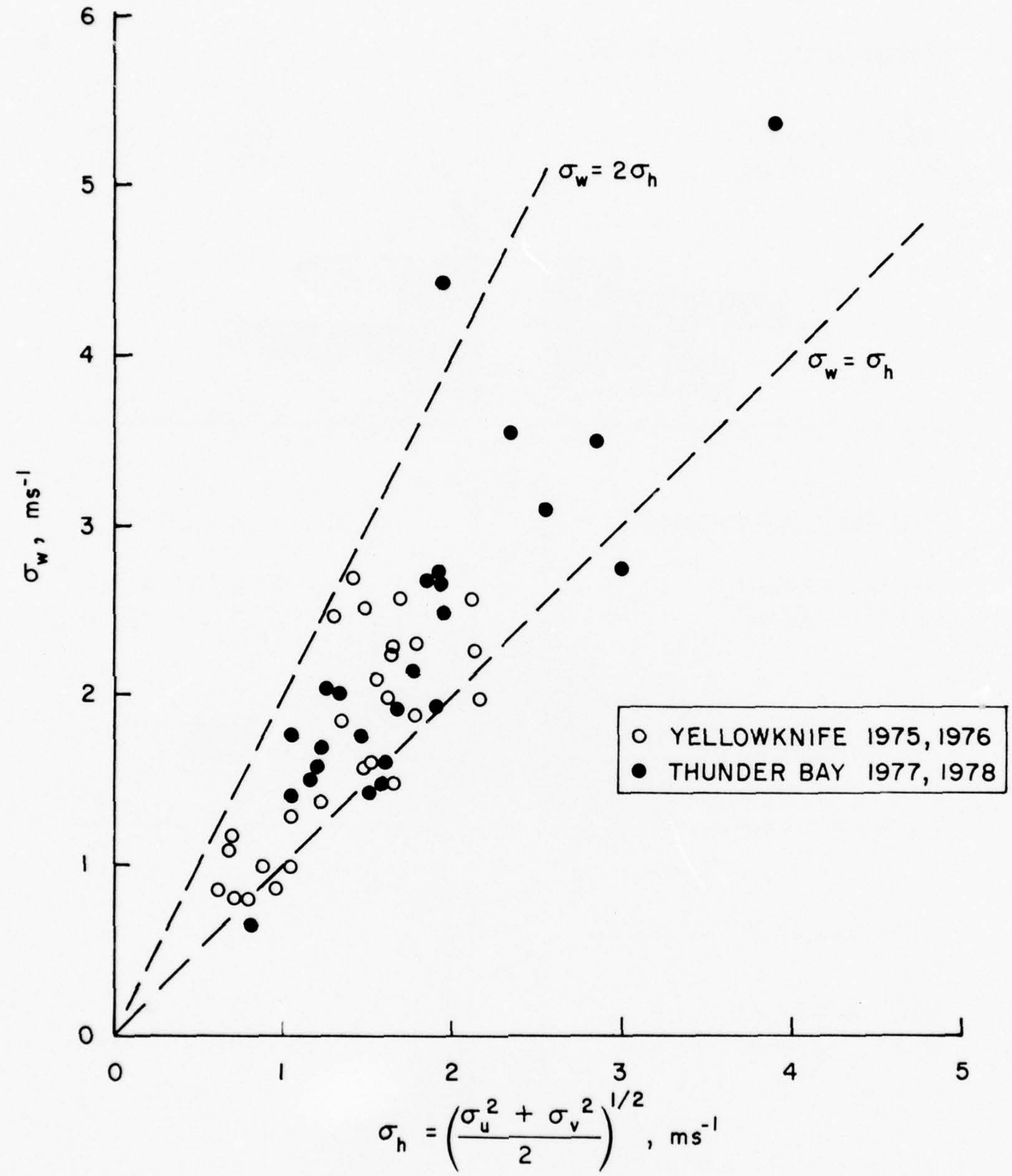


FIG. 6: VERTICAL VERSUS HORIZONTAL RMS GUST VELOCITIES

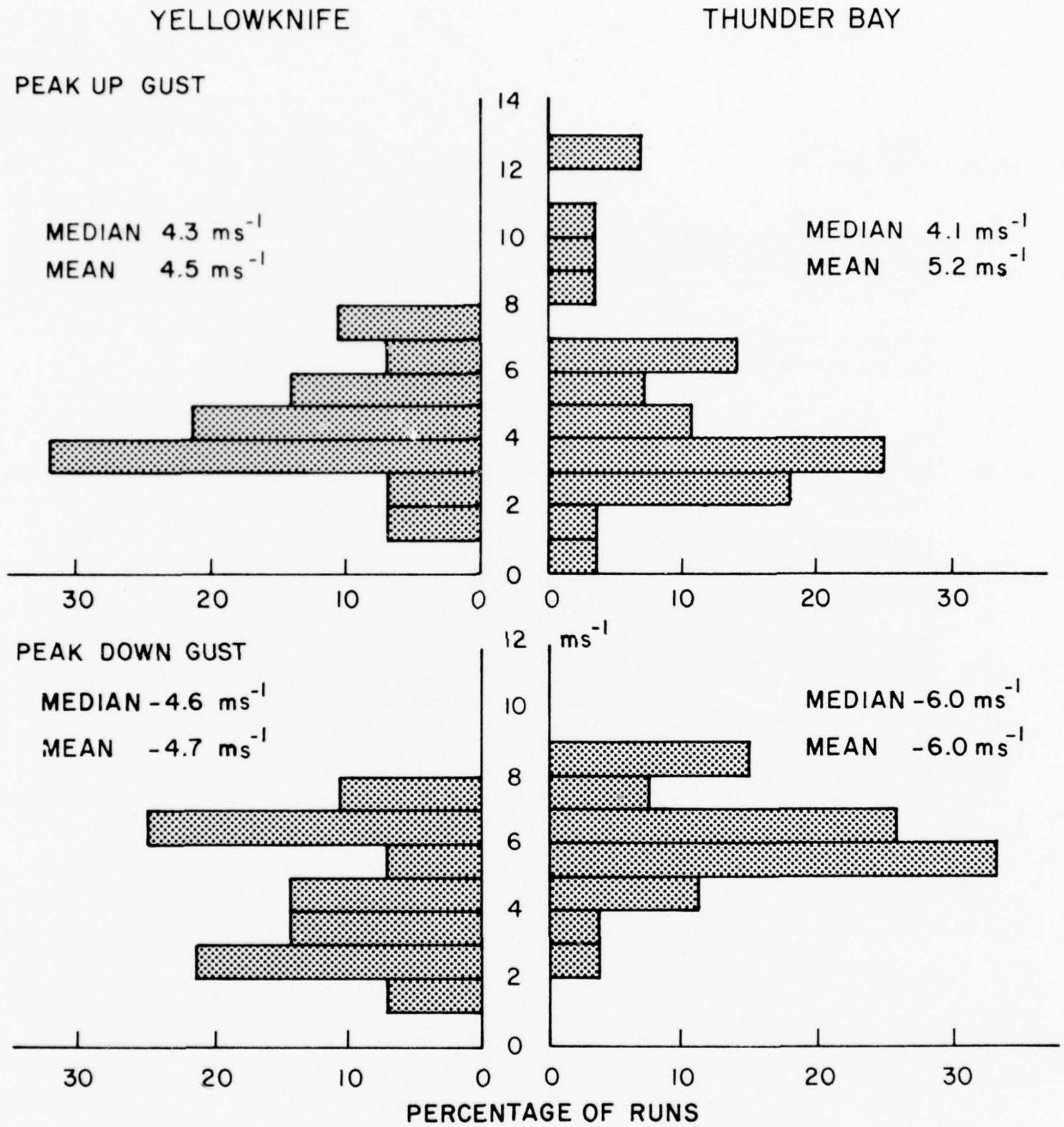


FIG. 7: HISTOGRAMS OF PEAK VERTICAL GUST VELOCITIES MEASURED BY THE T-33 IN CUMULUS CLOUD TOPS – THUNDER BAY AND YELLOWKNIFE DATA COMPARED

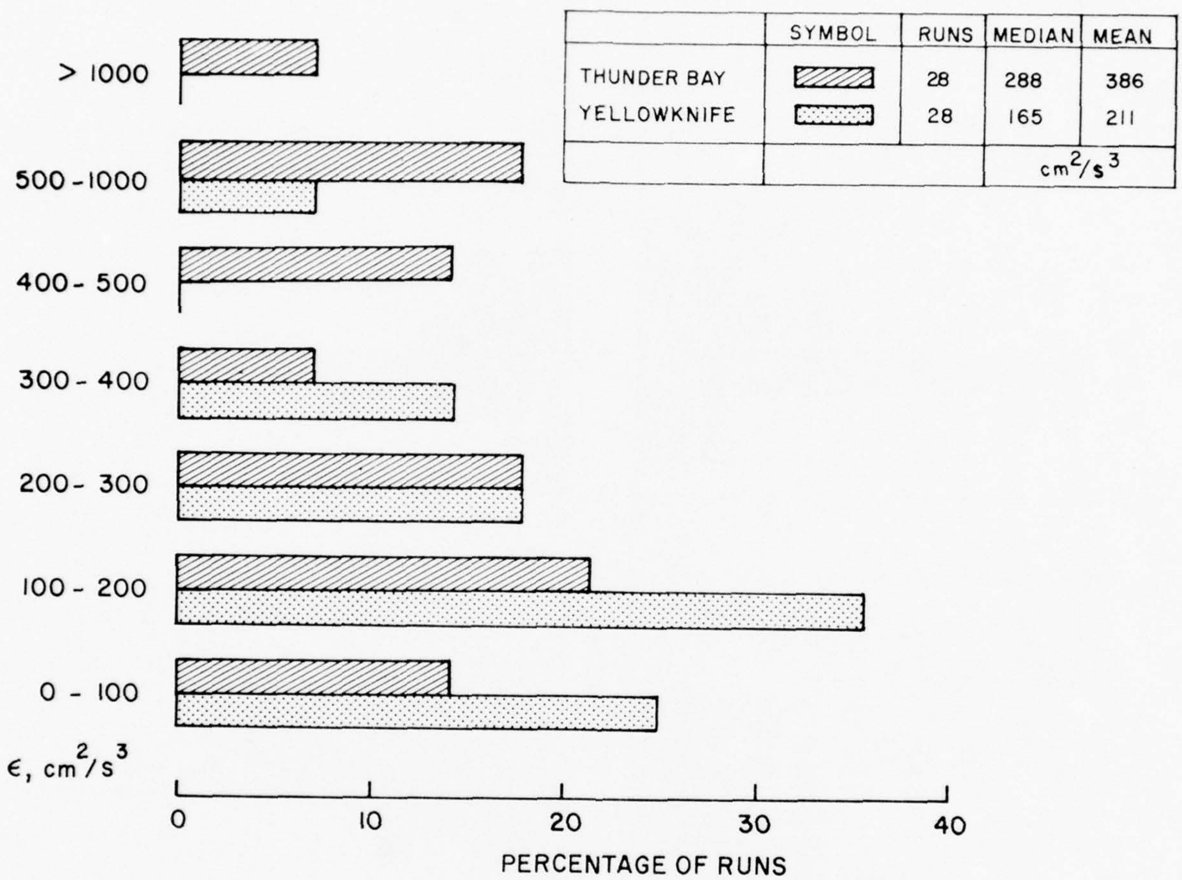


FIG. 8: DISSIPATION RATES MEASURED BY THE T-33 IN CUMULUS CLOUD TOPS – THUNDER BAY AND YELLOWKNIFE DATA COMPARED

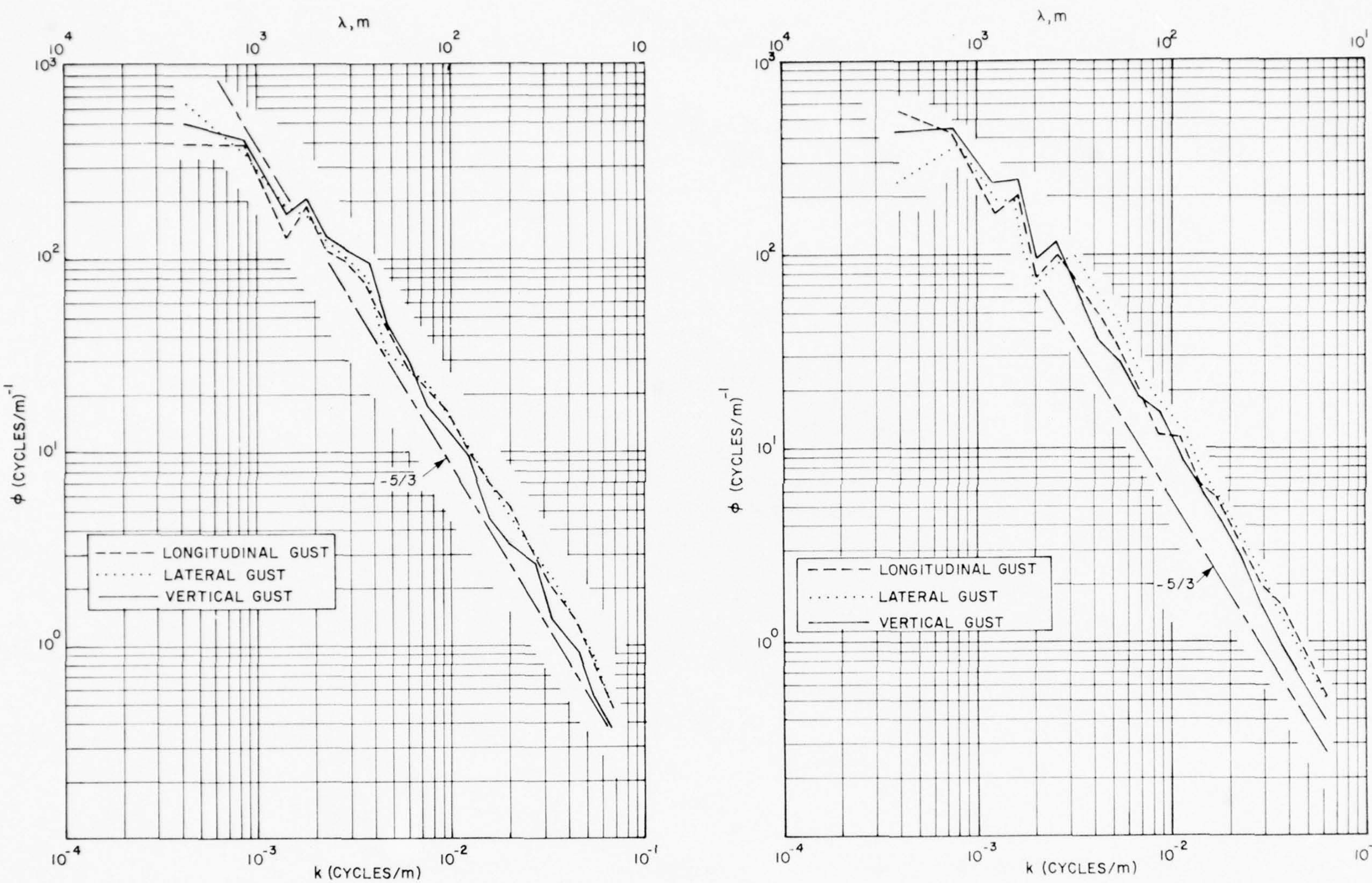


FIG. 9

AVERAGE T-33 GUST SPECTRA FOR 28 CUMULUS CLOUD TOP PENETRATIONS – YELLOWKNIFE – 1975 AND 1976

AVERAGE T-33 GUST SPECTRA FOR 30 CUMULUS CLOUD TOP PENETRATIONS – THUNDER BAY – 1977 AND 1978

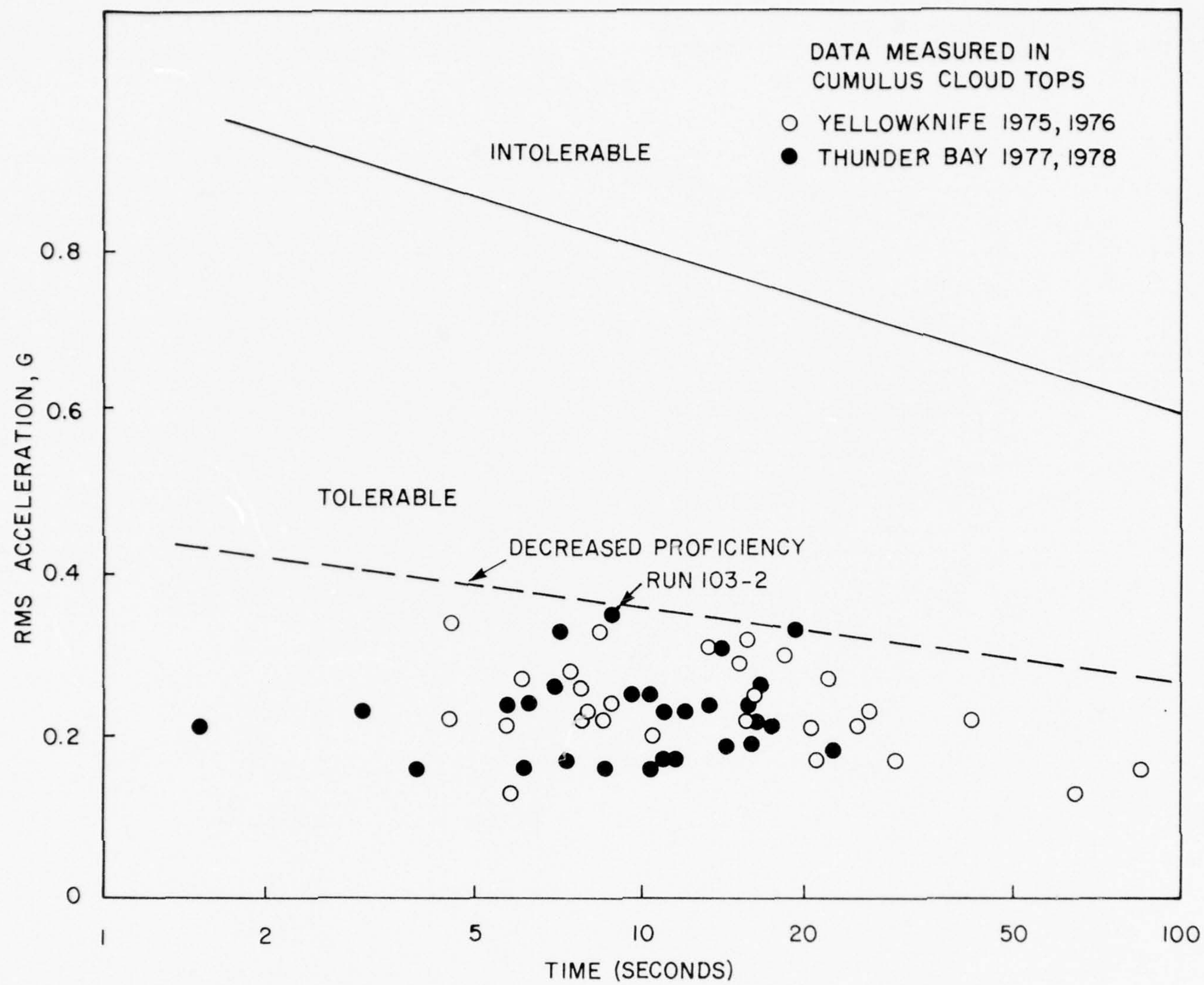


FIG. 10: T-33 VERTICAL ACCELERATION VERSUS TIME IN CLOUD COMPARED WITH THRESHOLDS OF CREW TOLERANCE

# INDIRECT MEASUREMENT OF TURBULENT SKIN FRICTION*

by

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## 1. INTRODUCTION

The total drag on a body moving through a fluid is made up of skin friction drag due to viscous shear, and pressure drag, due to incomplete pressure recovery near the tail end. In order to estimate the skin friction drag, the local skin friction coefficient must be known at each point along the body. Direct measurement of this parameter is possible only in a few special instances, and indirect methods are often resorted to. This paper will present an overview of direct and indirect methods available and will then concentrate on one recently developed indirect technique. Another, more comprehensive overview of this subject complete with historical anecdotes, is given in Reference 1.

## 2. DIRECT MEASUREMENT TECHNIQUES

### 2.1 Skin Friction Balance

There are a few commercially made devices which can measure local skin friction directly. One of these is shown in Figure 1. The "drag piece" is kept in a centered or "null" position by a servo-controlled electromagnetic force system. Another balance is shown in Figure 2. This one is also a null-balance type: A linearly variable differential transformer (LVDT) is used to indicate a position error and a miniature linear motor provides the restoring force.

Both devices are very linear over about two orders of magnitude load range. The Kistler balance is more compact and can operate at elevated temperature. The Laval balance is less expensive and due to its stainless steel and plexiglass construction can be used underwater. This balance was used in a boundary layer experiment (described later).

In general balances have rather restricted application due to their bulky nature and due to operational problems associated with the alignment of the drag piece. However, they are often the "standard" used to calibrate devices which measure skin friction indirectly, particularly when new flow fields are encountered.

### 2.2 Pressure Drop in Pipe

A simple momentum balance will show that the pressure drop in a pipe is directly proportional to the average skin friction along its walls. This point is mentioned because such an experimental set-up can be used to check a skin friction balance calibration or to calibrate a device which measures skin friction indirectly. This will be illustrated later.

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* Presented at Hydrodynamics Colloquium, David Taylor Naval Ship R & D Centre, Bethesda, Md., February 2, 1979.

## 3. INDIRECT MEASUREMENT OF SKIN FRICTION

### 3.1 Clauser Plot

For turbulent boundary layer flows, one can make use of the logarithmic portion of the velocity profile to estimate skin friction. Clauser (Ref. 2) first pointed out this possibility. The technique is as follows: the velocity profile is plotted in a semi-logarithmic form, as illustrated in Figure 3, and an overlay which has theoretical curves for various values of skin friction is used to estimate the local skin friction coefficient.

