Pressure-Humidity Apparatus[1]

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An apparatus for producing atmospheres of known relative humidity, based on the "two-pressure principle", is described. It has a working space (test chamber) of 1 cubic foot, in which the relative humidity may be varied and controlled from 10 to 98 percent, the temperature from −40° to +40° C, the air flow up to 150 liters per minute, and the test-chamber pressure from ½ to 2 atmospheres. The humidity in the test chamber may be set and maintained to an accuracy of at least ½ of 1-percent relative humidity.

1. Introduction

The pressure-humidity equipment is a laboratory apparatus for producing atmospheres of known relative humidity by control of the pressure in the test chamber of air saturated at a higher pressure. As this apparatus was developed primarily for hygrometer research and calibration, especially on electric hygrometer elements, which, during use, are subjected to a wide temperature range, it was essential that the temperature of the working space should be adequately controlled and maintained at any desired value from −40° to +40° C. Futhermore, it was desirable that any relative humidity, from 10 to 98 percent, should be conveniently produced and that a change could be made rapidly from any one value of relative humidity to any other value. Finally, it was also desirable to have a means of varying the rate of air flow through the working space, selected to have a volume of about 1 ft^3.

An apparatus has been developed that successfully meets the above requirements. It operates on what may be called the "two-pressure principle." Basically, the method, shown in elemental schematic form in figure 1, involves saturating air, or any gas, with water vapor at a high pressure and then expanding the gas to a lower pressure. If the temperature is held constant during saturation and upon expansion, and the perfect gas laws are assumed to be obeyed, then the relative humidity, RH, at the lower pressure, P_t, will be the ratio of the absolute values of the lower pressure, P_t, to the higher pressure, P_s, that is, $RH=100\times P_t/P_s$.

Water vapor-air mixtures depart from ideal gas behavior, so that the simple pressure ratio does not strickly define the relative humidity. Weaver [2] [3] has shown that an empirical equation of the form

$$RH=100\times\frac{P_t}{P_s}\frac{(1-KP_t)}{(1-KP_s)},$$

where the constant K has a value of 0.00017 when the pressure is expressed in pounds per square inch, more closely yields the true relative humidity. The magnitude of the correction introduced by the term $(1-KP_t)/(1-KP_s)$ is shown in table 1 for the applicable range of test-chamber pressures (½ to 2 atm) and relative humidities (10 to 100%). With atmospheric pressure in the test chamber the maximum error does not exceed ¼ of 1-percent relative humidity and hence, for most work, may be neglected. Even at a test-chamber pressure of 2 atm, the maximum error is less than 0.5-percent relative humidity. For very precise work, it is preferable to use the empirical equation.

TABLE 1. *Error due to nonideal behavior of water-vapor–air mixtures*

Test-chamber pressure	Relative humidity, percent					
	100	80	60	40	20	10
	Error in relative humidity, percent					
abs atm						
½	0	0.02	0.05	0.08	0.10	0.11
1	0	.05	.10	.15	.20	.23
2	0	.10	.20	.30	.41	.47

The pressure method was developed by Weaver and Riley (see footnote 2) for the calibration of electrically conducting hygroscopic films used in the measurement of water vapor in gases. Their equipment was designed for low rates of gas flow and was used under ambient room-temperature conditions.

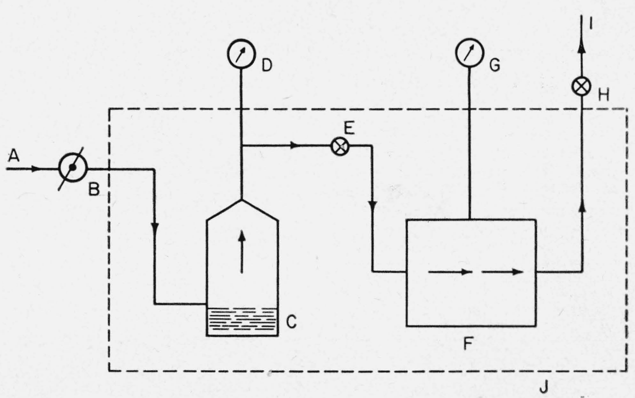

FIGURE 1. *Simplified schematic drawing of the principle of operation of the pressure-humidity apparatus.*

A, high-pressure air source; B, pressure regulator; C, saturator; D, pressure gage; E, expansion valve; F, test chamber; G, pressure gage; H, exhaust valve; I, atmosphere or vacuum source; J, constant-temperature bath.

[1] The development of this apparatus was sponsored by the Aerology Branch of the Bureau of Aeronautics.
[2] E. R. Weaver, and R. Riley, J. Research NBS **40**, 169 (1948) RP1865.
[3] E. R. Weaver, Anal. Chem. **23**, 1076 (1951).

