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A SYSTEM TO MEASURE FLOW MOISTURE CONTENT IN HYPERSONIC WIND TUNNELS

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SUMMARY

This paper describes the technique and equipment used for obtaining data on the moisture content in two NASA Langley hypersonic wind tunnels. A detailed description of the sampling system and its operation is presented along with the moisture analyzer employed. The procedure used for converting dew point to parts of water per million by volume (ppmv) is included with graphs that show tunnel moisture content at various pressures.

INTRODUCTION

A system has been developed to accurately measure the moisture content of hypersonic free streams using a custom designed sampling system in conjunction with a sensitive, fast responding moisture analyzer. This method allows researchers to monitor tunnel moisture in real-time without using "grab" sample bottles that are easily contaminated and must be analyzed in a laboratory.

HISTORY

Langley researchers use laser based measurement techniques that require moisture level information in order to assess its impact on wind tunnel measurements. Rayleigh scattering measurements in the 0.5 Meter Quiet and Mach-6 High Reynolds Number tunnels indicated that some type of molecular clustering took place in the tunnel free stream and affected the Rayleigh signals. Water was considered the most likely cause. An investigation was subsequently initiated to measure moisture levels and identify sources. Preliminary measurements at the high pressure compressor station (4250 psi) using a pressurized chilled mirror (EG&G 300) and a coated crystal oscillator (Dupont/Ametek 5700) established moisture levels of 3 ppmv with fresh dryers to 10 ppmv just before the dryers were recyled. These levels were not considered high enough to be responsible for the clustering effects observed inside the wind tunnels. A system was then developed to allow direct measurement of the moisture present in the free stream of the tunnel test section. This paper describes the system developed to provide that information.

THE SAMPLING SYSTEM

A primary consideration when attempting to make any type of moisture measurement is to ensure that the sample delivered to the analyzer is not contaminated by either atmospheric leaks or water trapped on the interior surfaces of the sample line tubing. When making measurements in the ppm range, clean seamless stainless steel tubing with a minimum of fittings and voids is required. Regulators, valves, and pressure transducers can take days to dry out after being exposed to ambient moisture levels and were, therefore, installed downstream from the sensor whenever possible.

The moisture sampling system (see figure 1) used for hypersonic flows utilized either 316 or 304 stainless steel for sample lines, bulkhead feed-throughs into and out of the tunnel test section, couplings and tees, moisture sensor housing, flow sensor, and wetted surfaces of the pressure transducer. The sample pick-up and return lines were located in the tunnel test section with the return line several feet down-stream from the pick-up; both lines were away from the boundary layer and in the free stream flow. The sampling system was designed to allow the moisture analyzer to monitor the nitrogen purge gas moisture content as it was used to dry the lines so that tunnel operators could determine when the system was conditioned and ready for the introduction of the free stream.

During operation, the nitrogen (N_2) purge gas flows continuously through the system in the opposite direction of normal sample flow, preventing atmospheric contamination and keeping the sample lines dry until the moment a three way solenoid shuts off the N_2 purge (see figure 1). When the N_2 pressure starts to drop, the sample flow begins to enter the system, forcing the purge gas to reverse direction and exit the system, allowing the sensor to measure only the sample moisture. A by-pass system was included that provides 16 times more flow in the main sample lines than is passing through the sensor in order to assure that sufficient flow is present to remove the N_2 purge gas rapidly and provide a representative sample. A bidirectional flow meter was installed downstream in the sensor line to verify flow rate and direction in order to confirm whether purge gas or sample gas was being measured by the sensor. A pressure gage was also installed at this location to enable conversion from dew point to ppm. Data were recorded using the facility Neff 600 front end amplifier/multiplexer under Modcomp computer control.

THE MOISTURE ANALYZER

The selection of a moisture sensor and readout is not a simple task. It is necessary to consider response time, sensitivity, range, repeatability, sample flow rate tolerance, susceptibility to contamination and fouling, gas compatibility, dry down-time, pressure ratings and effects, temperature effects and overall accuracy, and ease of operation. Several techniques were evaluated for hypersonic applications. Chilled mirrors are too slow, especially at low moisture levels; capacitance based aluminum oxide hygrometers have poor repeatability and drift with temperature; electrolytic phosphorus pentoxide models are washed out by ambient moisture and also require accurate flow control; and infrared methods require long path lengths in addition to special tunnel windows and suffer from poor sensitivity at low pressure. Coated crystal oscillators have plenty of sensitivity, but are marginal in response time and ambient moisture will wash away the coating. However, one device has demonstrated capability for reliable moisture measurements in the hypersonic free-stream environment.