The method is obviously dependent on the choice of theory which is used to relate $C_f$ to Reynolds number, but other factors will influence the estimation. Under a strong adverse pressure gradient the "wake-like" region near the boundary layer edge will grow and may eventually obliterate the logarithmic region, rendering the method useless. The method has the obvious disadvantage of requiring cumbersome velocity traverses to be made at each station. However, under zero pressure gradient conditions, the method can be used as another technique for validating some other method of measuring skin friction.

### 3.2 Heat Transfer Analogy

The analogy between local skin friction coefficient and heat transfer from heated strips embedded in a surface is well known. Various commercial devices on the market utilize this principle. Two examples ("TSI" and "DISA") suitable for use in 2-D flows are given in Figure 4. Each "transducer" must be individually calibrated in the manner shown. Evaluation of quantities at "wall" temperature conditions means that the calibration should be independent of compressibility effects. Rubesin et. al. (Ref. 3) have developed an alternative design which involves laying a platinum-rhodium wire in a plastic substrate. This method is better suited for flows with pressure gradient.

A gauge ("Micro") suitable for 3-D flows is also shown in Figure 4. The function $f(\beta)$ involves measured output of both films — see Reference 4, for example. Here again a buried wire gauge has recently been developed for such flows (see Ref. 5). Both the 2-D and 3-D gauges have one advantage over previously mentioned devices: their frequency response is usually high enough to permit detection of laminar-turbulent transition and separated flow. A drawback is that they must often be hard-wired into a model, thus restricting the flexibility of their use.

### 3.3 Surface Flow Visualization

The reason for noting this technique here is that it allows the researcher to establish estimates of relative magnitude and direction of surface shear prior to using one of the indirect methods described below.

Surface oil has traditionally been used to indicate the direction of surface streamlines, but Meyer (Ref. 6) noted that oil dots respond to both the magnitude and direction of surface shear stress. In particular he observed that to a large extent the streak length is dependent only on the magnitude of the local shear stress, and not on the dot size. This is illustrated in Figure 5. The technique is ideally suited for intermittent facilities where the starting transients are of short duration. In a continuous-running tunnel, where the starting transient is long, the consistency of the oil dots must be such that they do not respond to the starting transient. In this case a long run time is necessary to streak the dots. An example of this is given in Figure 6. As seen, the streak pattern cannot be relied upon to yield quantitative answers.

### 3.4 Obstacles

Various devices have been designed which exploit the wall-similarity of the flow in a turbulent boundary layer. In a sense they are all obstacles to the flow in that they stagnate a small region of the flow adjacent to the surface. Historically the Preston tube and razor blade (both shown in Fig. 7) were regarded as velocity-measuring devices brought close to the surface and thus are often not regarded as being protrusions from the surface. In the end they all cause a pressure rise which is proportional to skin friction. One point to be noted is that these "calibrations" shown in Figure 7 are valid only for smooth surfaces. Very little investigation of their performance in rough surfaces has been carried out.

### 3.4.1 Razor Blade

A razor blade, whose leading edge is aligned with the leading edge of a static pressure orifice, is a device which is designed to operate in the sublayer of a turbulent flow. There are potential pitfalls which have been documented in Reference 7. These are illustrated in Figure 8.

In spite of its shortcomings, the razor blade can be used successfully, provided care is taken when mounting them. Measurements taken by Brown (Ref. 8) using razor blades on an airfoil model in the NAE 15-in. X 60-in. test section were of great value in analyzing Reynolds number effects on airfoil performance.

### 3.4.2 Sublayer Fence

This device, like the razor blade senses the flow very close to the wall. It has a higher sensitivity because of its differential made of operation it senses the upstream pressure rise and the downstream suction (relative to the local static pressure). Due to its small size achieving a specified accuracy is rather difficult, and thus each unit must be calibrated.

### 3.4.3 Preston Tube

This device is regarded as being one which senses part of the logarithmic portion of a velocity profile. The Preston tube has been used in an enormous number of flow cases, even in supersonic flow (Ref. 9), with a great deal of success. Some problem areas associated with its operation are shown in Figure 9. The alignment of the nose of the tube is critical — it must be perpendicular to the surface and to the surface shear direction.

### 3.4.4 Obstacle Block

In an attempt to overcome many of the practical difficulties mentioned above, Nituch (Ref. 10) set out to determine an alternative device which could be easily specified and which would give as large a value of pressure rise as possible. A sketch of the final design is given in Figure 10. As shown in Figure 7, its performance is relatively quite acceptable. Its development and application are described below.

## 4. PRINCIPLES OF OBSTACLE BLOCK OPERATION

### 4.1 Optimization of Geometry

The simplest shape would be a rectangular block. However, there are two problems associated with this choice:

a) sensitivity to yaw error
b) errors associated with block location.

In addition it was discovered that a secondary separation line (see Fig. 11) forms over the static pressure hole. This lowers the maximum attainable pressure rise and introduces the possibility of an unsteady pressure signal. A semi-circular cutout, congruent with a static pressure orifice, is better in both these regards, as well as a) and b). Data leading up to the final optimized geometry are shown in Figure 12. A width/height ratio (b/h) of 1.5 was selected for the final design. Two height/hole diameter ratios (h/d) were chosen, 1 and 3: these permit use of blocks over a wide range of hole sizes and boundary layer thicknesses.

## 4.2 Calibration

Nituch calibrated these two families of block geometry using a flat plate boundary layer under zero pressure gradient. Skin friction was obtained by using carefully constructed Preston tubes, and checked using Clauser plots (e.g. Fig. 3).

Two forms of presentation of the calibration were given (Figs. 13 and 14). The calibration equations are of the form

$$\frac{\Delta p}{\tau_w} = K \left[\frac{\Delta p h^2}{\rho \nu^2}\right]^{.117} \qquad \text{where } K = 15.1 \text{ for } h/d = 1 \text{ and } K = 20.3 \text{ for } h/d = 3$$

This version permits $C_f$ to be obtained as a function of $Cp_b$, something which is useful in airfoil testing. For the special case of a flat plate boundary layer flow under zero pressure gradient, where $U_e = U_\infty$, the calibration equations can be written as

$$\frac{Cp_b}{C_f} = K\left[\tfrac{1}{2}\, Cp_b \cdot Re_h{}^2\right]^{.117}$$

One feature worth noting is that there is an upper limit to the block height/momentum thickness ratio ($h/\theta$). The data indicate that a maximum value of 3 ensures no effect on the reading, and an upper limit of 6 restricts the error to a few percent.

To verify the "universal" nature of their calibration, these devices were check-calibrated in the NAE 8-in. pipe facility, shown schematically in Figure 15. It has a honed section about 45 ft. long, has a very linear pressure drop along the pipe and thus the skin friction is constant along its length. Samples of each family of blocks were calibrated using static pressure orifices .0197-in. diameter. The agreement with Nituch's calibration (see Fig. 16) is quite good, which suggests that the blocks will measure skin friction in any flowfield. It is worthwhile to note that Granville (Ref. 11) has suggested that there is a slight difference between the calibration of Preston tubes in pipes and flat plates. His proposed modification has been applied to Nituch's calibration, as shown. This appears to work quite well in this case.

## 4.3 Practical Aspects of Use

The semi-circular cutout should mean that the block is less sensitive to yaw misalignment than other devices — this point has not yet been verified, however.

The interference of one block on another is illustrated in Figure 17. The influence of an upstream block on the indicated skin friction is a strong function of the level of skin friction itself. When blocks are directly in line, they should be separated by a distance of 300 - 400 block heights for no interference. Staggering the blocks offers the possibility of shortening this distance. The data of Figure 17 indicate that if the blocks are offset along a line about 25° from the tangent to the flow direction, there will be no interference. This angle is larger than that expected from the "turbulent wedge" concept. This is presumably due to the rather gross disturbance imparted by the block.

If pressure scanning systems are used, such as the "Scanivalve" system, then low stepping rates must be used (due to pressure jumps from block to static hole). For example, at $M_\infty = .3$, $P_0 = 74$ psia, a maximum stepping rate of 10 ports/sec. was found to be permissible (where the usual rate is 20 ports/sec.).

### 4.4 Special Uses

In theory it is possible to use the blocks to measure skin friction at high speeds. Calibration at supersonic speeds has not yet been undertaken. However, it seems reasonable to assume that if "wall" conditions are used, compressibility effects should not be noticed. Alternatively a "friction velocity Mach number" correction could be applied, e.g. Reference 12.

Another use is in the detection of boundary layer flow reversal, as indicated in Figure 18. When a block is facing opposite to the local flow direction, it will sense a base flow whose pressure will be slightly lower than the local static pressure. This can be only regarded as a qualitative method since the block will severely affect the local flowfield.

### 4.5 Examples of Application

#### 4.5.1 Basic Research on Turbulent Boundary Layers

The obstacle blocks have been used to measure skin friction over a wide Reynolds number range in a recent experiment at NAE. The zero pressure gradient results are given in Figure 19. With the exception of one outlying point the obstacle block data agree quite well with those obtained using a balance loaned by Laval University, and both of these tend to substantiate schlichting's correlation (Ref. 13). A full report on the first phase of this experiment is in preparation.

#### 4.5.2 Airfoil Skin Friction

Two recent experiments which used obstacle blocks to measure skin friction will now be described. The first was carried out on a 16% thick airfoil, the second on a NACA 0020 airfoil loaned by the David Taylor Naval Ship Research and Development Center.

The first airfoil had local supersonic flow and associated shock waves, and thus provided a good test of the compressibility effect and block response to sudden changes in skin friction. The compressibility effects, based on "wall condition" computations appear small, as seen in Figure 20. The response to pressure gradient seems excellent. Blocks placed both forward and rear-facing indicated no separated flow at the trailing edge.

Ideally, the obstacle block can be used to detect the transition from a laminar to turbulent flow by a sudden increase in skin friction. The data do not show such a trend, probably because $h/\theta$ is enormous near the airfoil leading edge. This is an unfortunate result because it implies that exceedingly small blocks are required. In this regard, it should be noted that the blocks used here were already quite small (h = .0145 in.).

The results for the low speed airfoil are shown in Figure 21. Here no distinction has been made between upper and lower surface data since this symmetrical airfoil is at zero incidence. Once again the data do not indicate transition. The data for $Re_c = 5 \times 10^6$ exhibit a scatter which increase towards the leading edge. Most likely this is due to spanwise variations in the transition process.

The drag ($C_{DW}$) of this airfoil was measured by a wake traverse and found to be independent of $Re_c$. If it is assumed that most of the surface of a given airfoil is covered by a turbulent boundary layer, then $C_{DW}$ should decrease as $Re_c$ increases. To help explain this discrepancy, the measured skin friction was integrated to obtain the viscous drag. Since the local skin friction coefficient was not known at every point, some assumptions were made.

The first concerns the location of transition. To estimate transition, the following prediction method was evolved. Through flow visualization and use of a boundary layer trip, the end of transition for the supercritical airfoil was identified for a few flow conditions. An example is shown in Figure 20. A modified version of a method (Ref. 14) for predicting the beginning of transition as a function of pressure gradient and freestream turbulence was used along with this information to arrive at an "equivalent" freestream turbulence level. Then the reverse process was used to estimate the transition location on the NACA 0020 wing.

The next step was to estimate the skin friction for all three regimes: laminar, transitional and turbulent flow. The laminar skin friction was determined theoretically up to the start of transition. The turbulent skin friction was simply a smoothed version of the data, starting at the end of transition. A linear variation between the start and end of transition was assumed. This approach is illustrated in Figure 21. The integrated skin friction varies only slightly with $Re_c$, so we have an explanation for the constancy of $C_{DW}$: the movement in the transition location compensates for the change in turbulent skin friction.

## 5. CONCLUSIONS

An overview of various direct and indirect methods of estimating turbulent skin friction has been given. A comparative summary is given in Table 1: selected references are included to assist the reader in persuing subject matter further.

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## LIST OF SYMBOLS

| | |
|---|---|
| $b$ | width of obstacle |
| $c$ | model chord |
| $C_{DW}$ | drag coefficient $= D/q_\infty S$ from wake traverse |
| $C_f$ | local skin friction coefficient $= \tau_W/q_\infty$ |
| $C_L$ | lift coefficient $= L/q_\infty S$ |
| $C_p$ | pressure coefficient $= (p - p_\infty)/q_\infty$ |
| $d$ | pressure orifice diameter |
| $D$ | drag on body |
| $h$ | height of obstacle block |
| $I$ | current through heated film |
| $L$ | lift on a body, also length of obstacle or model |
| $M$ | Mach number |
| $p$ | pressure |

## LIST OF SYMBOLS (Cont'd)

| | |
|---|---|
| $\Delta p$ | difference between pressure sensed by a device and local static pressure |
| $q$ | dynamic head = $\frac{1}{2} \rho U^2$ |
| $R$ | electrical resistance (of heated film) |
| $Re_c$ | Reynolds number based on model chord = $U_\infty c/\upsilon$ |
| $Re_h$ | Reynolds number based on block height = $U_\infty h/\upsilon$ |
| $Re_x$ | Reynolds number based on distance from leading edge = $U_\infty x/\upsilon$ |
| $S$ | model surface area |
| $\Delta T$ | difference between heated film temperature and unheated surface temperature |
| $U$ | local velocity |
| $u_\tau$ | friction velocity = $\sqrt{\tau_w/\rho}$ |
| $x$ | streamwise co-ordinate |
| $y$ | distance normal to surface |
| $\beta$ | yaw angle |
| $\mu$ | viscosity |
| $\upsilon$ | kinematic viscosity = $\mu/\rho$ |
| $\rho$ | density |
| $\tau$ | shearing stress |
| $\theta$ | boundary layer momentum thickness |
| $\delta^*$ | boundary layer displacement thickness |
| $\delta$ | nominal boundary layer thickness |

**Subscripts**

| | |
|---|---|
| b | conditions sensed by obstacle |
| e | edge of boundary layer |
| w | wall conditions |
| $\infty$ | freestream static conditions |
| o | reference condition |

**TABLE 1**

**RELATIVE MERITS OF VARIOUS DEVICES FOR MEASURING TURBULENT SKIN FRICTION**

| Device or Technique | References | Method | | Flow Intrusion | Response to Skin Friction | Validity in Pressure Gradient | Sensitivity to Misalignment Errors | Ease in Achieving Specified Geometry | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | Direct | Indirect | | | | | | |
| Skin friction Balance | 15 | √ | | | ●●●● | ●● | ●●● | ●●● | Space limitations |
| Momentum balance | 13 | √ | | | ●●● | ● | N.A. | N.A. | Limited to simple flows (e.g. pipe flow) |
| Clauser plot | 2 | | √ | ●●● | ●● | ● | N.A. | N.A. | Cumbersome |
| Heated film | 3,4,5 | | √ | ● | ●●● | ●●●● | ●● | ● | 3D as well as 2D flows |
| Surface oil dots | 6 | | √ | ● | ● | ● | N.A. | ●● | Qualitative only |
| Razor blade | 7 | | √ | ●● | ●● | ●● | ●●●● | ●●● | |
| Sublayer fence | 16 | | √ | ●● | ●●●● | ●●●● | ●●●● | ● | Each unit needs to be calibrated |
| Preston tube | 9,17 | | √ | ●●● | ●●● | ●●● | ●● | ●● | |
| Obstacle black | 10 | | √ | ●●●● | ●●● | ●●● | ● | ●●●● | |

NOTE: dots (●) indicate relative magnitude (out of a maximum of 4)

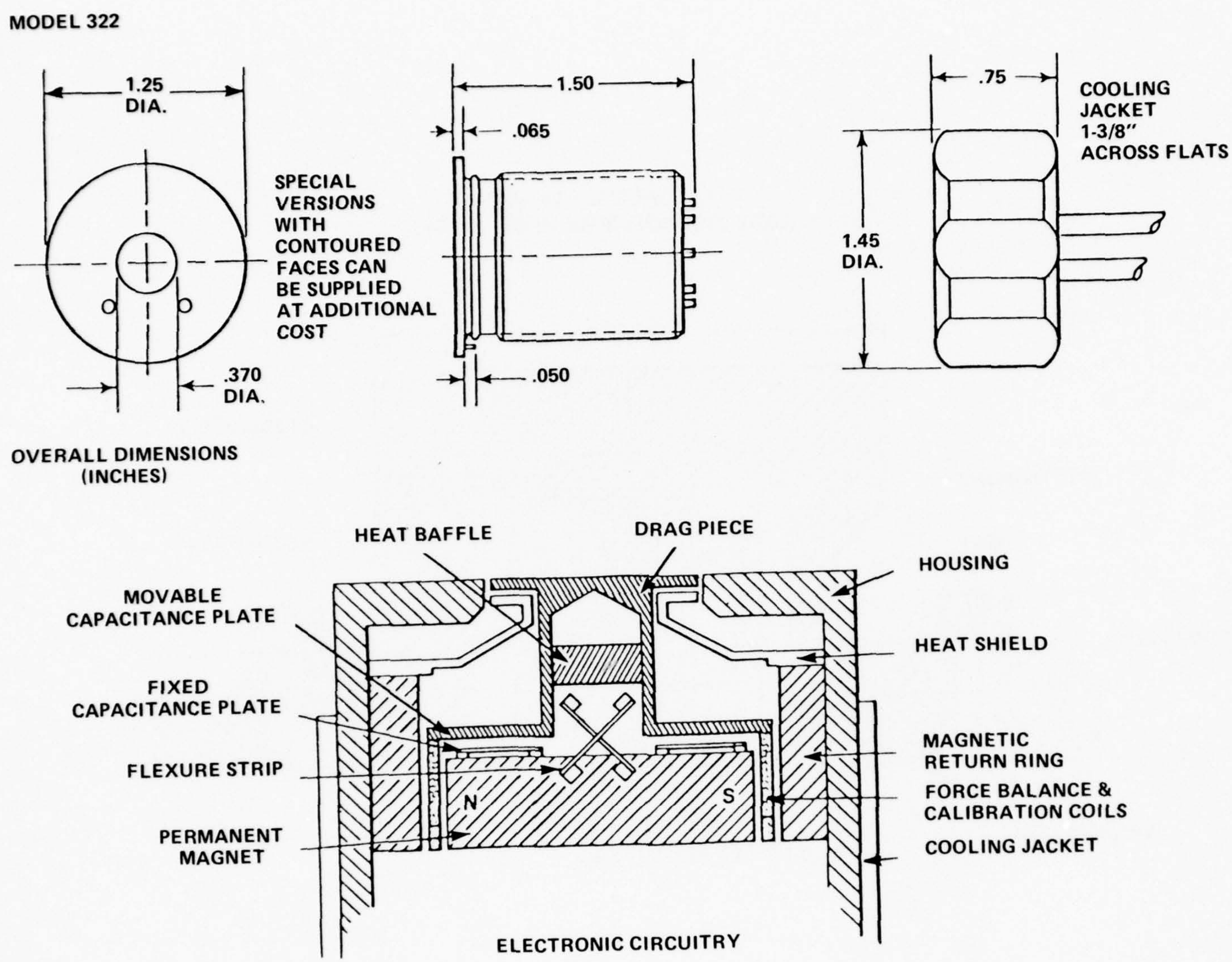



FIG. 1: SKIN FRICTION BALANCE – KISTLER CO.