Their saturator was a small cylinder, containing water and filled with fragments of pumice or stream-washed gravel through which the gas could be bubbled under pressure.

2. Description of Apparatus

The apparatus is shown in block diagram in figure 2 and schematically in figure 3. It consists, essentially, of the following functional components, through which air flows continuously: A high-pressure air source, a low-temperature drying system, a filtering system, a warm-up unit, a pressure regulator, a humidifying system, an expansion valve, a test chamber, and an exhaust control system.

Air is supplied from a 250-psig reciprocating compressor, *A1*, figure 3, capable of delivering 5 ft^3/min of free air at room temperature. This air is filtered (*A2*) to remove pipe scale, dirt, dust, or other solid material, and is then introduced into the drying system (fig. 4).

Water from the air at the supply pressure is removed by freezing in a train of four drying units immersed in a bath, *D*, containing a mixture of dry ice and Stoddard solvent. The first two units, *A4* and *A5*, are large-capacity centrifugal water separators. These are followed by a copper coil, *A6*, and a baffle dryer, *A7*. Particles of snow or ice and droplets of oil (from the compressor) are caught by a filter, *A8*, which is maintained immersed in the same low-temperature bath, *D*.

The air emerges from the dryer at about −78° C. It is then heated in the warm-up unit to a temperature somewhat greater than that being maintained in the thermostatted liquid bath, *B*. The warm-up unit consists of an electric heater, *A9*, that is controlled by a thermoregulator, *A10*. Two pressure regulators, *A13*, and *A14*, in series reduce the pressure and maintain it constant in the hymidifying system.

Saturation is accomplished in four stages. The air is first passed through the external gross saturator, *A15*, which is kept at a higher temperature than the bath, *B*, and then through the three bath saturators, *A18*, *A20*, and *A22*. The gross saturator, because of its higher temperature, introduces water vapor in excess of that required for complete saturation at bath temperature. The combination of heat exchangers *A17*, *A19*, and *A21* and centrigfugal saturators *A18*, *A20*, and *A22* precipitates this excess water vapor so that just complete saturation is obtained in the final saturator, *A22*. The bath saturators and heat exchangers are shown in figure 5.

The saturators are simple in design and function equally well below as well as above the freezing point of water. They are similar to a type previously used [4] with considerable success. Each saturator consists of a cylinder to which water is added to a convenient depth. Air is discharged through a nozzle into the chamber above the water surface and tangential to the vertical walls and is exhausted through a central port in the top. The centrifugal force creates a whirlpool action that thoroughly mixes the water vapor with air. Spray and liquid water are forced to the walls by centrifugal force, so there is little tendency for liquid water