A silicon chip based sensor developed in the U.K. has some unique characterisitics that set it apart from the methods mentioned above. The model "DEWLUXE 20" manufactured by Moisture Control and Measurement Ltd. of Great Britain and distributed in North America by Stephens Analytical, utilizes a low-mass temperature-controlled sensor that can respond to a step change in moisture from 20,000 ppmv to 10 ppmv in less than 1 minute with a dew point sensitivity of 0.001 °C. The push purge (heat) feature allows the operator to "dry" the sensor at any time in a matter of seconds. Even though the overall dew point uncertainty is rather high (+/- 3 °C), it is partially offset by the fast response and sensitivity.

Prior to testing, the "DEWLUXE 20" was evaluated in a moisture lab using National Institute of Standards and Technology (NIST) calibrated standards. The results verified instrument accuracy and indicated that the response time was on the order of seconds for a dew point step change from 0 ° to -50 °C.

CONVERSION FROM DEW/FROST POINT TO PPMv

The "DEWLUXE 20" moisture analyzer measures the dew point above 0 °C and frost point below 0 °C. By definition, dew point is that unique temperature to which a gas must be cooled in order to be saturated with respect to its water content. Any further reduction in temperature will cause moisture to condense onto the water or ice; likewise, any increase in temperature will cause moisture to evaporate from the liquid or ice into the gas. This state of equilibrium can also be referred to as the saturation pressure. Because the partial pressure of the water vapor present in the gas is equal to the saturation pressure at dew point, then Dalton's Law of Partial Pressures allows the use of established Meteorological Tables to relate the water saturation pressure to the quantity of water in that gas if the total pressure of the gas is also known.

Dalton's Law of Partial Pressure states that the total pressure of a mixture of gases is equal to the sum of the partial pressures that each individual gas component would exert were it to occupy the entire volume by itself.

For water vapor: $P_{total} = P_{dry} + P_{water}$

For example: a frost point of -50 °C is measured in a vessel that has a total pressure of 100 PSIA (approximately 6895 millibars)

P_{total} = 6895 mb (sum total of the vapor pressures of all gases present)

P_{water} = .03935 mb (from the Meteorological Tables, the saturation pressure of water vapor over ice at -50 °C)

For parts per million by volume:

$$\text{ppmv} = \frac{\text{saturation pressure}}{\text{total pressure - saturation pressure}} \times 10^6$$

$$\text{ppmv} = \frac{.03935}{6894.7 - 0.03935} \times 10^6 = 5.7 \text{ ppmv}$$

TUNNEL MOISTURE LEVEL MEASUREMENT RESULTS

A series of moisture measurements were made at Langley's Mach-6 High Reynolds Number tunnel with a second series of measurements being made in the 0.5 Meter Quiet Tunnel. In both locations, dew/frost point and pressure data were taken under various tunnel conditions and converted to ppmv using the method described. As discussed earlier, a purge gas was used to condition all sample lines prior to taking moisture data. The results of the these tests are provided on the following graphs (figures 2 and 3). The increase in moisture content with a decrease in pressure may be the result of outgassing or possibly undetected leaks in the sampling system. The Swagelok style tubing connections used are more reliable for pressure seals than vacuum and will be replaced with welded helium checked fittings in all future low moisture, low pressure measurements. At any rate, the Rayleigh scattering anomaly was observed at high total pressures only.

CONCLUDING REMARKS

Measuring moisture levels in the 10 to 6,000 ppmv range in less than a minute in hypersonic flows has been made possible by using a carefully designed sampling system that incorporates a built-in method to purge moisture while monitoring the sample lines prior to measurement. This feature adds confidence to the measurement, an ingredient that had been elusive when using other techniques. The system operator can verify the moisture analyzers operation by observing its response to the changing moisture levels as the nitrogen purges ambient moisture from the lines before actual data runs are performed. The moisture analyzer selected, a British silicon based sensor (DEWLUXE 20), has the unique ability to respond to fast changing, low level moisture without drift due to temperature effects and hysteresis.