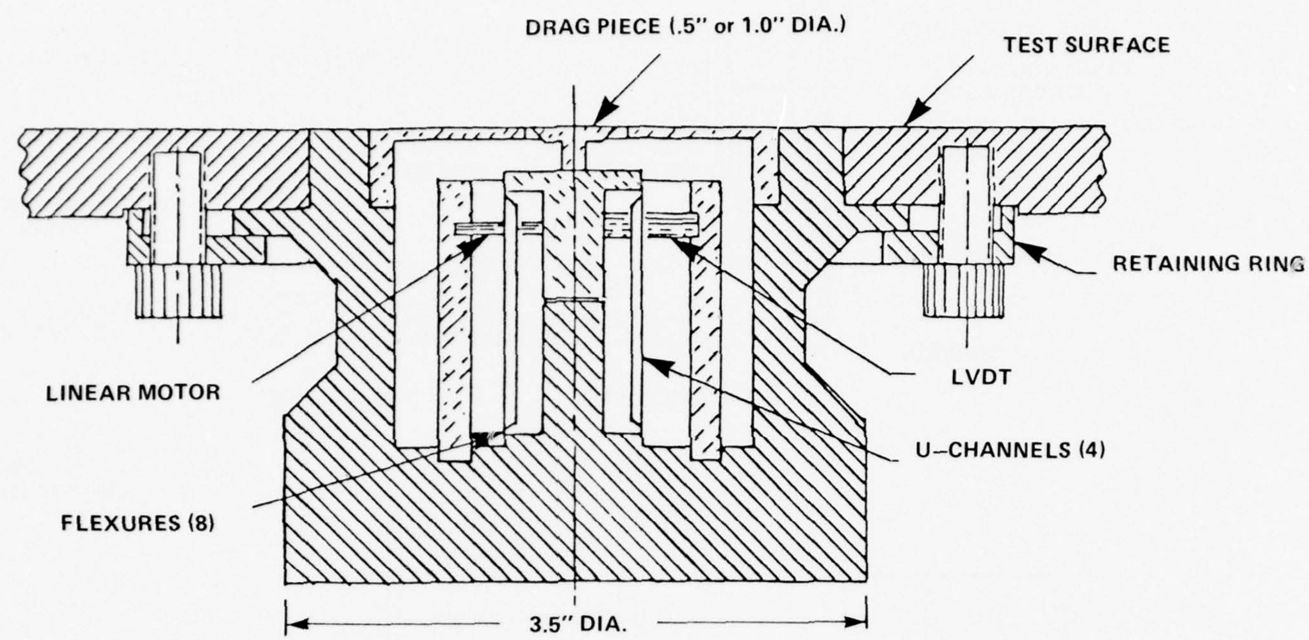



FIG. 2: SKIN FRICTION BALANCE – LAVAL UNIVERSITY

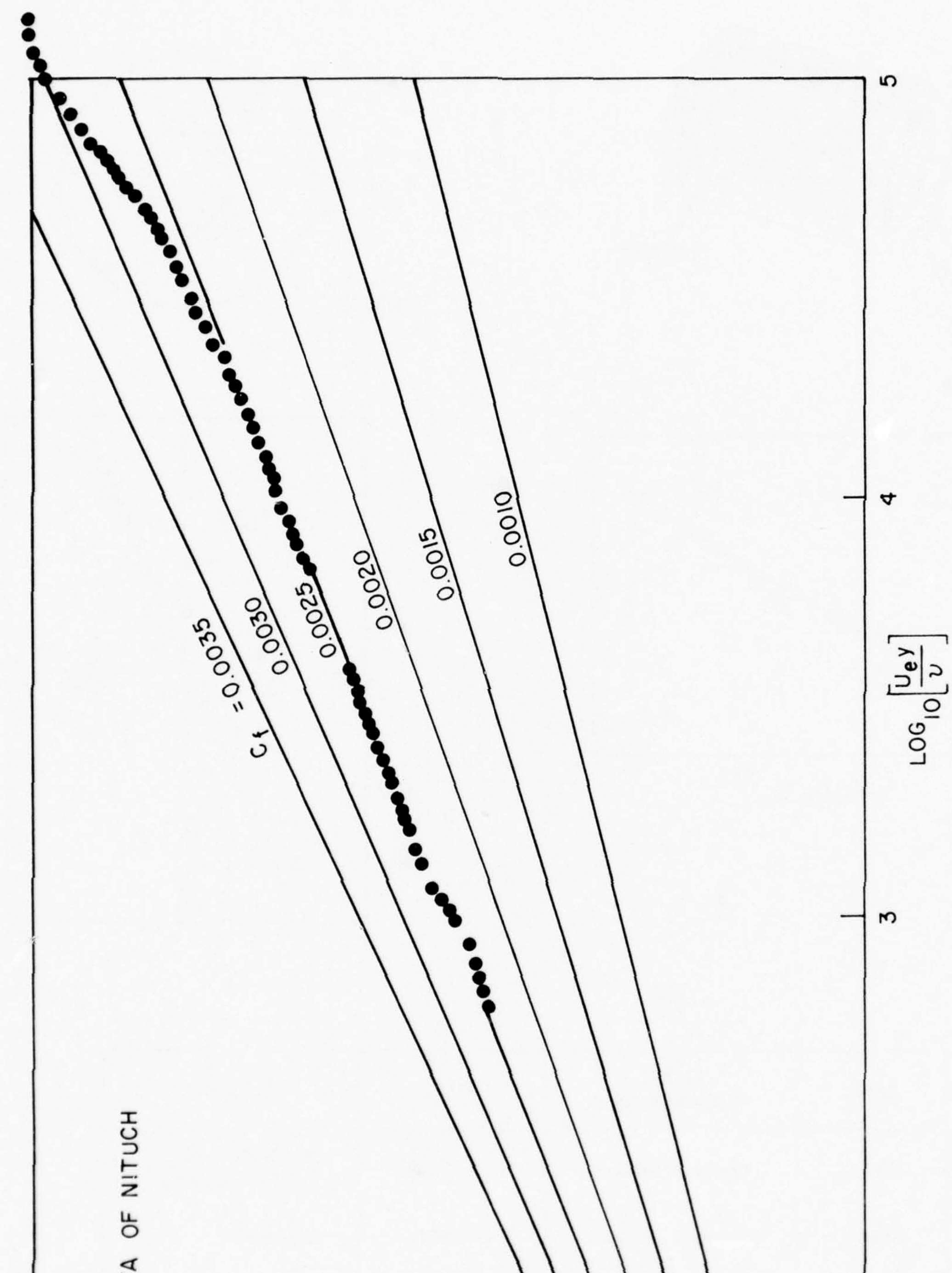
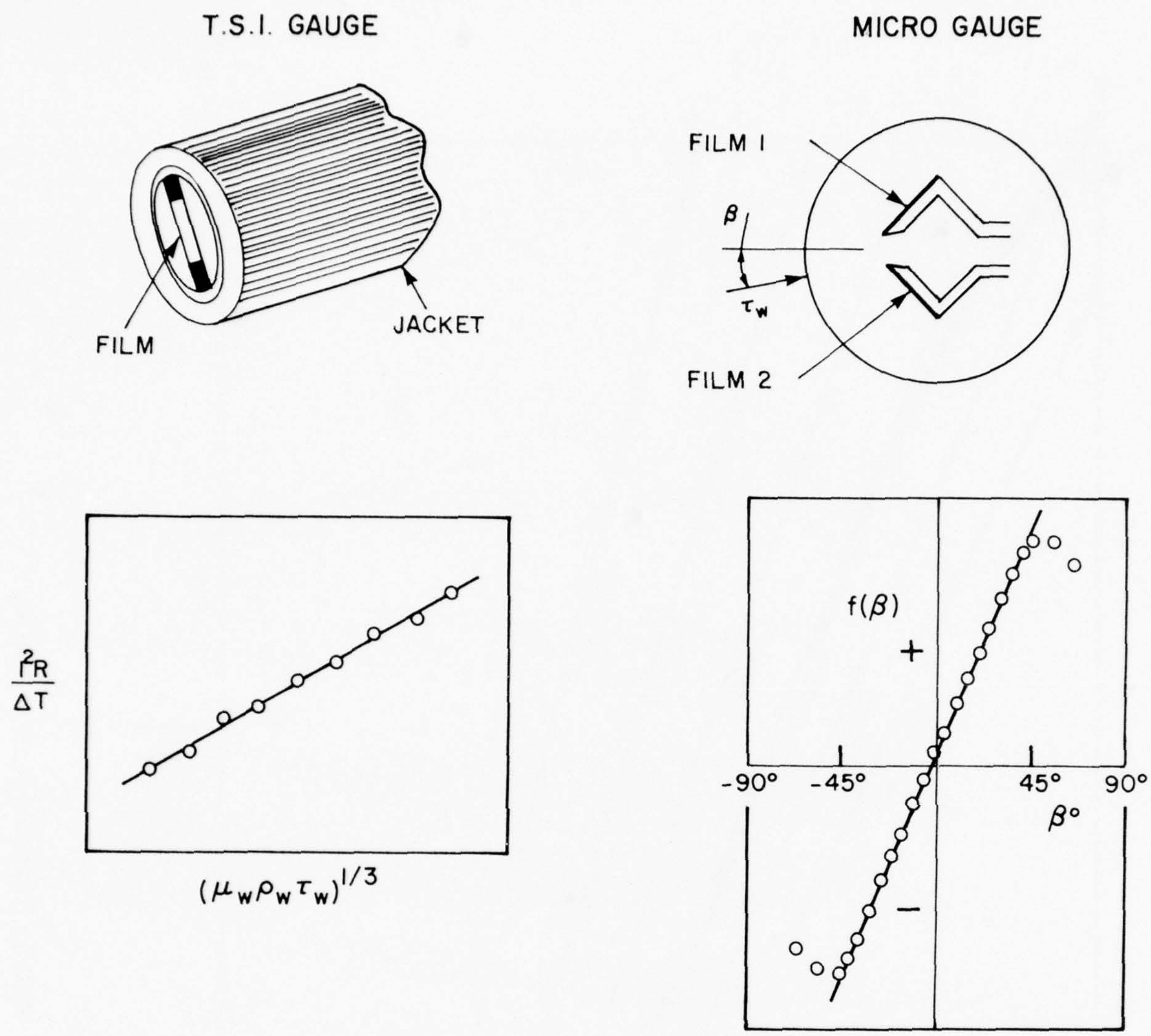



FIG. 3: CLAUSER PLOT OVERLAY




| MFR. | FILM DIMENSIONS | FILM | COATING |
|---|---|---|---|
| T.S.I. | .12 mm X 1.0 mm | PLATINUM | ALUMINA–AIR<br>QUARTZ–WATER |
| DISA | .20 mm X .75 mm | NICKEL | QUARTZ |
| MICRO | .05 mm X 5.0 mm | NICKEL | |

FIG. 4: SURFACE HEAT TRANSFER GAUGE

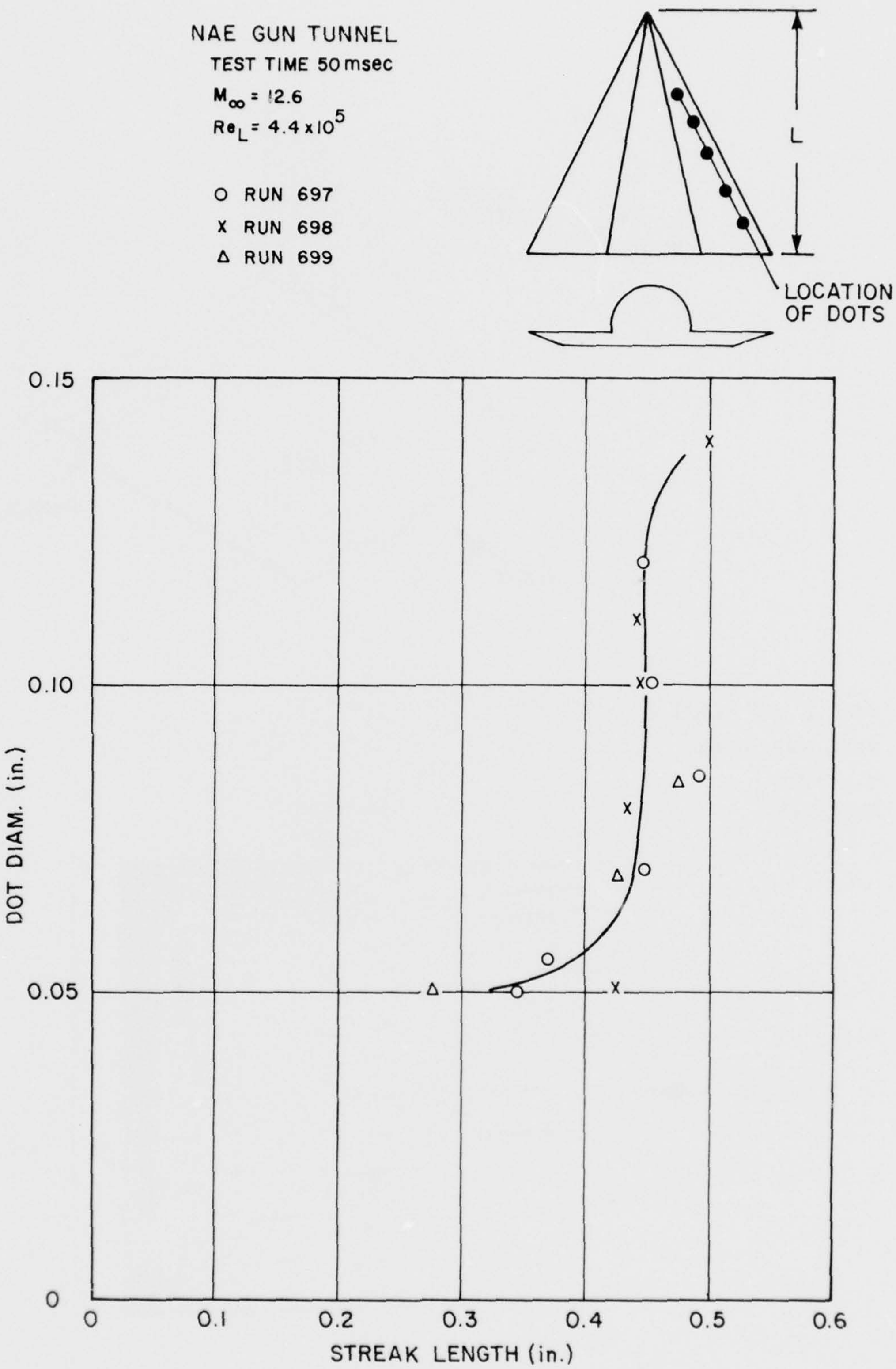
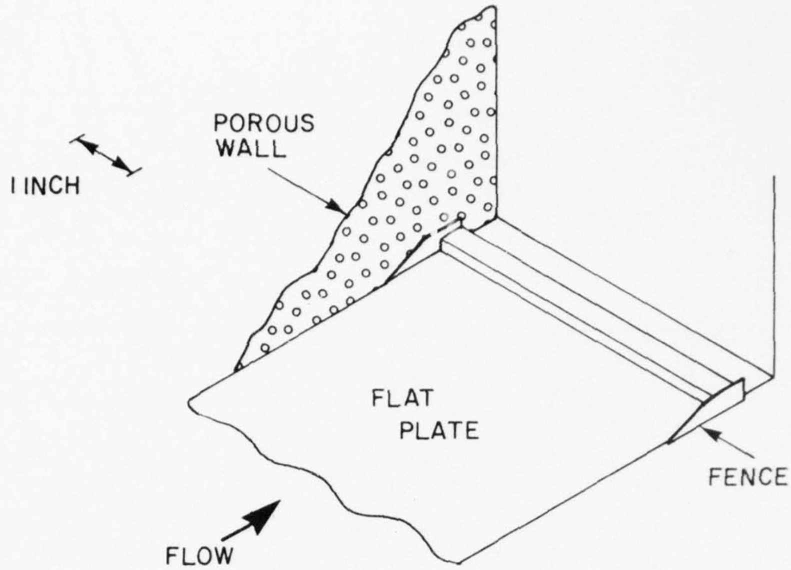



FIG. 5: THE DEPENDENCE OF STREAK LENGTH ON DOT SIZE-MEYER



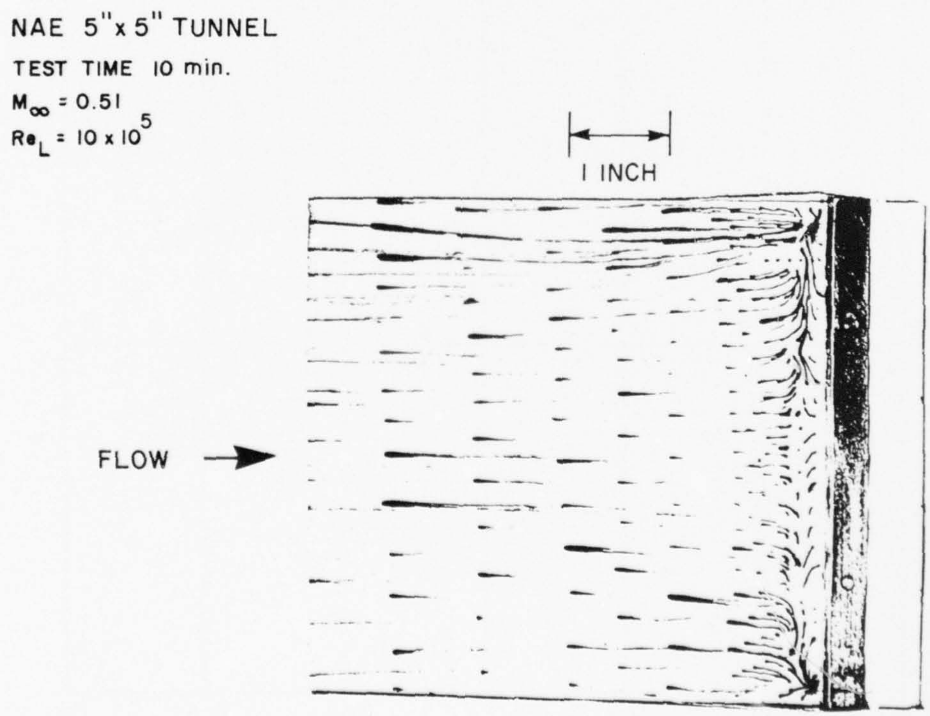




FIG. 6: EXAMPLE OF OIL DOT FLOW VISUALIZATION

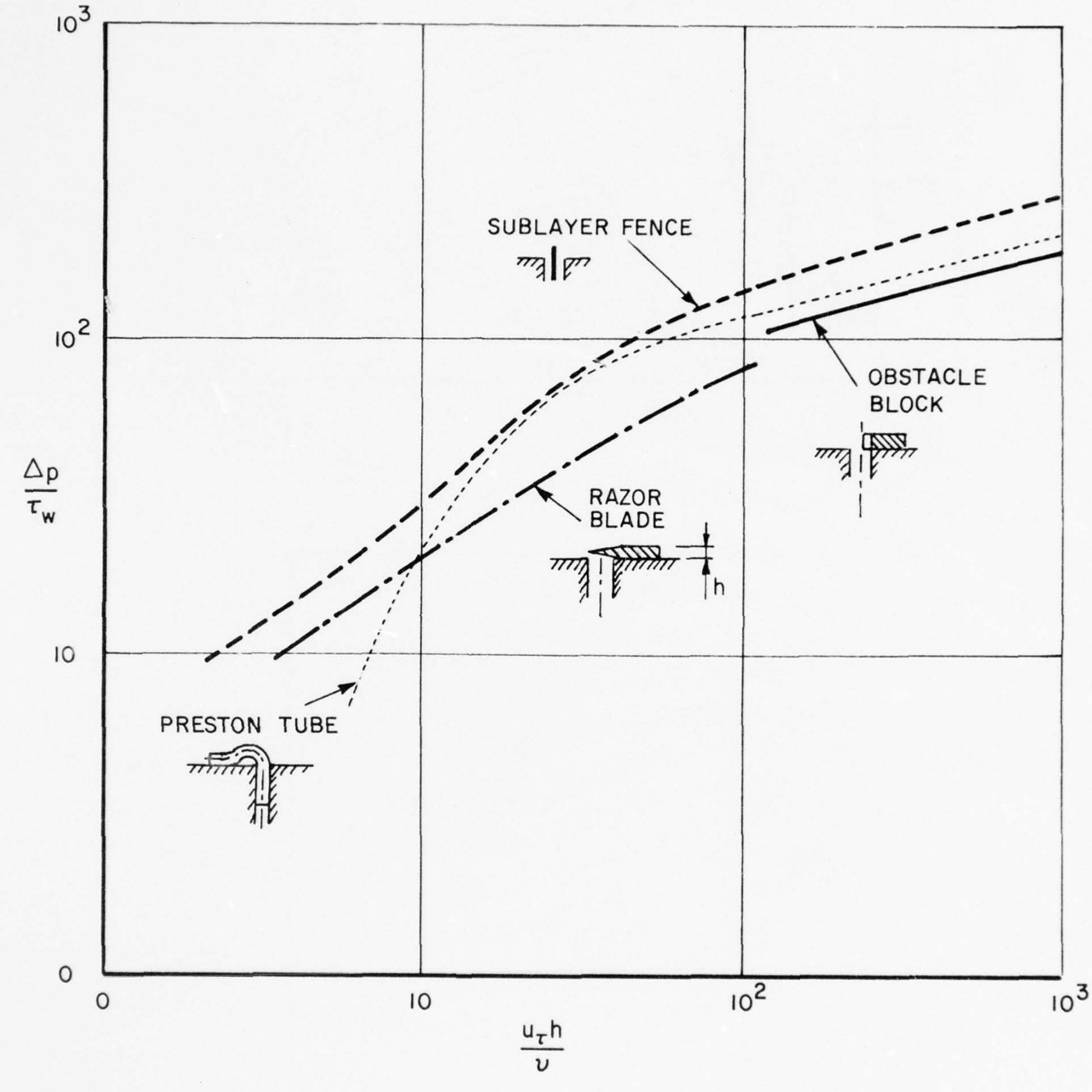



FIG. 7: SENSITIVITIES OF VARIOUS OBSTACLES TO SKIN FRICTION (AFTER WINTER)

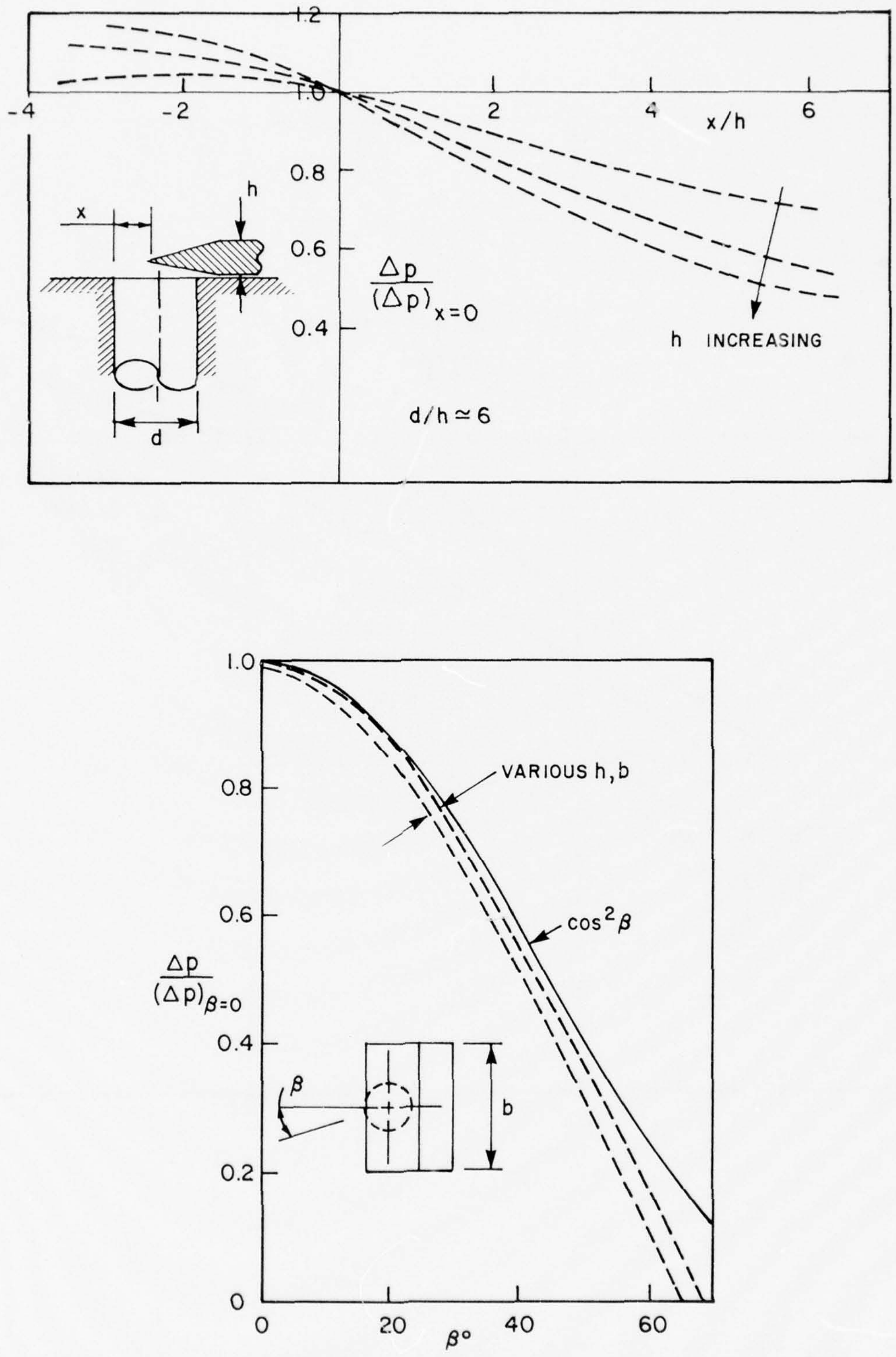
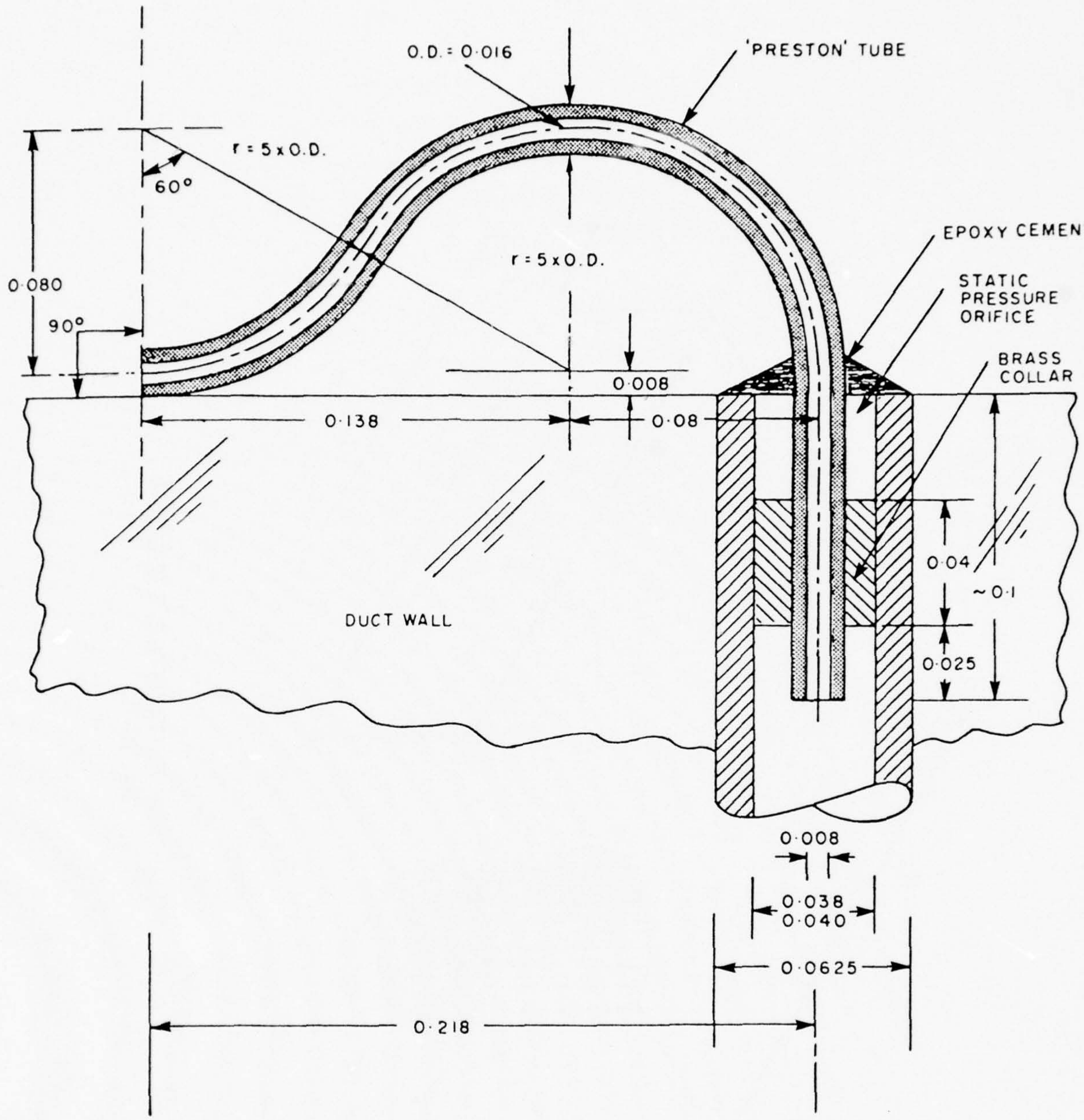