It is recommended that future systems incorporate welded fittings that have been leak tested at high vacuum in order to completely eliminate the possibility of atmospheric leaks at low pressures. Users should also be aware that while dew point is not affected by gas temperature, the equilibrium between the gas vapor and the surfaces it is in contact with is. As wall temperature rises, adsorbed surface moisture will evaporate into the gas at an increased rate, causing the overall moisture of the gas to increase.

In conclusion, measurements show that moisture levels in Langley's 0.5 Meter and Mach-6 High Reynolds Number tunnels are reasonably low and it is unlikely that moisture is the cause of the suspected molecular clustering. If researchers conclude that a reduction in these moisture levels are required, then extensive changes in tunnel operation would be needed, including not opening air supply lines to the atmosphere or allowing ambient moisture to enter the test section at any time.

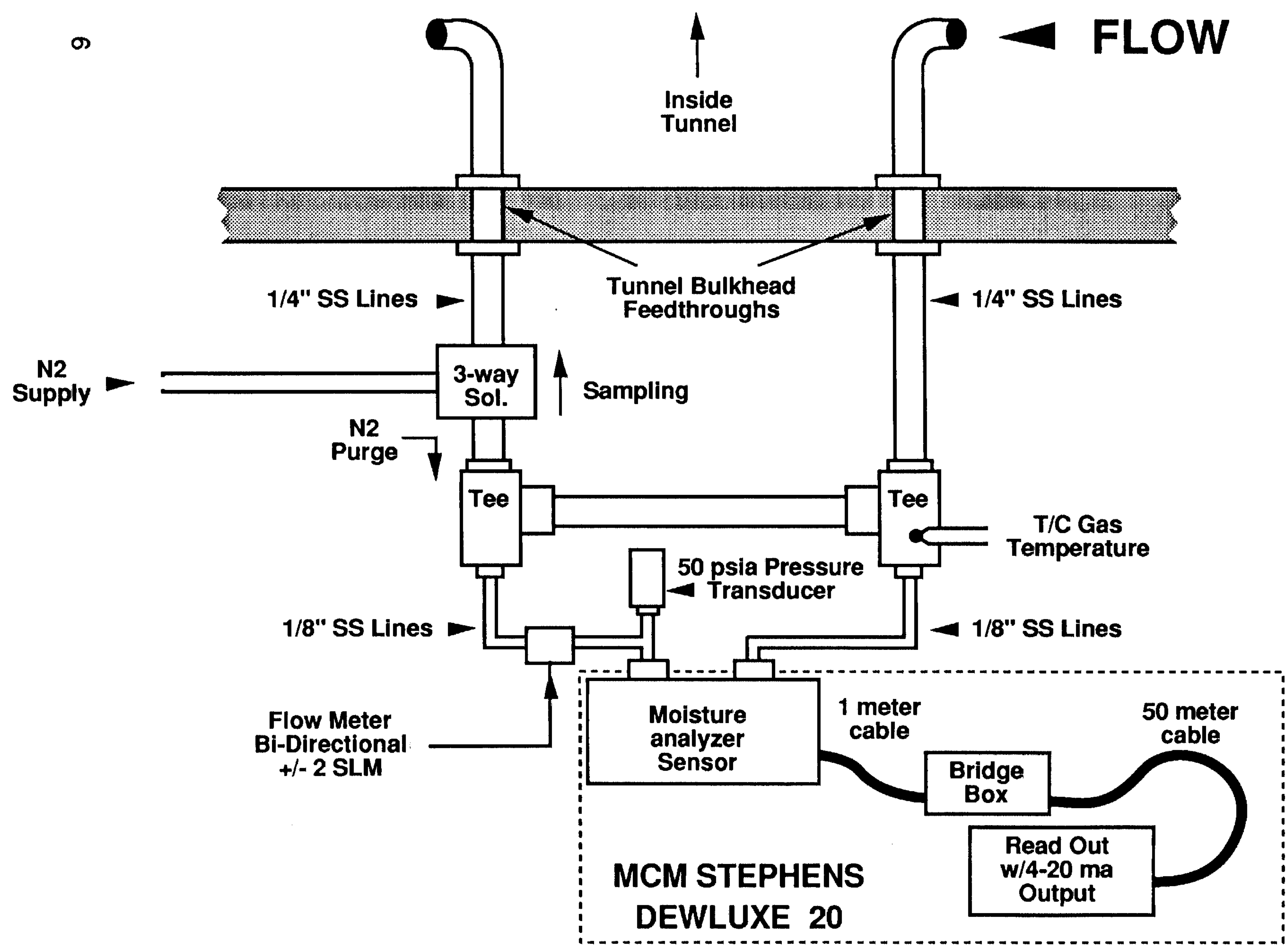

Figure 1. Sampling System for Low level Moisture Measurements In Hypersonic Free Stream