FIG. 8: SOURCES OF ERROR IN RAZOR BLADE MEASUREMENTS – EAST




NOTE: ALL DIMENSIONS ARE IN INCHES

PROBLEM AREAS

1. ALIGNMENT OF PITOT NOSE (IN 2 DIRECTIONS)
2. PITOT TIP CONTACT WITH SURFACE
3. FLOW INTERFERENCE

FIG. 9: THE PRESTON TUBE – PEAKE

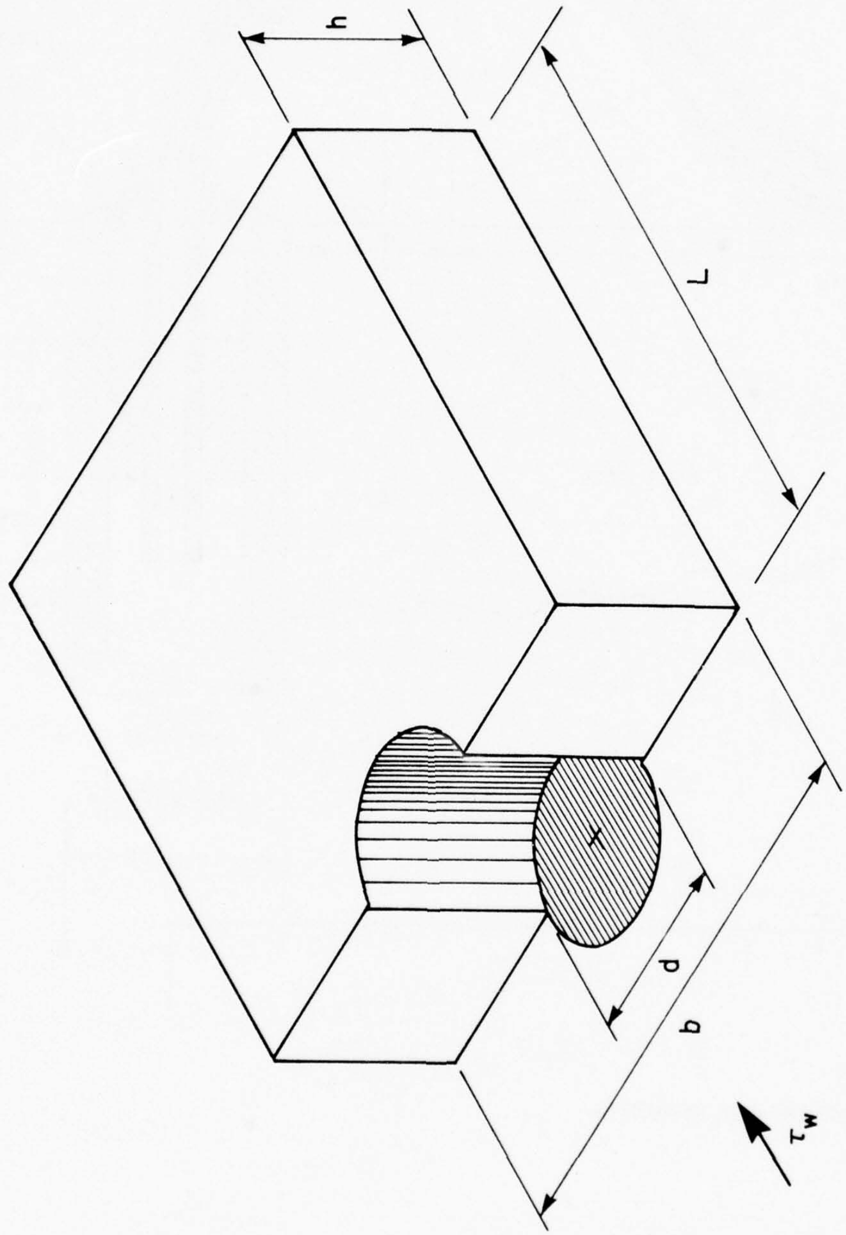



FIG. 10: THE CONGRUENT OBSTACLE BLOCK – NITUCH

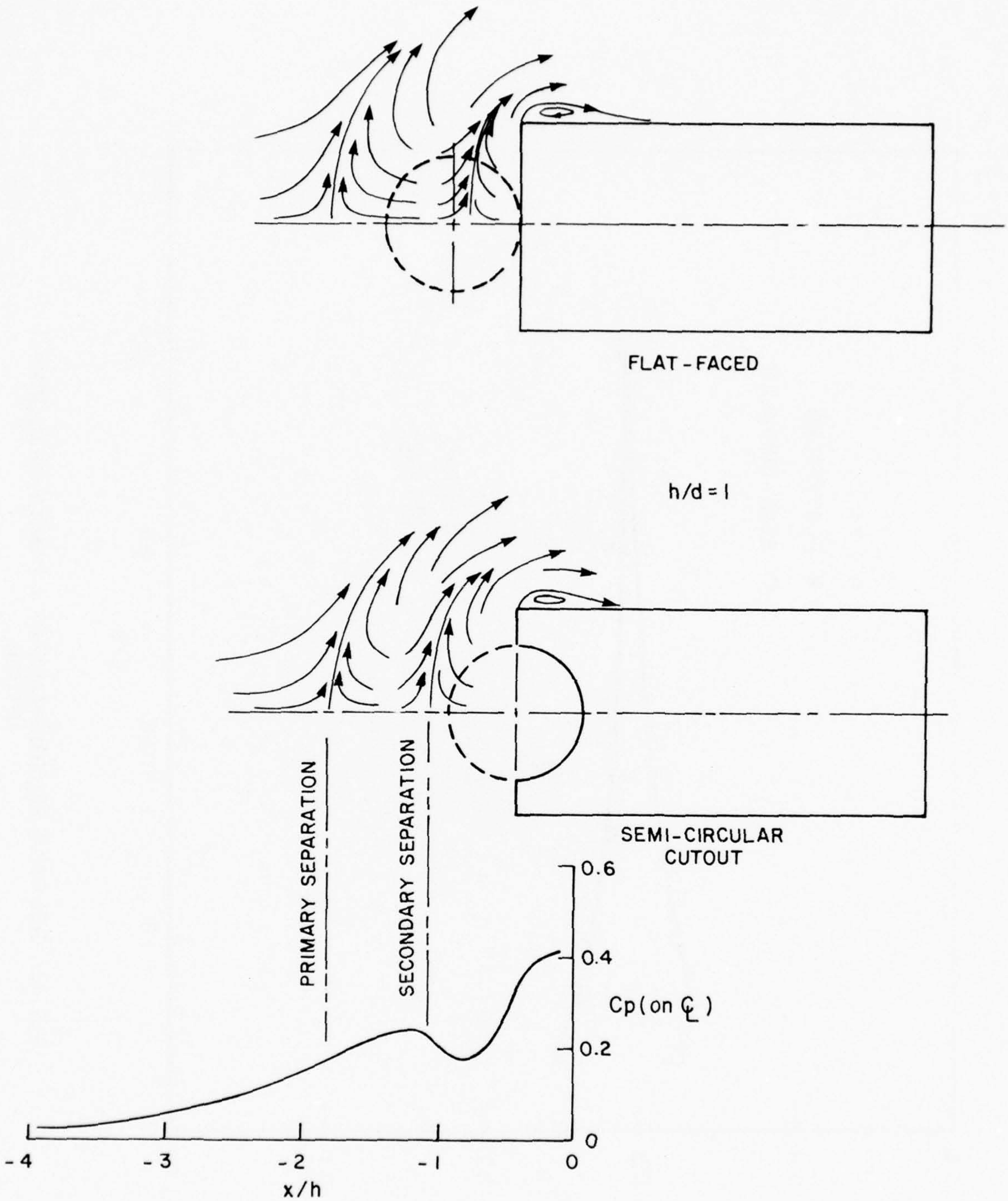



**FIG. 11: SURFACE FLOWFIELD AHEAD OF OBSTACLE BLOCK – NITUCH**

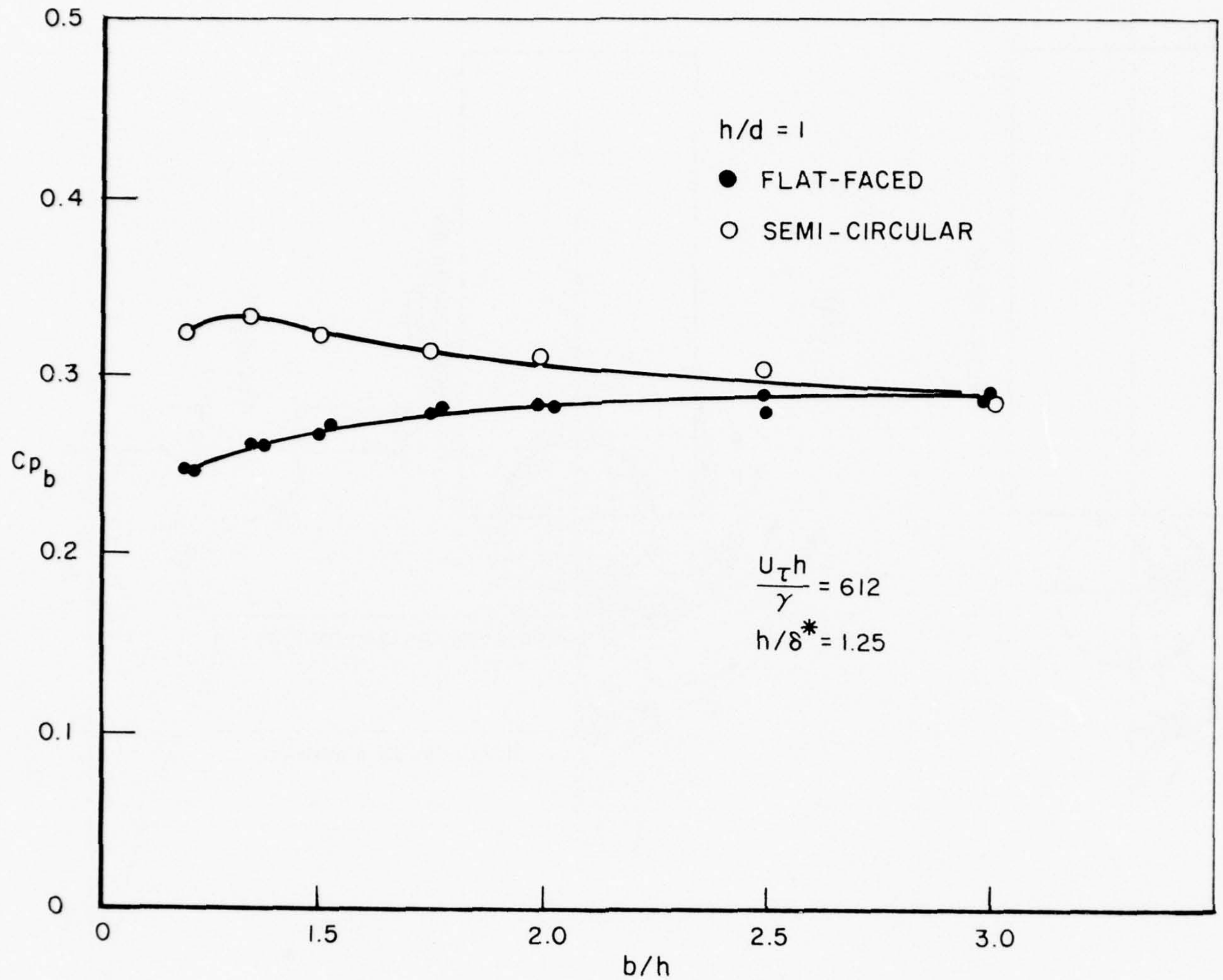



**FIG. 12: RELATIVE PERFORMANCE OF A FAMILY OF BLOCKS – NITUCH**

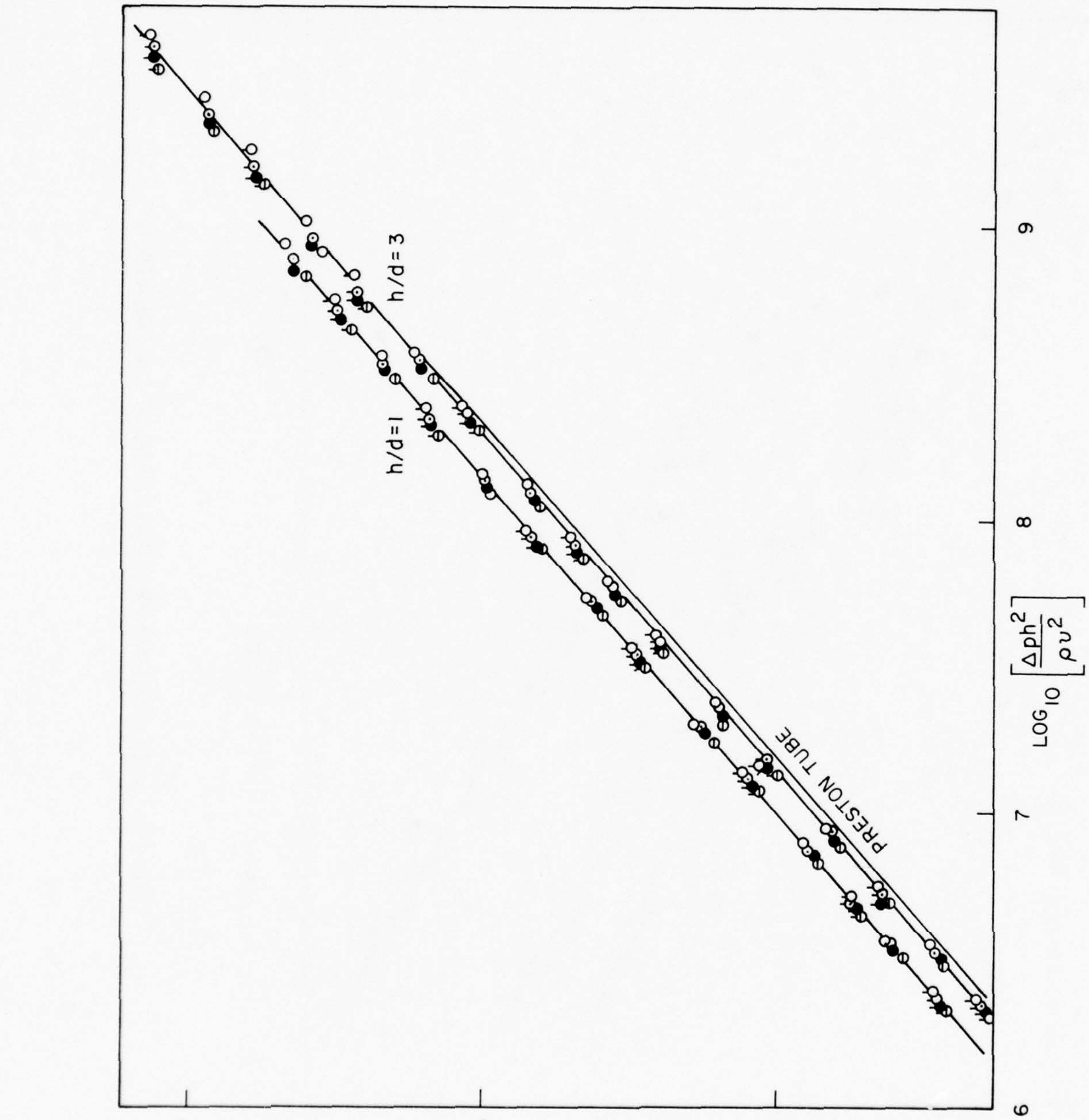



**FIG. 13: CALIBRATION OF OBSTACLE BLOCKS — NITUCH**

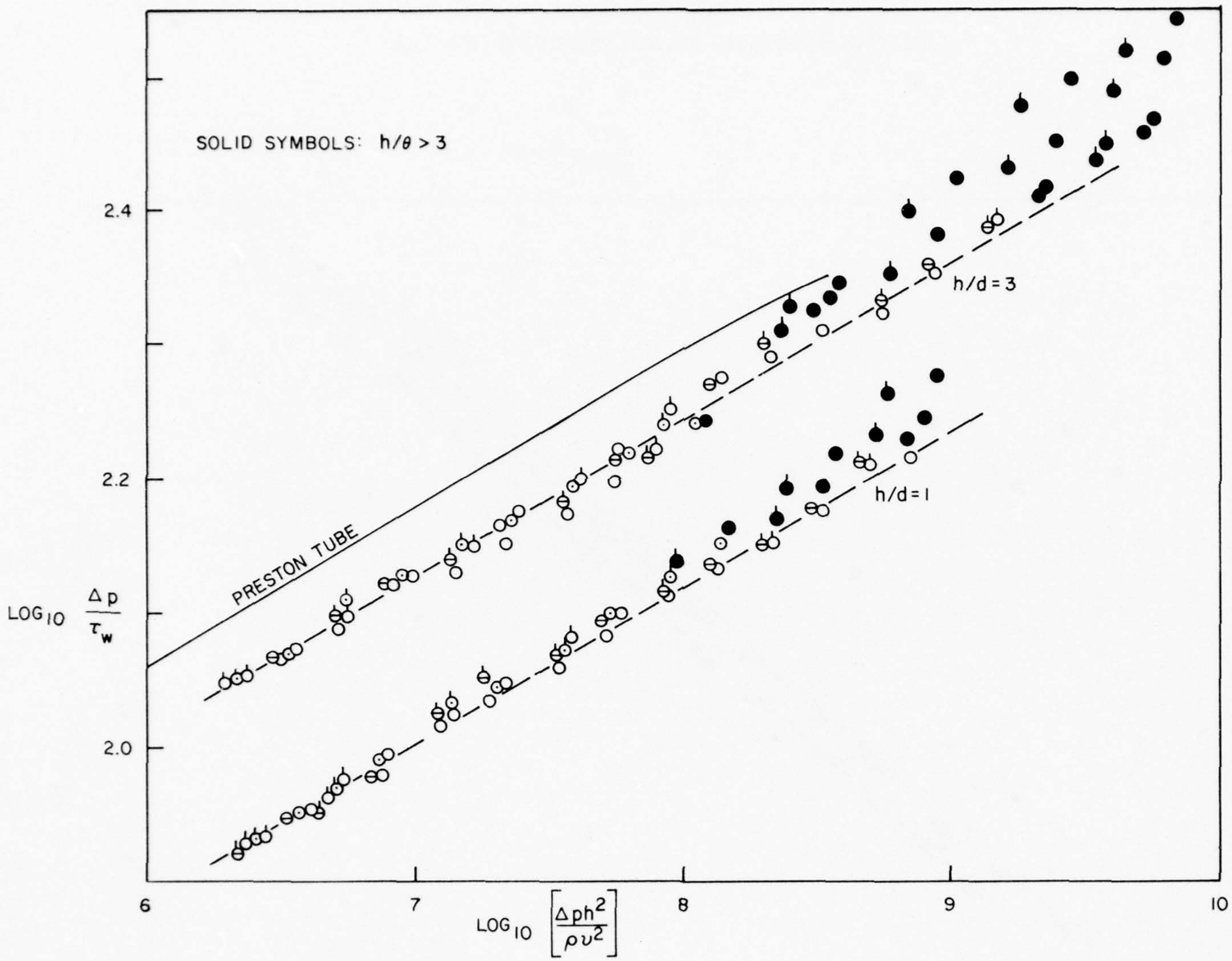



**FIG. 14: ALTERNATIVE PRESENTATION OF CALIBRATION**

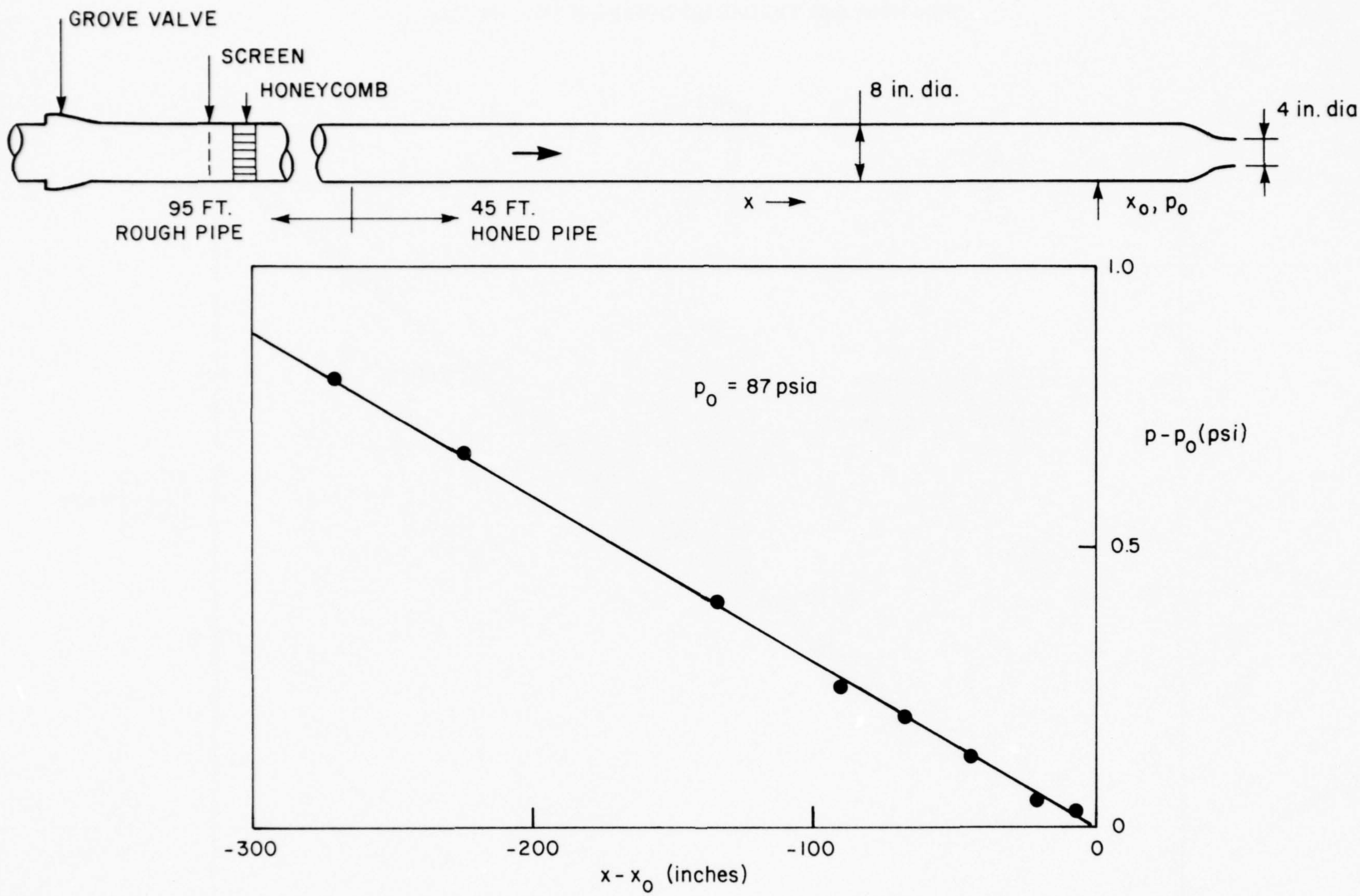



**FIG. 15: THE NAE 8-INCH PIPE FACILITY**

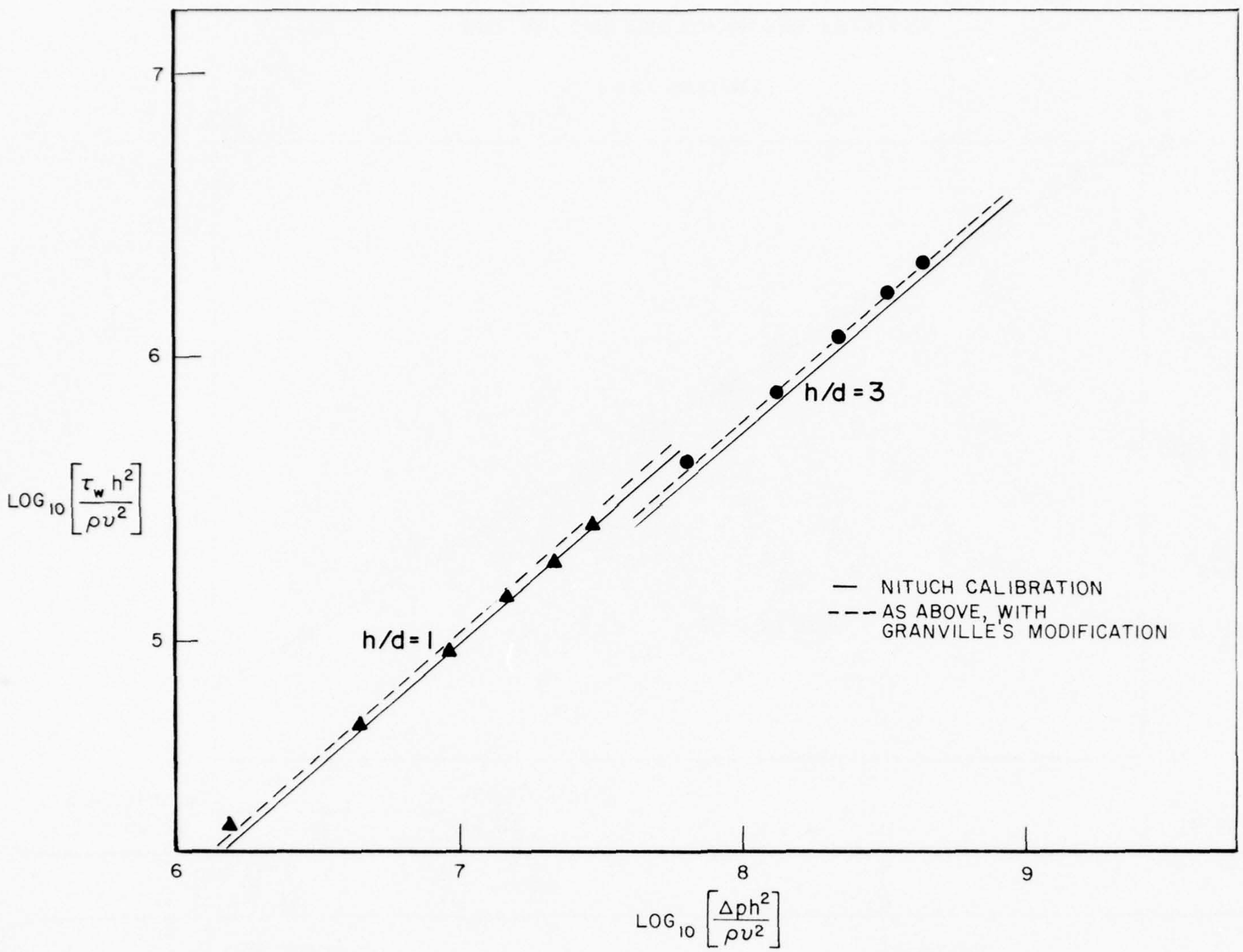



FIG. 16: CALIBRATION OF BLOCKS IN 8-INCH PIPE

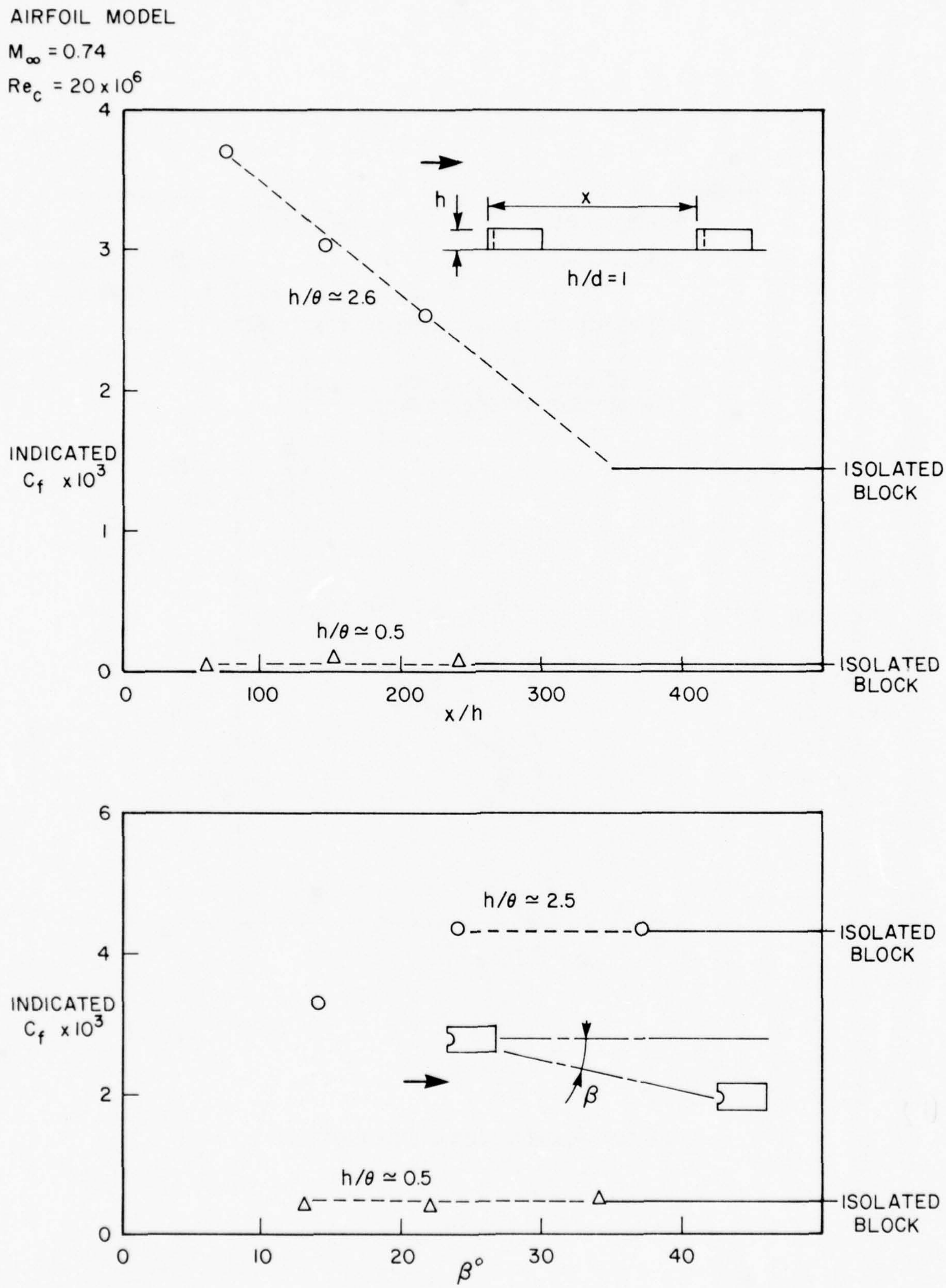



**FIG. 17: INTERFERENCE DUE TO UPSTREAM BLOCK**

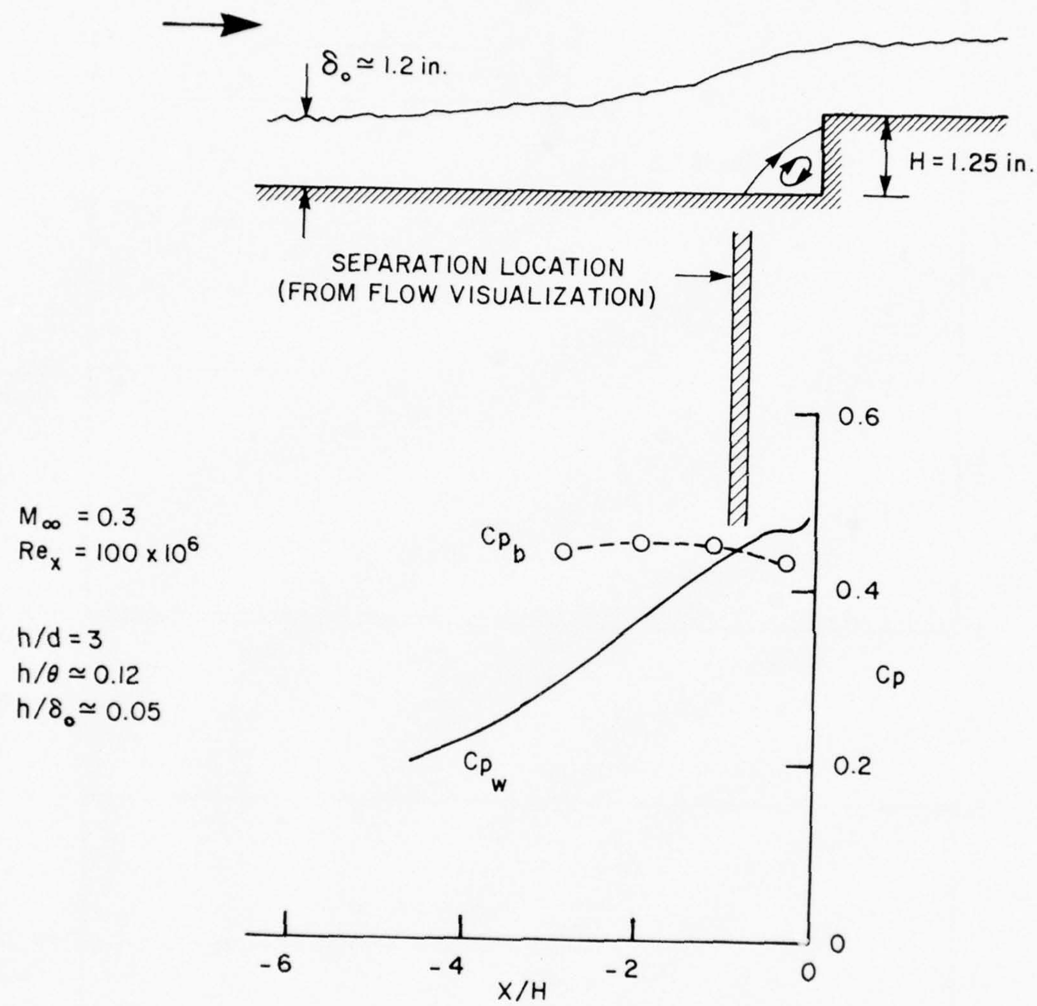



**FIG. 18: FLOW REVERSAL DETECTION**

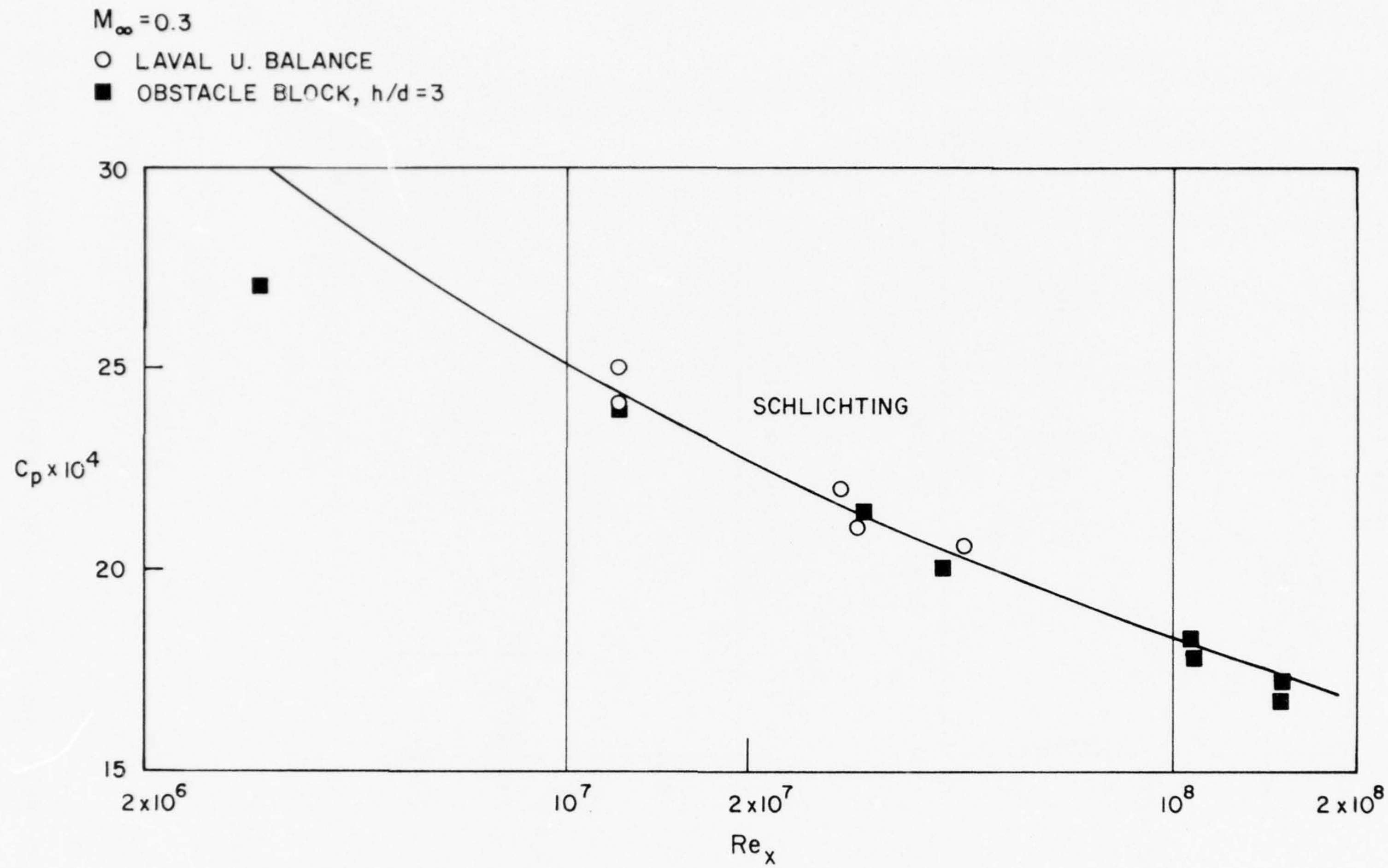



FIG. 19: MEASUREMENT OF SKIN FRICTION ON A FLAT PLATE

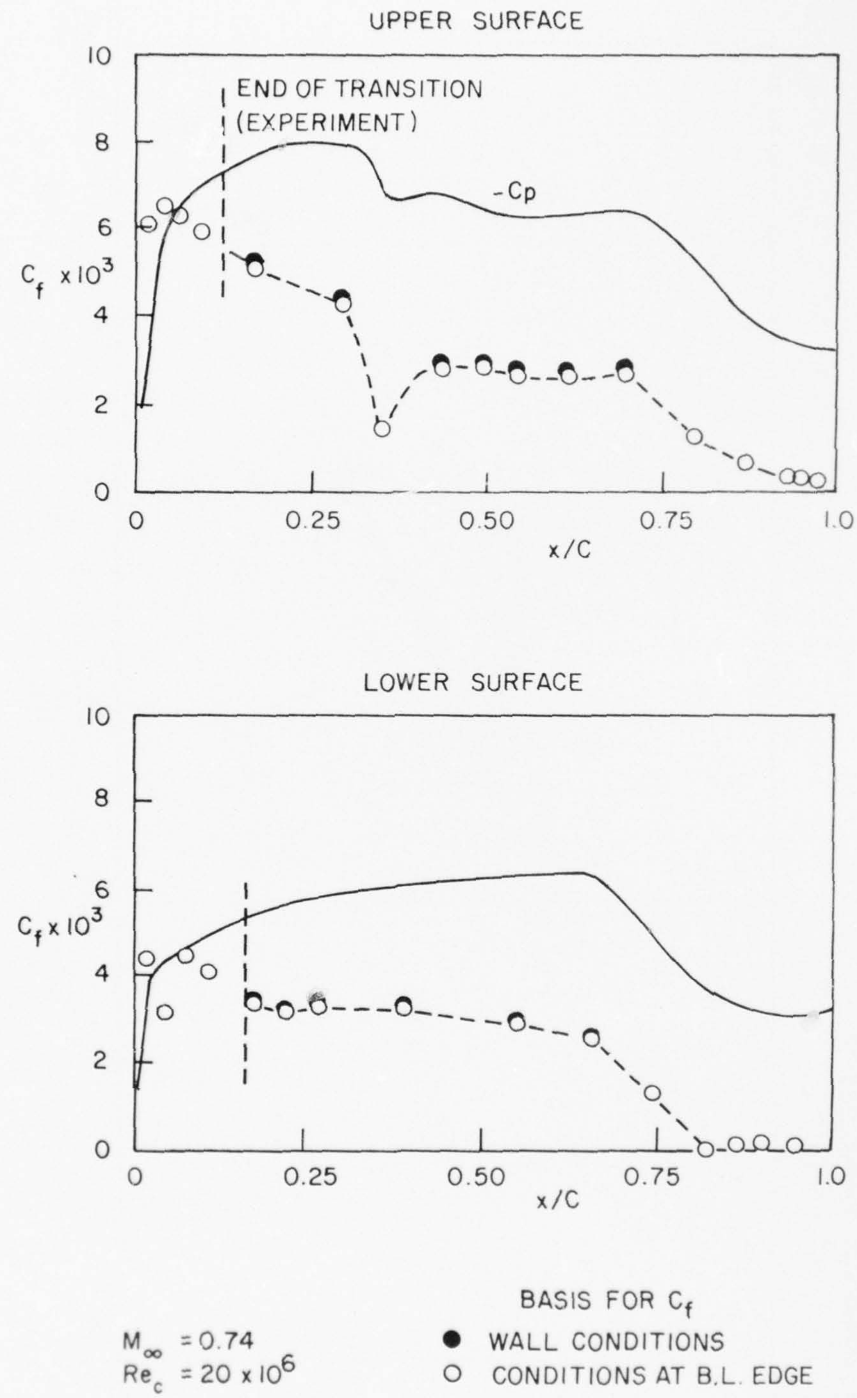
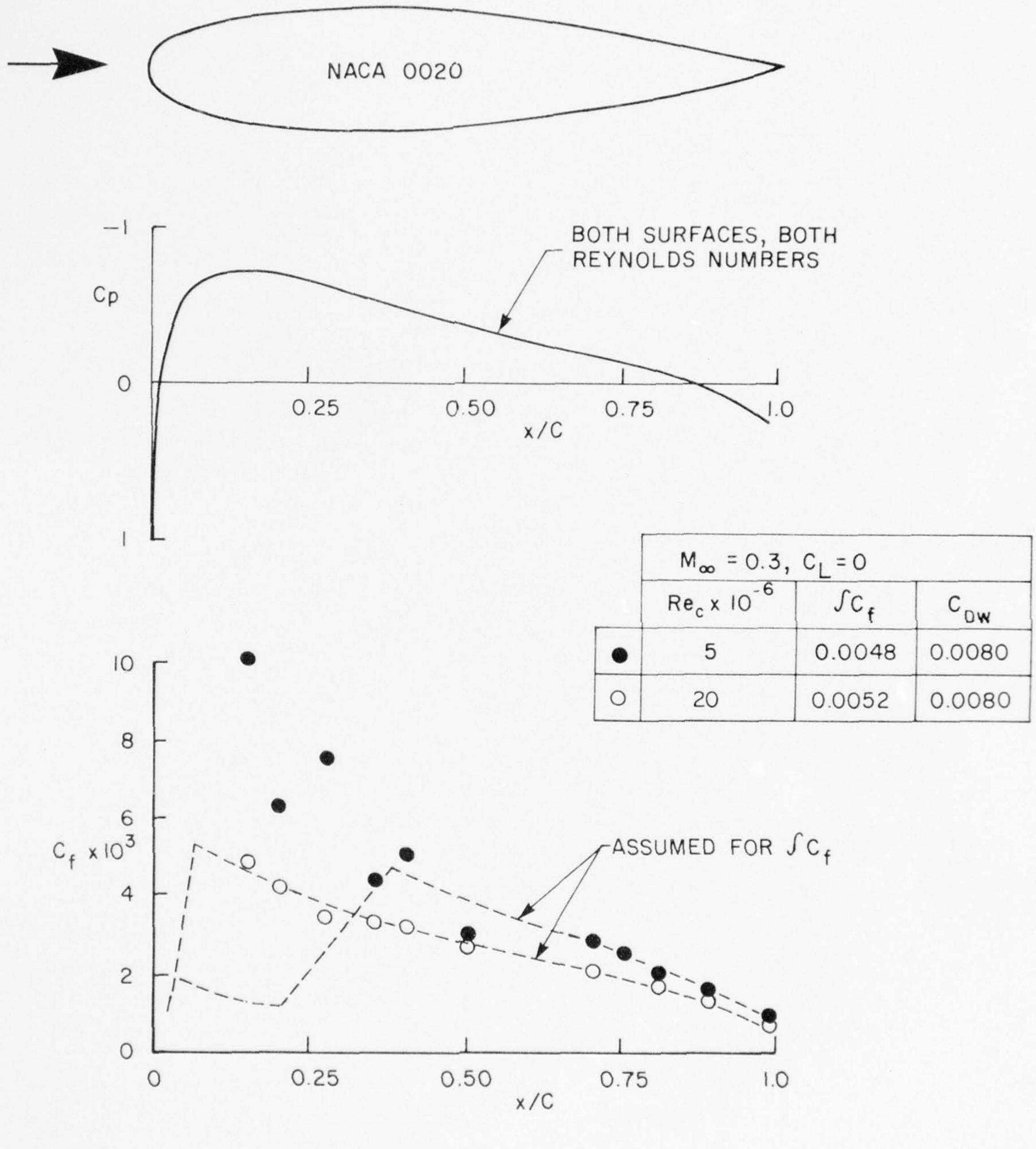



FIG. 20: SKIN FRICTION MEASUREMENTS ON A SUPERCRITICAL AIRFOIL




| $M_\infty = 0.3$, $C_L = 0$ | | | |
|---|---|---|---|
| | $Re_c \times 10^{-6}$ | $\int C_f$ | $C_{DW}$ |
| ● | 5 | 0.0048 | 0.0080 |
| ○ | 20 | 0.0052 | 0.0080 |

FIG. 21: SKIN FRICTION MEASUREMENTS ON A LOW SPEED AIRFOIL

## CURRENT PROJECTS

Much of the work in progress in the laboratories of the National Aeronautical Establishment and the Division of Mechanical Engineering includes calibrations, routine analyses and the testing of proprietary products; in addition, a substantial volume of the work is devoted to applied research or investigations carried out under contract and on behalf of private industrial companies.

None of this work is reported in the following pages.

# ANALYSIS LABORATORY

## AVAILABLE FACILITIES

This laboratory has analysis and simulation facilities available on an open-shop basis. Enquiries are especially encouraged from industry for projects that may utilize the facilities in a novel and/or particularly effective manner. Such projects are given priority and are fully supported with assistance from laboratory personnel. The facilities are especially suited to system design studies and scientific data processing. Information is available upon request.

## EQUIPMENT

An Electronic Associates 690 HYBRID COMPUTER consisting of the following:

(a) PACER 100 digital computer

- 32K memory
- card reader
- high speed printer
- disc
- digital plotter
- Lektromedia interactive terminal

(b) Two EAI 680 analogue computer consoles

- 200 amplifiers including 60 integrators
- 100 digitally set attenuators
- non-linear elements
- x-y pen recorders
- strip chart recorders
- large screen oscilloscope

(c) EAI 693 interface

- 24 digital-to-analogue converters
- 48 analogue-to-digital converters
- interrupts, sense lines, control lines

## GENERAL STUDIES

A microprocessor-based function generator for the hybrid computer is being designed. A TI 9900 development system has been obtained to be used for the project.

A study is being made on the use of topological methods to describe and analyze complex systems.

## APPLICATION STUDIES

In collaboration with Aviation Electric Ltd., modeling work is continuing in support of their advanced control concepts for both the small business jet engine and the helicopter engine. At present, the detailed model of a twin engine helicopter is being used for checkout of a prototype microprocessor-based fuel controller.

In collaboration with Canadian Westinghouse Ltd., a study is being made of the fuel controller requirements for a new family of industrial gas turbines. A hybrid computer model is being used to evaluate control system hardware.

In collaboration with Kendall Consultants Ltd., and SPAR Aerospace Products Ltd., a hybrid computer model of the remote manipulator arm for the space shuttle is being assembled. The model includes all allowable motions in three dimensions as well as arm flexibility effects. The three dimensional model is complete and arm control algorithms are being evaluated.

In collaboration with the Railway Laboratory, a pilot hybrid computer model of the NRC roller rig for railway vehicle testing is being used as an aid in the design of the roller rig and its controls.

In collaboration with the Control Systems and Human Engineering Laboratory and the International Nickel Co., Ontario Division, an interactive computer model of a copper-nickel smelter is being developed to study material handling and scheduling in the plant.

In collaboration with Engine Laboratory a study is being made to develop a computer model of air cushion vehicles.

In collaboration with Northern Telecom Ltd., an interactive computer program is being developed to schedule orders on cable stranding machines.

In collaboration with R.L. Crain Ltd., the interactive program for computer-aided paint shop scheduling is being extended to examine alternative order streaming and press allocation strategies. Further program development is underway with a view to incorporating the scheduling programs in the company's computer system.

In co-operation with Carleton University and Engine Laboratory a preliminary study is underway of a heavy equipment propulsion system using a co-rotating compressor.

In co-operation with Concordia University, a model of a heavy railroad freight vehicle is being assembled. Simulations of vehicle response to periodic and random excitations are to be conducted.

In collaboration with Stephens-Adamson of Belleville a hybrid computer model of long conveyor belts is being assembled.

In collaboration with Davis Eryou and Associates a hybrid computer model of an automobile is being assembled.

A joint project with ARCTEC Canada and Davis Eryou and Associates for reduction and analysis of oceanographic and ice breaking ship trials data is being carried out on the hybrid computer.

A hybrid computer model of high voltage impulse measuring systems is being developed by the Power Engineering Laboratory of the Division of Electrical Engineering.

A joint project with Low Speed Aerodynamics Laboratory and Davis Eryou and Associates for reduction and analysis of truck aerodynamic data is being carried out on the hybrid computer.

**SYSTEM SOFTWARE STUDIES**

A preprocessor for hybrid computer model digital programs.

Character string manipulation routines to be used in a Fortran environment.

# CONTROL SYSTEMS AND HUMAN ENGINEERING LABORATORY

## INDUSTRIAL CONTROL PROBLEMS

In collaboration with the Analysis Laboratory interactive computer models are being developed and applied to a variety of scheduling and materials handling projects in the mining and metal processing industries.

Application of microprocessors to improve quality, performance and efficiency in the appliance manufacturing industry is currently being undertaken in collaboration with a Canadian company. A microprocessor based dishwasher using state-of-the-art electronics and sensors has been designed.

To study distributed process control a network software system (DECNET) is being installed to connect together the PDP-11/45 and PDP-11/60 computers in the Laboratory. Also, a serial communication system based on the HDLC line protocol is being implemented with microprocessors. This activity is proceeding in parallel with the development of an international standard for industrial intersubsystem communication.

A flowmeter, viscometer, consistency sensor and control valve utilizing radial laminar flow have been developed and patented. The devices, currently under test for industrial application, are mechanically simple and have a minimum of machining tolerances. They offer significant advantages over those currently available in that the maintenance of laminar flow provides quiet operation while allowing accurate performance production.

## ADVANCED TRANSPORTATION CONCEPTS

The conceptual design for a high speed intercity magnetically levitated and linear synchronous motor propelled vehicle plus elevated guideway system as based on the results of a basic Maglev research program jointly conducted by Queen's University, University of Toronto and McGill University has been carried out in collaboration with Transport Canada. Ongoing study includes computer modeling for ride quality assessment, vehicle dynamic behaviour prediction and engineering design consideration of the magnets.

## HUMAN ENGINEERING – BEHAVIOURAL STUDIES

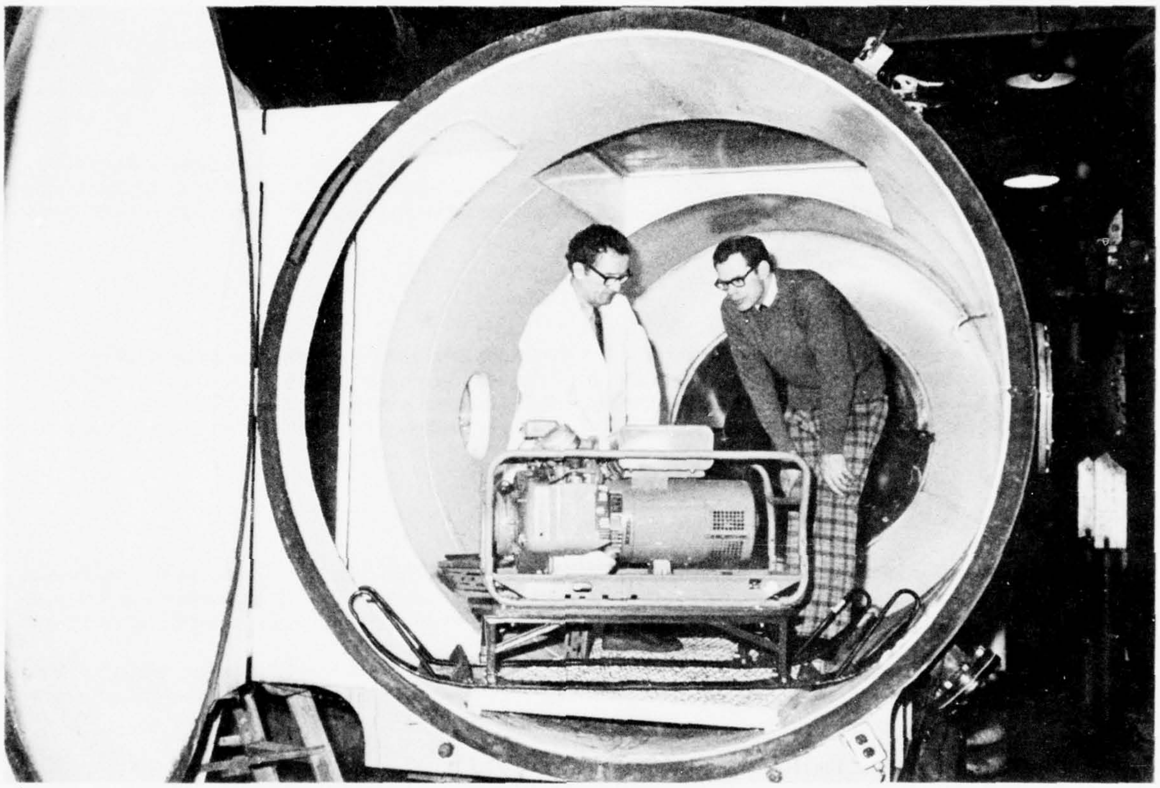
The investigation of the effect of internal and external environments on human psychomotor performance has been extended to Ministry of Transport radio communications staff operating in the high Arctic under conditions of continuous darkness. A study is also being conducted in collaboration with Indian Air Force on the psychomotor performance of aircrew on long range flights.

Another tracking experiment has been designed and initiated in the series dealing with precision of movement to a target. This is a further test of the hypothesis that subjects move in a frame of reference based on proprioceptive rather than visual information.

## HUMAN ENGINEERING – MEDICAL AND SURGICAL

A prototype model portable thermoelectric cooling system has been built in collaboration with the Montreal Neurological Institute for controlled cooling of the exposed spinal cord at operation.

Tests have been conducted on an experimental model of a miniature instrument for measuring the viscoelastic properties of skin.



GENERATOR-SET IN LOW-PRESSURE CHAMBER

GENERATOR-SET IN LOW-PRESSURE CHAMBER, BEING PREPARED FOR RUNNING AT SIMULATED HIGH ALTITUDE. THE GENERATOR WAS REQUIRED AS A POWER SOURCE BY THE GLACIOLOGY DEPARTMENT (ENVIRONMENT CANADA) FOR RUNNING EQUIPMENT USED TO MAKE MEASUREMENTS ON HIGH MOUNTAIN GLACIERS.

ENGINE LABORATORY

DIVISION OF MECHANICAL ENGINEERING

# ENGINE LABORATORY

## HOSPITAL AIR BED

The laboratory is continuing the support and direction of clinical hospital tests and evaluation of the air bed principle. The objectives of the clinical investigation are to study the effectiveness of the air bed, and the comfort provided by it, in the treatment of burns. The effects of reduced shear and support pressure, and a carefully conditioned micro-climate on wound healing are being studied in particular.

A special experimental air bed, the NRC Cairbed Mark I, was designed and built by NRC to allow a hospital in Kingston, Ontario to conduct a funded clinical study with the support of bio-medical engineering help from Queen's University.

The project has been highly successful with respect to demonstrating considerable advantage over other more conventional support methods, and to better defining the performance requirements necessary for improving epithelium thickness recovery. A new concept of support air bag structure was tested with complete success.

Arrangements are underway to have four of a more advanced air bed type, the Mark II Cairbed version, manufactured under contract. The Mark II beds will feature performance optima and will have the realness of commercial products. Clinical evaluations of these prototypes are being planned in order to demonstrate both performance and usefulness, and in order to verify the design.

## GAS TURBINE OPERATIONS

Investigative tests on a J85-CAN-15 gas turbine engine continued. Further refinements to the automatic data acquisition system have been carried out, enabling the collection of selective engine parameters in the steady-state and rapid transient modes. Test results can be obtained in form of printouts, time plots, and cross-plots.

## GAS TURBINE ICING INVESTIGATIONS

An icing program was carried out on an MHI aircraft engine nacelle, housing a Pratt & Whitney Aircraft of Canada JT15D turbofan engine. The installation incorporated an air ejector which enabled simulated flight velocities of up to 430 mph (740 km/h). The test icing environments were super-cooled water droplets and natural snow.

## AEROACOUSTICS

A study of the noise characteristics of centrifugal fans and blowers is in progress. The experiments to study the effect of impeller blade shape and casing geometry on the aerodynamic performance and noise generation are being carried out in a 5-horsepower fan test rig.

Methods are being developed to compute the propagating modes in ducts by measurements of sound pressure level around the circumference of the duct using cross spectral density and phase locked methods.

## ENGINE COOLING SYSTEM PERFORMANCE

Automobile engine cooling is normally a shared effort between the engine cooling fan and the ram air associated with forward speed. The full potential of the cooling fan is being studied in detail because the normal relative contributions of both these factors do not represent a fuel conservation optimum.

The study, which is being made in collaboration with Canadian industry, with support from Transport Canada, will involve full scale vehicle tests both on the road and in the NRC wind tunnels.

## AIR CUSHION VEHICLES

The main parts of the test rig for studying vertical instability in ACVs have been delivered, and fitting-out is proceeding. The large blower for this work has been calibrated to obtain the slope of the constant speed lines, which is vital to the study of the heave instability.

Design work has started on a mobile test rig for studies on the use of air cushions for the transport of very heavy concentrated loads.

A model is almost complete for an urgent program on the drag and stability of low-speed A.C. rafts over water. Experiments will commence in a Hydraulics Laboratory flume in the near future.

## AUTOMOTIVE FUEL ECONOMY

The second series of tests has just ended in Toronto. Runs are being analyzed.

## NRC–PRATT & WHITNEY HIGHLY LOADED TURBINE

The propane combustor used for pre-heating the air to the turbine inlet has been tested and found to be a completely satisfactory method of controlling inlet temperature. Some minor modifications had to be made to the mixing chamber to obtain a homogeneous mixture before distribution to the turbine inlet. Insulation is now being installed over the entry section.

The turbine nozzles and rotor disk are expected to be installed shortly and then final pressure distribution checks can be made.

## ROTOR DYNAMICS

The rotor dynamics test rig has undergone initial testing using a simple rotor supported in rolling element bearings. Laboratory-generated computer programs to predict critical speeds and mode shapes of the test shafts have been revised and improved for easier comparison with the experimental rotors and the initial tests have shown good agreement between experimental and computer predictions. Work is currently aimed at the acquisition of a fluid film bearing analytical capability, see below. In co-operation with a Canadian manufacturer a critical speed investigation of a pump/motor system has been completed recently.

## HYDROSTATIC BEARINGS

This laboratory continues to provide assistance and design service to other potential gas and fluid film bearing users both within NRC and in other government laboratories. In co-operation with three Canadian industrial firms a study is underway to compare the predicted results of computer programs designed to calculate the dynamic performance of self-acting bearings with incompressible lubricants. A recently completed literature survey has provided a broad cross-section of example bearings.

## VIBRATION MONITORING

An experimental rig has been assembled to allow the testing of rolling element bearings to failure. This rig is now being used to compare current methods of vibration detection and their ability to discover incipient faults in rolling element bearings. Because of the nature of fault generation in rolling element bearings the result gathering process is of a rather long-term nature.

A co-operative program with the Defence Research Establishment (Pacific) in Victoria will look at the combined merits of oil analysis and vibration monitoring as tools for helicopter transmission gear box monitoring.

This laboratory continues to provide vibration measurement and analysis assistance to both industry and government.