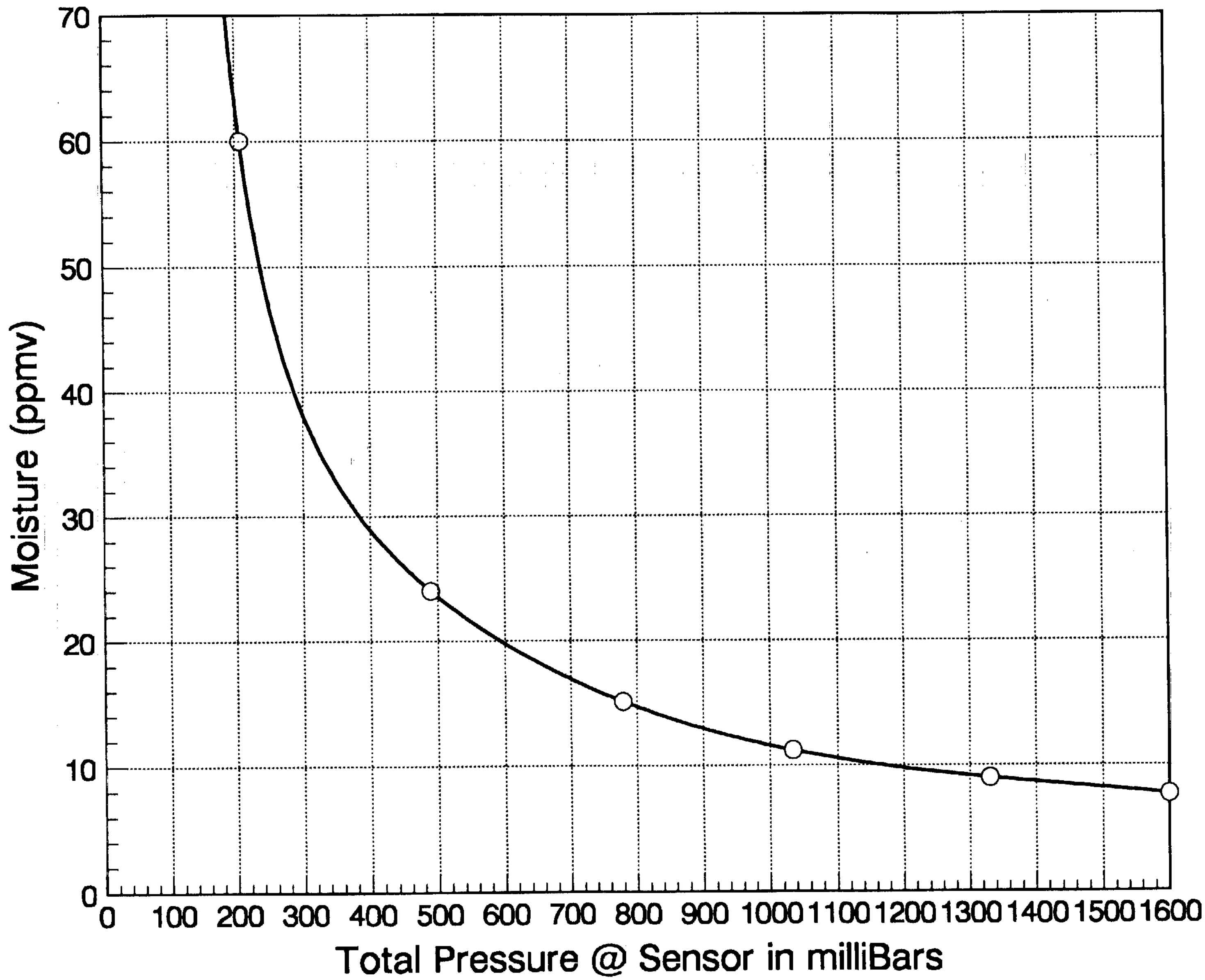

Figure 2 Moisture Measurement at the NASA Langley 0.5 Meter Quiet Tunnel

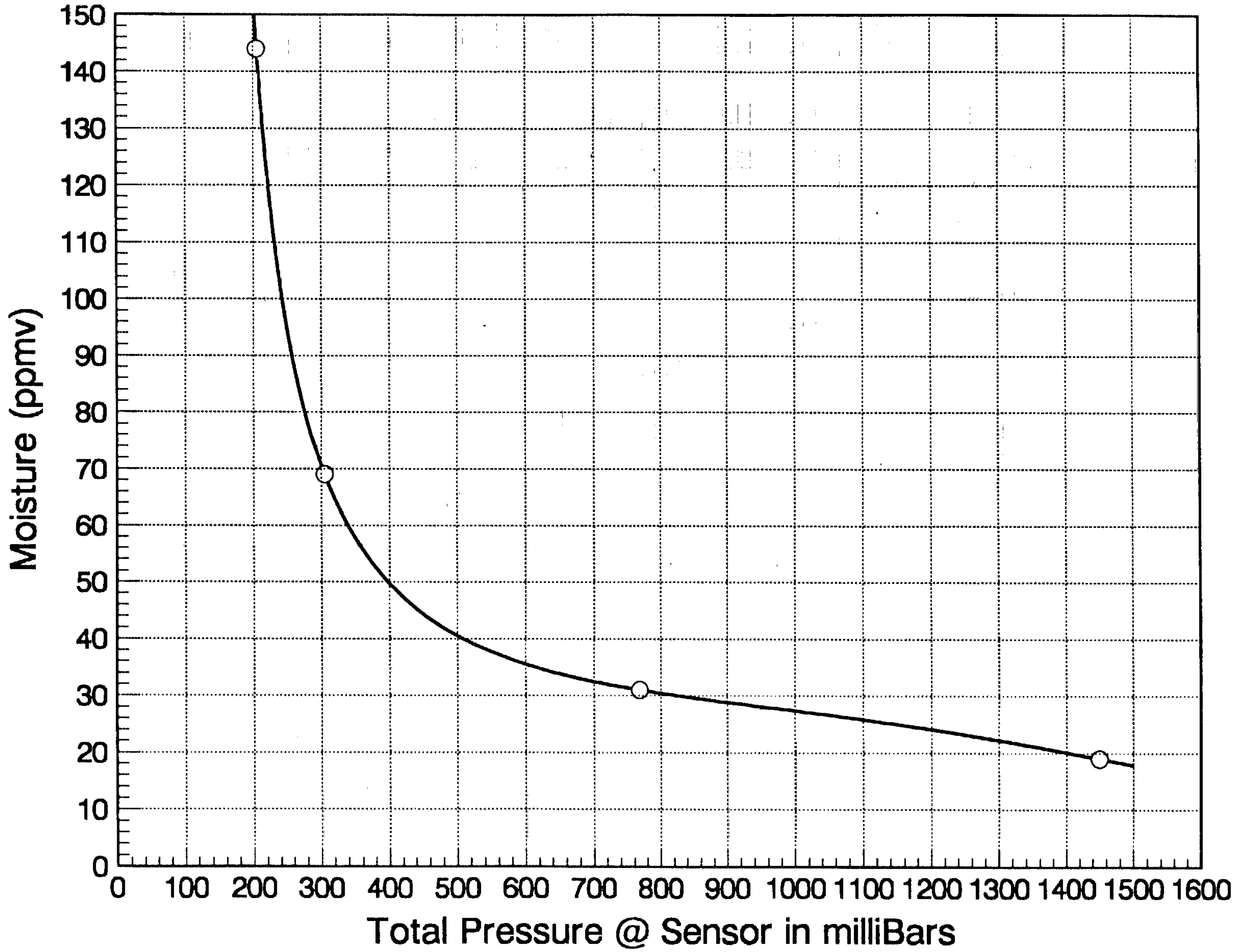

Figure 3 Moisture Measurement at the NASA Langley Mach 6 High Reynolds Tunnel

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