## FUEL CONTROL SYSTEMS

As the major Canadian manufacturer of fuel control systems for gas turbines in the general aviation market, Aviation Electric Limited of Montreal has developed an advanced concept digital fuel control system that was verified on a computer model of a gas turbine at the NRC. To prove the hardware of the system on a real engine, a co-operative program with AEL will use a Twin-Pac helicopter engine on a dynamometer to enable a steady-state and transient performance assessment to be made.

# FLIGHT RESEARCH LABORATORY

## AIRBORNE MAGNETICS PROGRAM

Experimental and theoretical studies relating to the further development of airborne magnetometer and gradiometer equipment and the application of same to submarine detection and geological survey, are currently in progress. The final report on methods of magnetic aircraft compensation, based on data collected with the North Star aircraft, has been published. A Convair 580 aircraft has been equipped as a multi-purpose flying laboratory for research in aeromagmetic detection and for development of radio and inertial navigation methods. Further modifications may be done to provide a capability for evaluating advanced synthetic aperture radar techniques.

## INVESTIGATION OF PROBLEMS ASSOCIATED WITH STOL AND V/STOL AIRCRAFT OPERATIONS

The Laboratory's Airborne V/STOL Simulator is being employed in programs to investigate STOL and V/STOL aircraft flying qualities and terminal area operational problems. Areas of research include a general investigation of flight path control and stability characteristics required to compensate for single engine failure in twin or multi-engine powered-lift aircraft, and the identification of minimum acceptable flying qualities for civil helicopters operating under instrument flight rules.

## INVESTIGATION OF ATMOSPHERIC TURBULENCE

A T-33 aircraft, equipped to measure wind gust velocities, air temperature, wind speed, and other parameters of interest in turbulence research, is used for measurements at very low altitude, in clear air above the tropopause, in the neighbourhood of mountain wave activity, and near storms. Records are obtained on magnetic tape to facilitate data analysis. The aircraft also participates in co-operative experiments with other research agencies, in particular, the Summer Cumulus Investigation (see below). A second T-33 aircraft is used in a supporting role for these and other projects.

## AIRCRAFT OPERATIONS

The Flight Recorder Playback Centre is engaged in the recovery and analysis of information from the various flight data recorders and cockpit voice recorders used on Canadian military and civil transport aircraft. The military systems are being monitored on a routine basis. Civil aircraft recorders are being replayed to investigate incidents or accidents at the request of the Ministry of Transport. Technical assistance is being provided during incident and accident investigations and relevant aircraft operational problems studied.

## INDUSTRIAL ASSISTANCE

Assistance is given to aircraft manufacturers and other companies requiring the use of specialized flight test equipment or techniques.

## INVESTIGATION OF SPRAY DROPLET RELEASE FROM AIRCRAFT

Theoretical and experimental studies of spray droplet formation from a high speed rotating disc have been conducted. Flight experiments utilize a Harvard aircraft modified to carry external spray tanks. Automatic flying spot droplet and particle analysis equipment is in operation for processing samples obtained in the laboratory and in the field by various agencies. The equipment has potentialities for the analysis of many unusual configurations provided that these may be photographed with sufficient contrast.

## AUTOMOBILE CRASH DETECTOR

There is a need for a sensing device to activate automobile passenger restraint systems in incipient crash situations. Investigations are in progress to determine the applicability of C.P.I. technology to this problem.

## SUMMER CUMULUS INVESTIGATION

At the request of the Department of the Environment flight studies of Cumulus cloud formations over Quebec and Ontario were instituted during the Summer of 1974. Instrumented T-33 and Twin Otter aircraft with a Beech 18 are being used to determine the properties of Cumulus clouds which extend appreciably above the freezing level. The measurements are being made to assess the feasibility of inducing precipitation over forest fire areas by seeding large cumulus formations. During 1975 a variety of cloud physics instruments were added to the Twin Otter, and special pods for burning silver iodide flares were attached beneath the wing of the T-33 turbulence research aircraft. The effects of seeding on the microstructure of individual cumulus clouds were studied in the Yellowknife area during the summers of 1975 and 1976 and in Thunder Bay in 1977 and 1978. This project is planned to continue for several years.

# FUELS AND LUBRICANTS LABORATORY

## COMBUSTION RESEARCH

Investigation of handling and combustion problems involved in using hydrogen as a fuel for mobile prime movers.

Co-operative studies with Advisory Group for Aerospace Research and Development (AGARD) Working Group 11 to produce a report on aircraft fire safety.

Biogas as an alternate fuel in engine operation.

## EXTENSION AND DEVELOPMENT OF LABORATORY EVALUATION

Development of new laboratory procedures for the determination of the load carrying capacity of hypoid gear oils under high speed conditions and under low speed high torque conditions.

Evaluation of filter/coalescer elements for aviation turbine fuels.

Evaluation of longlife filter/coalescer elements from aviation turbine fuel service.

Water separation characteristics of aviation turbine fuels.

## PERFORMANCE ASPECTS OF FUELS, OILS, GREASES, AND BRAKE FLUID

Investigation of laboratory methods for predicting flow properties of engine and gear oils under low temperature operating conditions.

Evaluation of static dissipator additives for distillate fuels.

Evaluation of properties of re-refined oils and by-product sludges.

Road test of re-refined automotive oils (co-operation with Environment Canada).

Investigation of the use of anti-icing additive in aviation gasoline.

Investigation of hydrogen content as a means of estimating the combustion characteristics of aviation turbine fuels.

## MISCELLANEOUS STUDIES

The preparation and cataloguing of infra-red spectra of compounds related to fuels, lubricants, and associated products.

The application of Atomic Absorption spectroscopy to the determination of metals in petroleum products.

Investigation of the stability of highly compressed fuel gases.

Analytical techniques for analysis of engine exhaust emissions.

Participation in the Canadian (CGSB), American (ASTM) and International (ISO) bodies to develop standards for petroleum products and lubricants.

The design and development of an internal combustion engine/hydraulic transmission hybrid power plant for the energy conserving car.

Further developments of specialized pressure transducers for engine health diagnosis and the development of diagnostic techniques and consultation with licencee in developing production methods for patented transducers.

Evaluation of various products, fuels, lubricants and hardware in respect of their effects upon overall vehicle fuel economy and energy conservation properties.

# GAS DYNAMICS LABORATORY

## V/STOL PROPULSION SYSTEMS

A general study of V/STOL propulsion system methods with particular reference to requirements of economy and safety.

## INTERNAL AERODYNAMICS OF DUCTS, DIFFUSERS AND NOZZLES

An experimental study of the internal aerodynamics of ducts, bends, diffusers and nozzles with particular reference to the effect of entry flow distortion is geometries involving changes of cross-sectional area, shape, and axial direction.

## SHOCK PRODUCED PLASMA STUDIES

A general theoretical and experimental investigation of the production of high temperature plasma by means of shock waves generated by electromagnetic and gas dynamic means, and the development of diagnostic techniques suitable for a variety of shock geometries and the study of physical properties of such plasmas.

## NON-DESTRUCTIVE SURFACE FLAW DETECTION IN HOT STEEL BILLETS

A flaw detection system for metal bars is being tested. Eight inductive bridge circuits, spaced around the bar and sequentially sampled, detect the flaw through a change in coil inductance. The system lends itself to easy elimination of stand-off and eccentricity errors and is currently being adapted to industrial use. Interpretation of test results via microprocessors is in hand. A rugged, heat-resistant circuit is being designed for in-plant application.

## HIGH PRESSURE LIQUID JETS

High speed water jets generated by pressures in the range of 1000 to 60,000 psi can be used for cutting a wide variety of materials, e.g. paper, lumber, plastics, meat, leather, rock, etc., and for cleaning surfaces such as masonry, tubular heat exchangers, etc. Nozzle sizes, depending on the application, are in the range from 0.002 to 0.15 in. diameter. A technique for manufacturing small nozzles in the range 0.002 to 0.015 has been developed using standard sapphire jewels available from industry. Larger orifices are manufactured and polished using standard shop procedures.

At present, the following investigations are active in the laboratory:

1. Drilling of rocks of various types, including granite, using a high pressure rotating seal and single and dual orifice nozzles specially developed for this purpose.

2. Study of the effects produced by cavitating jets, how best to produce them and where they may be usefully applied.

3. Experiments on the application of colliding jets.

4. Collaborative experimental work, in collaboration with the Low Temperature Laboratory, on the breaking and cutting of ice.

## HEAT TRANSFER STUDIES

An investigation of methods of increasing boiling and condensing heat transfer coefficients by treatment of the heat transfer surface is in progress.

A co-operative project with the Division of Building Research will determine the usefulness of the thermosiphon as a ground heat source for a heat pump.

Experiments continue on the use of steam as a heating method for soldering tubing to thin sheet, as in flat plate solar collectors.

An inexpensive, leakproof heat exchanger has been developed for use in solar energy systems. Fabrication is simple and it is suitable for production in small batches.

Work has started on a new type of temperature control thermosiphon. Previous types have been designed to control the temperature of a heat source; this design controls the temperature of a heat sink.

## COMPUTATIONAL FLUID DYNAMICS

Numerical simulations are carried out in connection with projects initiated internally or as collaborations with outside organizations. At present the field of greatest interest concerns the problems of absorption of laser energy by plasmas and three topics are currently being pursued:

1. A study of the mechanism of re-entry waves occurring when beam intensity is reduced below the level at which laser-supported detonation can exist.
2. Absorption of laser energy by hydrogen plasma confined by a magnetic field (laser heated solenoid).
3. A study of the fluid mechanics accompanying continuous discharge of laser energy into a spot fixed in space.
4. Laser-initiation of a high-density Z-pinch.

## GAS TURBINE BLADING STUDIES

A program on the theoretical and experimental study of the performance of highly loaded gas turbine blading has been undertaken as a collaborative program with industry and universities.

## INDUSTRIAL PROCESS, APPARATUS, AND INSTRUMENTATION

There is an appreciable effort, on a continuing basis, directed towards industrial assistance. This work is of an extremely varied nature and, in general, requires the special facilities and capabilities available in the laboratory.

Current and recent co-operative projects with manufacturers and users include:

(a) Flow problems associated with industrial gas turbine exhaust systems (Foster Wheeler).
(b) Combustion studies for industrial gas turbine applications (Westinghouse and Rolls-Royce).
(c) Application of thermosiphon as an energy conserving device in industrial applications (Dept. of Agriculture, Ministry of Transport, Farinon Electric, Chromalox Canada Ltd).
(d) Scaled model studies on steel and copper converters to establish relative performance and ceramic liner deterioration rates (Canadian Liquid Air and Noranda).
(e) High pressure water jet applications in industry (High Pressure Systems Ltd.).
(f) Scaled model studies to establish the performance of complex industrial flue systems with a view to establishing specific design and performance criteria. (Noranda and Inco Canada Ltd.).
(g) Model studies of internal flows in reactor hood and waste heat boiler (Noranda and Kennecott Copper Corp.).
(h) Altitude test chamber for small gas turbines (Pratt & Whitney Aircraft of Canada Ltd.).
(i) Experimental study of a novel fan design (Rolls-Royce).

# HIGH SPEED AERODYNAMICS LABORATORY

## CALIBRATION OF THE SUBSONIC AND TRANSONIC TEST SECTIONS OF THE 5-FT. × 5-FT. BLOWDOWN WIND TUNNEL

Further measurements that were referred to in Q.B. 1978 (4) were made in February and March 1979.

Static pressure measurements were made on the centre lines of the test section by use of a 4-in. diameter static pressure probe equipped with an internal scanivalve. Pressures were obtained at 2-in. intervals over a length of 6 ft. In addition, for the transonic test section the pressure distributions near the perforated floor and ceiling were also obtained from long static-pressure tubes that were fixed there. The static pressure probe also carried a hot-wire at its tip, mounted about 5.25 in. ahead of the vortex of the parabolic nose.

Results show that, for a 40-in. length ahead of the centre-of-rotation of the model support, small positive pressure gradients exist on the centre line. These have a tendency to decrease with increasing Mach number for the transonic test section and the gradient is almost zero at M = 1. For the subsonic test section the gradients are higher (typically $\frac{dC_p}{dx} = 0.0005$ per in.).

The pressure gradient along the floor and ceiling of the transonic test section are virtually zero.

The hot-wire measurements indicate a minimum value in ($\rho v$) fluctuations of about 0.5% of free-stream at M = 0.5 in the transonic test section. At lower and higher Mach numbers there is some increase e.g. to 0.6% at both M 0.3 and 0.8.

These results reflect a considerable improvement as a result of replacing the seven settling chamber screens. Some measurements that were made in 1977 with only three original screens left in the settling chamber revealed turbulence levels of more than 1% in the transonic test section for $0.4 \leq M \leq 0.7$.

The subsonic test section exhibits very slightly less turbulence than the transonic test section for the Mach number range $0.3 \leq M \leq 0.75$.

## DATA SYSTEM IMPROVEMENTS ON 5-FT. X 5-FT. WIND TUNNEL

Modernizing and upgrading of the data system on the 5-ft. tunnel has been progressing slowly towards the new PDP 11/55 system under RSX11-M.

New amplifiers have been installed, increasing the number of channels available to 40 of high quality and 40 of lower quality. These amplifiers have gains ranging from 1 to 5000 and switchable front end filters with cutoffs from 3 Hz to 10 kHz. Self-checking remote calibration and remote switch readouts are built in and will be used when the new system is installed, early 1979.

At that time, improved direct digital I/10 will be installed (for "status" type information) and a table-driven external multiple condition interrupt system should unload the processor significantly. This in turn should make possible on-line data reduction, which will be only partly available initially. Work is now proceeding on an A/D system based on 3, 15-bit, 180 kHz A/D converter with a 96 channel multiplexer. Interfacing between the A/D system and I/D controllers is nearing completion and operation up to 200 kHz has been demonstrated. Plans are proceeding for installation during a springtime servicing period. As part of the upgrading, a remote site capability will also be available at that time.

Software has been developed for "on-line" plotting of aerodynamic coefficients, such as $C_p(X/C)$, $C_L(\alpha)$, $C_D(C_L)$, $C_L/C_D(\alpha)$ etc.

## TRANSONIC EQUIVALENCE RULE INVOLVING LIFT

The classical area rule is well known and its application to wing-body design and drag reduction is demonstrated on many existing aircraft. Recent advances in transonic aerodynamic theroy show that the classical area rule requires a modification to account for lift. A series of experiments is being prepared in order to investigate these new concepts. The results of these experimental studies will provide criteria for wing-body design with emphasis on drag reduction for aircraft cruising at transonic speeds.

## TWO-DIMENSIONAL TRANSONIC FLOW STUDIES

The 2-D wall correction method of Mokry has been extended to determine the upper and lower wall porosities which will give the best agreement between theoretical and experimental wall pressures for each scan. These optimum porosities are then used to determine the Mach number and angle of attack corrections. A new finite difference method has been developed, which allows for variable porosity along the upper or lower walls. Some improvements in the theoretical model are thus expected since inflow and outflow along the same wall can now be accounted for.

**Supplementary Investigation of the BGK No. 1 Airfoil**

Earlier NAE investigations of this airfoil have been supplemented with measurements of wall boundary conditions. The "static rails" normally used were replaced by "static tubes" that extended through the whole 2-D section into the inlet contraction. In addition, measurements were made of the boundary layer on the floor and ceiling. Various wall porosity schemes were investigated. Also, recovery and model temperature were recorded to determine if significant heat transfer effects were present during the early part of a run. From the analyzed data it is concluded that the new "static tubes" are an improvement over the old "rails". They will thus be part of the standard set-up for future 2-D tests. The temperature results showed that, in spite of a rather pronounced transient during start-up, there is no significant heat transfer during the normal data phase of a run.

## STUDIES OF WING BUFFETING

A theoretical study of the transient response of a wing to non-stationary buffet loads is in progress. Various forms of the power spectral density of the aerodynamic loading on the wing have been considered for a number of load versus time history during buffet manoeuvres. A wind tunnel investigation of the surface pressure and normal force fluctuations associated with buffeting has been carried out on the BGK No. 1 airfoil.

## REYNOLDS NUMBER EFFECTS ON TWO-DIMENSIONAL AEROFOILS WITH MECHANICAL HIGH LIFT DEVICES

Under a joint NRC/de Havilland enterprise administered under the PILP program andextensive set of low speed aerodynamic measurements were made in the 2-D insert in the period September 26 – November 30, 1978, on a multi-component aerofoil model.

During the first phase of the work several trailing-edge flap geometries (with and without a leading-edge slat) were optimized at a chord Reynolds number of $6 \times 10^6$; subsequently their performance at lower and high Reynolds numbers were checked.

In a second phase of tests with this aerofoil some boundary layer measurements were made near the trailing-edge of the main element, utilizing a new boundary-layer traversing rig. These latter measurements were primarily directed at checkout of the traversing rig in its simplest form, with the objective of developing reliable gear for more extensive boundary layer measurements on high lift multi-component aerofoils in the near future.

Work on an iterative solution of the compressible boundary layer flows about multi-element airfoil is continuing at the University of Manitoba.

## HOLE ERROR INVESTIGATION

An experimental study has been completed, in collaboration with Professor J.C. Menneron, of the University of Sherbrooke, of the effect of orifice size on the measurement of pressure on the surface of an aerofoil at subsonic free-stream velocities. Speeds up to M = 0.7 and chord Reynolds number from $6 \times 10^6$ to $33 \times 10^6$ were used. Orifice diameters range from 0.006 in. to 0.016 in. Analysis of the data clearly indicates that the value of the chordwise force coefficient, obtained by integration of the surface pressure, consistently increases with the size of the orifice. The effect is rather more pronounced at M = 0.5 and 0.7 than at M = 0.3.

## MEASUREMENT OF SKIN FRICTION ON TWO-DIMENSIONAL AIRFOILS IN SUBSONIC FLOW

A summary of the measurements using obstacle blocks is included in this issue as an article.

## SUPERCRITICAL AIRFOIL DEVELOPMENT

Under an on-going joint NAE–de Havilland program, two 16% thick airfoil designs have been tested in the NAE 15-in. × 60-in. test facility, and their performance compared. The second airfoil, which incorporated design improvements over the first, generally displayed drag values which were higher than those observed for the first. A complete analysis of this investigation was presented in March 1979, at the Atlantic Aeronautical Conference in Williamsburg, Va.

## TESTS FOR OUTSIDE ORGANIZATIONS

**SAAB-Scania, Sweden.**

Tests were conducted at transonic and supersonic Mach numbers on a series of schematic aircraft models.

# HYDRAULICS LABORATORY

## ST. LAWRENCE SHIP CHANNEL

Under the sponsorship of the Ministry of Transport, a study to improve navigation along the St. Lawrence River, using hydraulic and numerical modeling techniques.

## NUMERICAL SIMULATION OF RIVER AND ESTUARY SYSTEMS

Mathematical models have been developed to simulate tidal propagation in estuaries, wave refraction in shallow water and littoral drift processes. The feasibility of using array processors to solve the hydrodynamic equations is presently under study.

## WAVE FORCES ON OFF-SHORE STRUCTURES

Wave flume study to determine design criteria for off-shore structures, such as cooling water intakes or outfalls, mooring dolphins, drilling rigs, etc.

## RANDOM WAVE GENERATION

A study of random waves generated in a laboratory wave flume by signals from a computer. Special attention is paid to the simulation of wave groups.

## STABILITY OF RUBBLE MOUND BREAKWATERS

A flume study for the Department of Public Works to determine stability coefficients of armour units and the effect of a number of wave parameters on the stability of rubble mound breakwaters, including the effect of wave grouping.

## WAVE LOADS ON CAISSON TYPE BREAKWATERS

A flume study for the Department of Public Works to determine the overall loading, as well as the pressure distribution on various Caisson-type breakwaters.

## WAVE POWER AS AN ENERGY SOURCE

A general study to assess the wave power available around Canada's coast and to evaluate various proposed schemes to extract this energy. International co-operation is taking place through the International Energy Agency of OECD.

## MOTIONS OF LARGE FLOATING STRUCTURES, MOORED IN SHALLOW WATER

A mathematical and hydraulic modeling program will be carried out to develop techniques and methods to forecast motions of, and mooring forces on large structures moored in shallow water.

## CALIBRATION OF FLOW MEASURING DEVICES

Facilities to calibrate various types of low meters up to a maximum capacity of 5,000 gpm are regularly used for/or by private industry and other government departments.

## OSHAWA HARBOUR MODEL STUDY

A hydraulic model study for Public Works, Canada of Oshawa Harbour on Lake Ontario, to investigate changes in the layout of the present breakwaters to reduce the level of wave agitation inside the harbour basin.

## TRANSPORT OF SAND ON BEACHES

A method has been developed for calculating rates of sand transport in the presence of waves, a modification of the Ackers and White method for river flows. A new flume was recently constructed in which the method can be tested.

## LOW HEAD WATER TURBINES

A research program has been started to investigate the feasibility of extracting power from water currents, by using low head turbines.

## HYBRID MODELING TECHNIQUES USING ARRAY PROCESSORS

Estuaries where tidal power can be developed require the use of large physical models of the area. The laboratory has demonstrated that a "hybrid model" can dynamically couple together a mathematical model to the physical model at the boundaries, therefore the physical model need not be very large in extent. An array processor will be used to realize the mathematical portion of the hybrid model.

# LOW SPEED AERODYNAMICS LABORATORY

## WIND TUNNEL OPERATIONS

The three major wind tunnels of the laboratory are: the 15-ft. diameter open jet vertical tunnel, the 6-ft. × 9-ft. closed jet horizontal tunnel, and the 30-ft. V/STOL tunnel. During the quarter, a number of test programs were carried out for groups both within and outside of the government. Within the government, test programs included studies on building aerodynamics and ship-hull flow visualization. Studies for non-government groups included the aerodynamics of a road vehicle, an aircraft, a building, a vertical-axis wind turbine, an aircraft insecticide spray-boom system and downhill skiers.

Work continues on the contract for the new data acquisition, reduction and control system for the 6-ft. × 9-ft. wind tunnel. Final installation at the site will take place in April 1979.

## WIND ENGINEERING

In collaboration with the Division of Building Research, an aerodynamic investigation of Commerce Court, Toronto is being undertaken. The purpose is to obtain wind tunnel comparisons with full-scale measurements of surface pressures and building movements. An aeroelastic model has been designed and constructed. Dynamic calibration of the model will be carried out in preparation for wind tunnel tests in June 1979.

A series of six 1:10 scale truck models are being designed and constructed to continue NRC's program in truck energy conservation through aerodynamic drag reduction and in support of a joint NRC/Transport Canada – DOT/SAE (U.S.A.) wind tunnel testing program.

A comparison between road measurement of fuel savings and wind tunnel predictions has been performed for large highway trucks. The work was sponsored by Transport Canada and carried out by Davis Eryou and Associates in collaboration with NRC.

Measurements of wind properties are being continued on the Lions' Gate Bridge, Vancouver as part of an aerodynamic investigation of the bridge. Outputs from five anemometers and two accelerometers that measure bridge motion are recorded by an automated system. Site assistance is being provided by Buckland and Taylor Limited, Vancouver.

An investigation into the aerodynamic stability of an ore conveyer bridge was completed in the 15-ft. vertical wind tunnel using a 1:12 scale sectional model. The proposed suspension bridge will cross the Similkameen river valley and will be 1350 ft. between towers. A program of wind measurements is underway at the site. The work is being done for Buckland and Taylor Ltd., Vancouv Canada.

A study of street level winds in the downtown core of the City of Ottawa is underway. The first phase will establish a probability distribution of the existing wind climate and the second phase will be the simulation of the wind conditions using a 1:400 scale model in the NAE 30-ft. × 30-ft. wind tunnel. The study is jointly sponsored by the City of Ottawa, the Department of Public Works, the National Capital Commission and the National Aeronautical Establishment. A contract for the construction of remote wind sensing units has been let and a PDP 11/03 micro system has been received.

An investigation was conducted in the 30-ft. × 30-ft. wind tunnel for the Department of Energy, Mines and Resources on a 4.3-ft. diameter tethered spherical balloon to be used as a marker for aircraft in an Arctic survey. Measurements of the forced in the tether and observations of the balloon motion were made.

A 1:8.1 scale model of an airborne towed target and miss-indicator was constructed and wind tunnel tested in the 3-ft. wind tunnel for the Department of National Defence, the object being to diagnose the cause of and devise modifications to eliminate severe instability of the target on the end of its towing cable. The tests were successfully completed.

## FLUIDICS

Co-operative studies with D.G. Instruments of a 3-axis velocity sensor are continuing using both NRC and industry developed concepts. Studies of vortex excitation of velocity sensor probes have been carried out in co-operation with Fluidynamics Devices Ltd. A program of applications of laminar flow in thin passages is being carried out in co-operation with the Control Systems and Human Engineering Laboratory of DME.

## VERTICAL AXIS WIND TURBINE

In July, the rotor of the 230-kw demonstration wind turbine on the Magdalen Islands collapsed while the drive train was undergoing maintenance. An investigation of the causes of the accident has uncovered no basic flaw in its design or construction and a decision has been made to rebuild it. Two 50-kw plants are now in operation, directly connected to local power networks in Newfoundland and Saskatchewan.

**AERIAL SPRAYING OF PESTICIDES**

A new spray boom, designed in co-operation with CONAIR Aviation Ltd., has been used on the spraying operations in Newfoundland, this past summer. The performance of the new boom configuration is satisfactory with regard to both aerodynamic drag, and spray characteristics. It was the opinion of DC-6 flight crews that the aircraft performance with streamline booms installed was essentially that of the clean aircraft, and that a saving of 400 hp was realized at a flight speed of 185 kts.

Research into the behaviour of spray droplets emitted into the aircraft vortex wake is continuing. A wind tunnel model of a Grumman Avenger has been tested with spraying from various parts along the span.

# LOW TEMPERATURE LABORATORY

## THERMAL PROTECTION OF TRACK SWITCHES

The use of heat to eliminate switch failures from snow and ice is a standard approach to this problem. Work has been carried out on improving the efficiency of forced convection combustion heaters and the means of distributing heat to the critical areas of a switch.

## HORIZONTAL AIR CURTAIN SWITCH PROTECTOR

A non-thermal method of protecting a switch from failure due to snow has been undergoing development and evaluation. This method consists of high velocity horizontal air curtains designed to prevent the deposit of snow in critical areas of a switch. The tests conducted to date are especially encouraging with respect to yards and terminals. Additional evaluation is required for the line service application.

## NEW RAILWAY SWITCH DEVELOPMENT

The ultimate solution to the existing problem of snow and ice failure of the point switch would appear to be replacement by a new design that is not subject to failure in this way. A switch has been designed, fabricated, laboratory tested and has now completed one winter season of field trials. The design involves only shear loading from snow and ice.

## MISCELLANEOUS ICING INVESTIGATIONS

Analytical and experimental investigations of a non-routine nature, and the investigation of certain aspects of icing simulation and measurement.

## TRAWLER ICING

In collaboration with Department of Transport, an investigation of the icing of fishing trawlers and other vessels under conditions of freezing sea spray, and of methods of combatting the problem.

## AIRBORNE SNOW CONCENTRATION

To provide statistical data on the airborne mass concentration of falling snow in order to define suitable design and qualification criteria for flight through snow, measurements of concentration and related meteorological parameters are being made.

## SEA ICE DYNAMICS

Analytical and experimental work on the techniques of forming low-strength ice from saline solutions is being carried out in connection with proposed modeling studies of icebreaking ships and arctic port facilities.

An investigation is being made into the modeling of sea ice based on the freezing of aqueous solutions. The objective of the investigation is to improve the dynamic similarity in model testing in simulated sea ice.

## LOCOMOTIVE TRACTION MOTORS

An investigation into the failure of locomotive traction motor support bearings due to winter service has been undertaken. The presence of moisture either as water or ice in the oil reservoirs is suspected to be a contributing cause of the failures.

## HIGH PRESSURE CUTTING OF ICE

Experimental work is being carried out in collaboration with Gas Dynamics personnel on the cutting of ice with high pressure water jets. One phase of this work has been concerned with the removal of ice from a substrate such as concrete. The other work on ice cutting has been for possible application to ice breaking ships.

# MARINE DYNAMICS AND SHIP LABORATORY

## HIGH SPEED CRAFT

Several models in a systematic series have been studied and others are being prepared to determine their performance in still water and in waves.

## COMBINATION FISHING VESSEL

Model tests have been completed on a new design of 70 ft. West Coast combination salmon and herring fishing vessel.

The basic hydrodynamic efficiency of the design was investigated through resistance and self-propulsion experiments in calm water and studies were made of the performance of the vessel and its safety against capsize in waves. These experiments were carried out in the 130 m. X 65 m. X 3.5 m. seakeeping and manoeuvring basin using a radio-controlled free-running model.

## 65 FT. EAST COAST FISHING VESSEL

The laboratory is currently investigating whether increase in the beam of small fishing vessels, which has advantages for deck working, leads to any deterioration in seakeeping qualities.

Beam wave rolling experiments, both with and without passive anti-rolling tank stabilization, have been completed. Empirical coefficients obtained from these model experiments are being used to continue the study with the laboratory's five degrees of freedom ship motion program.

## SWATH MANOEUVRING INVESTIGATION

The laboratory is currently building a model of a Small Waterplane Area Twin Hull (SWATH) vessel for an investigation into the effect of the positioning of the rudders on the vessel's manoeuvrability.

## LOCK MODEL STUDY – EXTENSION

The second series of model tests for the St. Lawrence Seaway Authority into the effect of vessel size and lock geometry on lock transit times in the Welland Canal has been completed. These studies are in direct support of a prototype marine shunter trials program.

The marine shunters are small tugs which would attach to the bow and stern of vessels and provide the motive power and control to manoeuvre them through the canal and locks. The experiment data would allow the Authority to extrapolate from full scale trials data and predict the value of the marine shunter concept for a much wider range of vessel size and type than it is practical to test full scale.

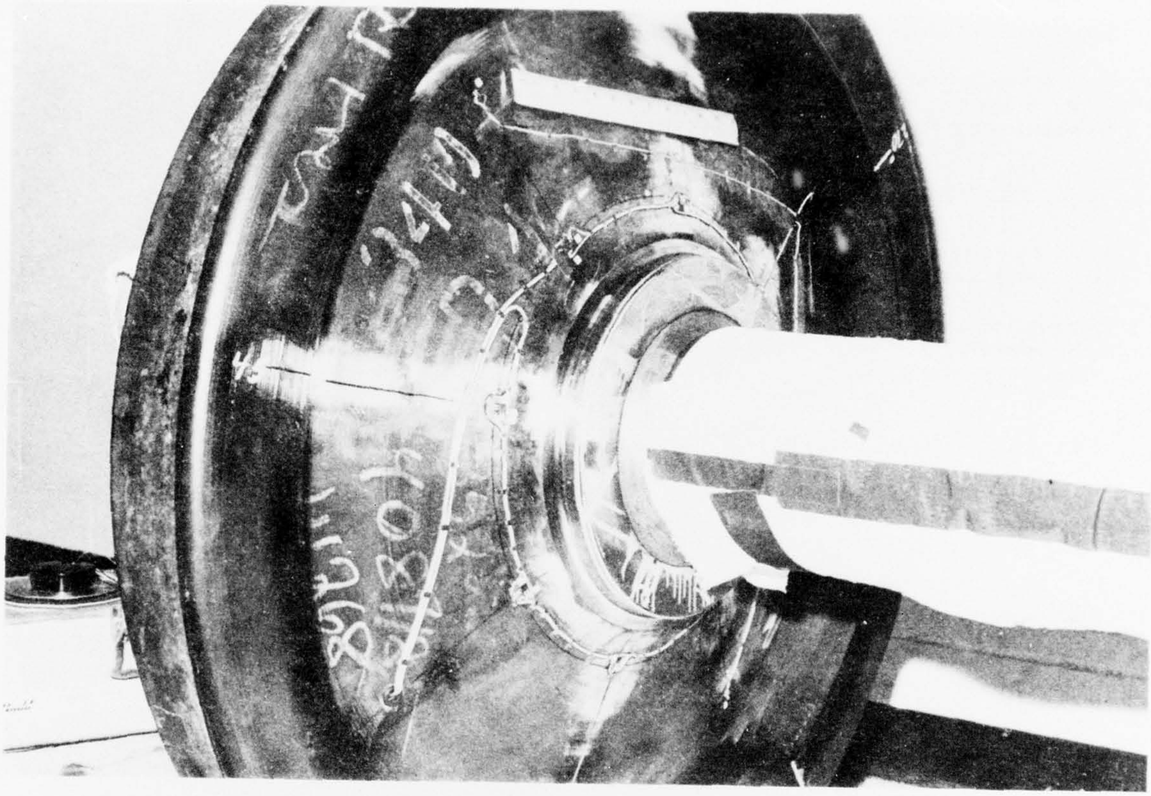
## ANTI-PITCHING

Reduction of ship motions is of major importance in the design of small fast warships. While roll stabilization is common, it is generally believed that pitch stabilization is not practical because of the large forces involved.

The laboratory is engaged in experiments in which hydrofoil technology is being applied to anti-pitching fins. In a first series two models, fitted with fins, have been run in calm water to determine the forces and moments acting for a range of attitudes of the hull.

## M.V. "ARCTIC"

The laboratory will shortly be participating in dedicated icebreaking trials aboard the M.V. Arctic. This is Canada's first icebreaking bulk cargo vessel and has been built to meet the Arctic Waters Pollution Prevention Regulations as a Class 2 ship. The laboratory has advised in the design and installation of a sophisticated data system with which the vessel has been equipped to measure ice loadings, using 160 strain gauges mounted on the hull, as well as ship motions and propulsion parameters. The data from these trials should be extremely valuable for the design of future Arctic bulk carriers.



INSTRUMENTED LOCOMOTIVE WHEELSET NEAR COMPLETION

THE CONTINUOUS OUTPUT LATERAL FORCE BRIDGE CONSISTS OF THE EIGHT 90° ROSETTE GAUGES SEEN ENCIRCLING THE WHEEL HUB, THE TWO REMAINING GAUGES (5 AND 10 O'CLOCK POSITION) FORM PART OF THE SAMPLED OUTPUT VERTICAL FORCE BRIDGE.

# RAILWAY LABORATORY

## LABORATORY FACILITIES FOR RAILWAY RESEARCH

The curve position control lever system design for the track simulator has been modified to increase its rigidity. Details of the revised design and the construction of these lever arms will be carried forward by our Manufacturing and Technology Centre. A temporary power hookup for the 150 hp and 50 hp motors is being set up in Building M-3 for tests of the track simulator differential drive gear units.

In collaboration with the Analysis Laboratory, work continues on a mathematical model of the curved track simulator. In particular, the wheel-roller interaction phenomenon is being studied.

Instrument Car 62 has been fitted with a floor to absorb longitudinal shocks, racks for instrumentation, and a work bench.

Lighting in certain work areas of our dynamics test building has been improved, and the cooling system for the hydraulic power supply for the rail car shaker system is almost complete. A contract has been let and work has started on lighting and power outlets for our new squeeze frame cover building.

## GENERAL INSTRUMENTATION

The Laboratory, in co-operation with the Marine Dynamics and Ship Laboratory, have built a micro-processor based ship's motion analyzer. Development of the digital programs for computation and control, including laboratory checks of the instrument, using field data, are presently being carried out by the Marine Dynamics and Ship Laboratory.

A non-contacting transducer is being developed to measure speed and displacement of ferro-magnetic surfaces by correlating two magnetic noise signals.

An instrumented locomotive wheelset for measuring vertical and lateral rail/wheel forces in service is being developed for Transport Canada Research and Development Centre. Strain gauging, wiring, and calibration of the vertical and lateral force bridges on each wheel have been completed. Spin tests and check out of the telemetry is under way.

## *TECHNICAL PHOTOGRAPHY*

Assistance was given to the Low Temperature and Gas Dynamics Laboratories and the National Aeronautical Establishment's research section using stills and high speed movies.

# STRUCTURES AND MATERIALS LABORATORY

## MOTOR VEHICLE SAFETY

In collaboration with the Road and Motor Vehicle Traffic Safety Branch of Transport Canada the second phase of the studies evaluating headlamp performance is underway. Attention is focussed on the determination of population characteristics of headlamps presently in use. Mean illuminance and glare quandrant values together with data describing the influence of dirt, aim and voltage for a large sample of vehicles are being analyzed within the previously defined system's concept.

## VIDEO PHOTOGRAMMETRY SYSTEM FOR REAL TIME THREE-DIMENSIONAL CONTROL

Potential applications for an NRC/NAE 30 Hz Video Photogrammetry System developed for three-dimensional machine control tasks are being examined. The system is based on the principle that knowledge of the centroid data for four targets on a rigid body permits the single camera photogrammetric solution to be solved for each video frame to determine the position and orientation of the body, in real time, for three-dimensional machine control. Initial applications will focus on remote manipulator systems.

## METALLIC MATERIALS

Structure-property relationships in aerospace alloys, including cast or wrought nickel and cobalt-base superalloys, high strength titanium and aluminum alloys. Studies on the consolidation and TMT processing of titanium and superalloy compacts by hot isostatic pressing, isothermal and superplastic forging, and extrusion. Studies on the mechanical properties of these materials. The mechanics of cold isostatic compaction of metal powders, and properties of hydrostatically extruded materials. Studies of the oxidation/hot corrosion behaviour of coated and uncoated refractory metals and superalloys.

## FRACTOGRAPHY AND FAILURE ANALYSIS

Utilization of transmission and scanning electron microscopes in the study of fracture surfaces, leading to the identification of the micromechanisms of fracture involved in the failure of structural components. From such information it is frequently possible to determine the causes of failures and to suggest remedial action.

## FATIGUE OF METALS

Studies of the basic fatigue characteristics of materials under constant and variable amplitude loading; fatigue tests on components to obtain basic design data; fatigue tests on components for validation of design; studies of the statistics of fatigue failures; development of techniques to simulate service fatigue loading.

## OPERATIONAL LOADS AND LIFE OF AIRCRAFT STRUCTURES

Instrumentation of aircraft for the measurement of flight loads and accelerations; fatigue life monitoring and analysis of load and acceleration spectra; full-scale fatigue testing of airframes and components. Non-destructive testing and damage tolerance evaluation.

## THEORY OF STRUCTURES

Studies of the application of finite element methods to structural problems. Assessment of commercially available computer programs for structural analysis. Calculation of stress-intensity factors for cracked three-dimensional bodies. Damage tolerance analysis.

## AEROACOUSTICS

Studies of aerospace-related acoustical problems with special reference to intense noise and its effect on structures. Evaluation of aerospace hardware in intense noise. Studies of jet exhaust noise, wind-tunnel noise, techniques for digital signal processing, enhancement of signals obscured by noise.

## FLIGHT IMPACT SIMULATOR

Simulator developed and calibrated to capability of accelerating a 4-lb. mass to a velocity of 1000 ft./sec., and an 8-lb. mass to a velocity of 760 ft./sec. Available to Canadian and Foreign manufacturers for certification of aircraft components and structures. Also used for fundamental studies of the impact process and evaluation of transparencies.

## CALIBRATION OF FORCE AND VIBRATION MEASURING DEVICES

Facilities available for the calibration of government, university, and industrial equipment include deadweight force standards up to 100,000 lb., dynamic calibration of vibration pick-ups in the frequency range 10 Hz to 2000 Hz.

## NON-METALLIC COMPOSITE MATERIALS

Studies of non-metallic composites including resins, cross-linking compounds, polymerization initiators, selection of matrices and reinforcements, application and fabrication procedures, material properties, and structural design.

## POLICE EQUIPMENT STANDARDS

The NRC/CACP Technical Liaison Committee on Police Equipment is a bilateral arrangement for bringing together police and government personnel to review police equipment requirements, equipment performance specifications, and conformance testing procedures. Work of the Committee is expedited by a permanent Secretariat which has a primary responsibility for continuity in the activities of a number of Sections, each dealing with a particular area of expertise, and for co-ordinating work and specialist contributions from various participating Departments and organizations.

# UNSTEADY AERODYNAMICS LABORATORY

## DYNAMIC STABILITY OF AIRCRAFT

Development of a forced-oscillation rolling apparatus.

Development of a translational-oscillation apparatus.

Vertical acceleration experiments.

Measurements of cross-coupling derivatives at high angles of attack.

Development of hydraulic drive systems for high-load oscillatory apparatuses.

## ATMOSPHERIC DISTRIBUTION OF POLLUTANTS

Instrumentation of a small mobile laboratory to measure airborne particulates and of an aircraft to detect atmospheric tracers.

Analysis of the downwind vertical spread and turbulent deposition of gaseous and aerosol pollutants from sources near the ground, with special emphasis on the effect of droplet evaporation.

## TRACE VAPOUR DETECTION

Development of highly sensitive gas chromatographic techniques for detection of trace quantities of vapours of pesticides, explosives and fluorocarbons.

Sensitivity evaluation of commercially available explosive detectors.

Development of stopped-flow and continuous-flow vapour concentrators.

Testing of biosensors.

Development and construction of a portable explosives vapour detector.

## WORK FOR OUTSIDE ORGANIZATIONS

Damping and cross-coupling experiments for NASA.

Feasibility and design studies for NASA.

Aircraft-security feasibility studies and development projects for Transport Canada.

Feasibility studies for DSMA, Toronto.

Experimental assistance to RCMP.

# WESTERN LABORATORY (VANCOUVER)

## PRACTICAL FRICTION AND WEAR STUDIES

Laboratory simulations of practical tribological systems to study friction, wear and lubrication behaviour of lubricants and bearing materials in response to specific external requests. For example, studies of methanol lubricity and wear in fuel pump gears with methanol as the working fluid are in progress.

## FUNDAMENTAL STUDIES IN TRIBOLOGY

A special rolling contact apparatus is being built that will allow experimental studies of rail and wheel wear, and lubrication to be made in the laboratory.

## LUBRICANTS

Physical testing for load capacity, wear mitigation, etc. of both a solid and several types of liquid lubricants has been carried out at the request of local industry and utility organizations.

A Ferrograph has been obtained and commissioned to provide the capability to separate and identify wear particles from used oils and other liquid lubricants.

## INSTRUMENTATION

Digital counters, stepping motor controllers and a prototype 'tribometer' have been designed, built and tested for use on the new rail-wheel wear test rig now under construction. An instrumentation control and communication bus is also under development for use with this test rig as well as for general laboratory use.

An analogue/digital divider circuit is being designed and built to compute friction coefficients for the 'pin-on-disc' wear tester in the tribology laboratory.

A preliminary design study is being made for a computerized optical density measuring system for use as a microscope attachment for assessing relative wear particle concentrations in lubricants.

Vibration spectrum analyses are continuing on the methanol/fuel pump lubricity experiment in an effort to relate spectral changes to pump wear.

## NUMERICALLY CONTROLLED MACHINING

Technical assistance on this subject is being provided to firms and other institutions in Western Canada which are considering the purchase of numerically controlled machines to improve their production efficiency. Seminars are held to explain the fundamentals of numerical control and programming.

Use is being made of computer-assisted programming and punched-tape preparation as a means of reducing manual programming time for items requiring a large number of geometrical statements. Seminars are held to demonstrate the principles and features of this method of NC part programming. This technique is being used to assist new users of NC equipment to get their equipment quickly into production.

A preliminary design and feasibility study has been completed of an NC machine to cut the wooden plugs for the manufacture of moulds for fibreglass boats up to 80 ft. long. Also the design of a low cost NC machine for the wood cabinet making industry is being examined.

## APPROPRIATE TECHNOLOGY

The laboratory has recently been monitoring the progress of this new technological movement towards smaller scale, environmentally and socially appropriate decentralized industrial development. The laboratory is now undertaking one or two small projects on the development of appropriate but economic small scale products or processes. Enquiries regarding these developments and proposals for co-operative projects are welcomes.

## LOW TEMPERATURE TEST FACILITY

The refrigeration plant of the test facility has been replaced to increase its low temperature capacity to $-45°C$.

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* V.R.O. on study leave from University of Alberta, Dept. of Geography.

** University of Western Ontario.

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