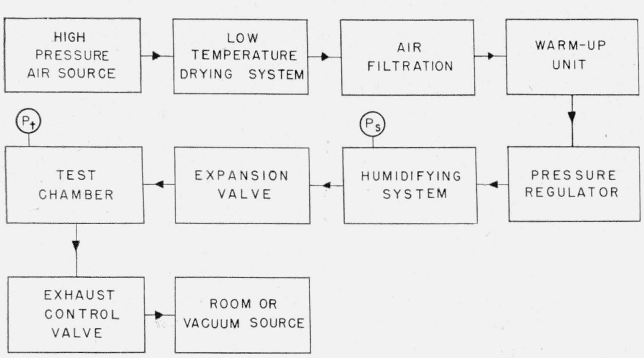

FIGURE 2. *Block diagram of the pressure-humidity apparatus.*

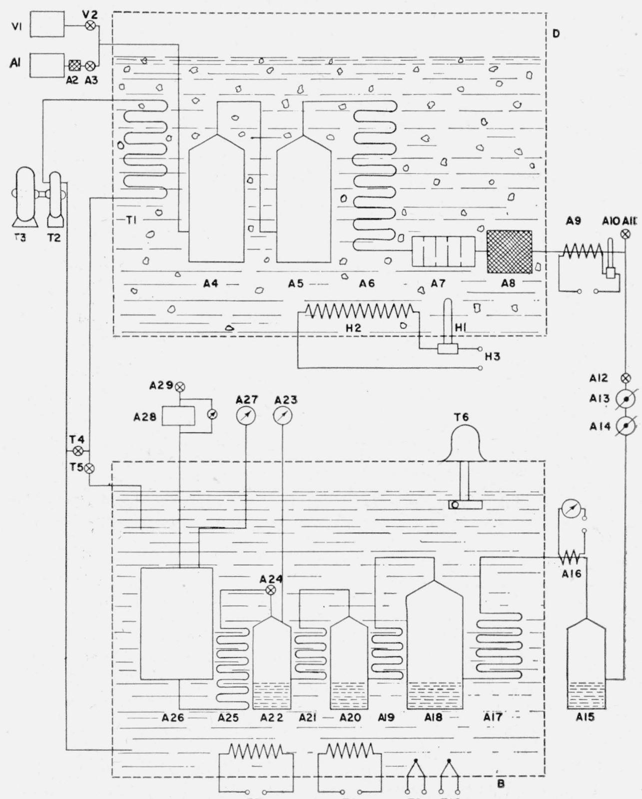

FIGURE 3. *Schematic flow diagram of the pressure-humidity apparatus.*

A1, high-pressure source; A2, filter; A3, valve; A4, centrifugal water separator; A5, centrifugal water separator; A6, copper cooling coil; A7, fin air dryer; A8, low-temperature filter; A9, electric heater; A10, bimetal thermoregulator; A11, air reversal valve; A12, shut-off valve; A13, pressure regulator; A14, pressure regulator; A15, external gross saturator; A16, resistance thermometer and indicator; A17, 19, 21, 25, copper coil heat exchangers; A18, 20, 22, centrifugal saturators; A23, 27, pressure gages; A24, expansion valve; A26, test chamber; A28, linear flowmeter; A29, exhaust control valve; B, insulated liquid (Stoddard solvent, constant-temperature bath; D, insulated dry-ice bath; H1, bimetal thermoregulator; H2, electric heater; H3, input voltage; T1, Stoddard solvent cooling coil; T2, positive rotary displacement pump; T3, motor; T4, Stoddard solvent bypass valve; T5, Stoddard solvent control valve; T6, centrifugal stirrer; T7, constant electric heater; T8, intermittent electric heater; T9, 10, thermistors; V1, vacuum source; V2, vacuum shut-off valve.

[4] Arnold Wexler, J. Research NBS **45**, 357 (1950) RP2145.

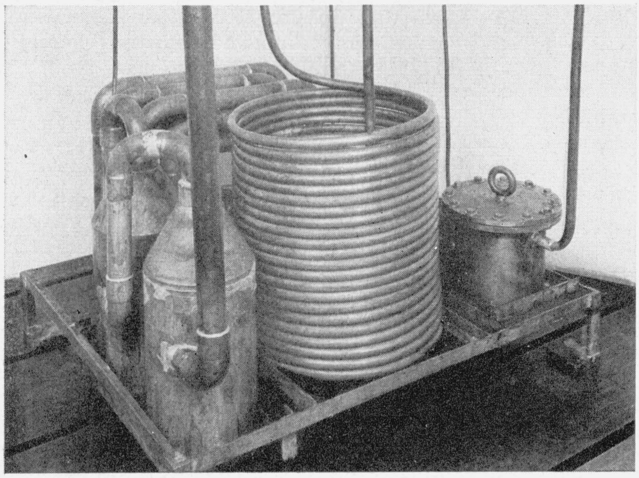

FIGURE 4. *Drying system and Stoddard solvent cooling coil.*

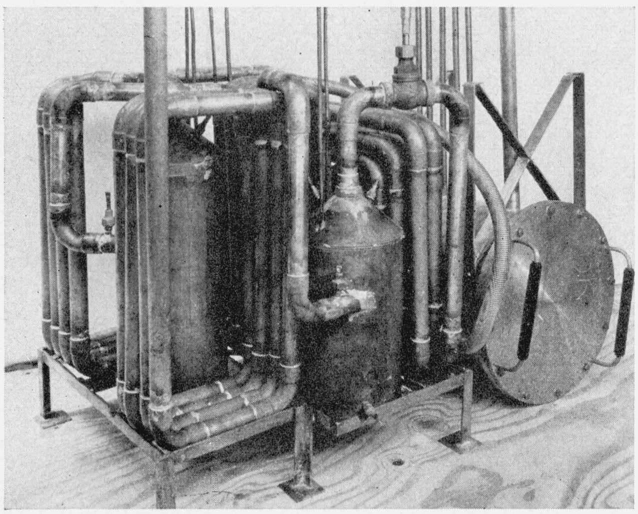

FIGURE 5. *Bath saturators, heat exchangers, and test chamber.*

to emerge through the exit port. A multilayer fine-wire screen baffle is used at the exit as a further guard against the escape of liquid water. As air does not bubble through the water but only passes over its exposed surface, the water may be frozen without impairing the functioning of the saturator.

Upon emerging from the final saturator, *A22*, the pressure of the air is reduced by expansion valve *A24*. Because a temperature drop may occur in the air at the expansion valve, a final heat exchanger, *A25*, is provided for bringing the air to bath temperature before it enters the test chamber, *A26*.

The working space, *A26*, is a cylindrical chamber having a nominal volume of 1 ft^3. It is shown with the cover removed in figure 6. Tubular outlets extend from the chamber to allow electric leads to be brought in and out of the working space. The air discharges from the chamber into a linear flowmeter, *A28*, and then through an exhaust control valve, *A29*, into a vacuum source or simply into

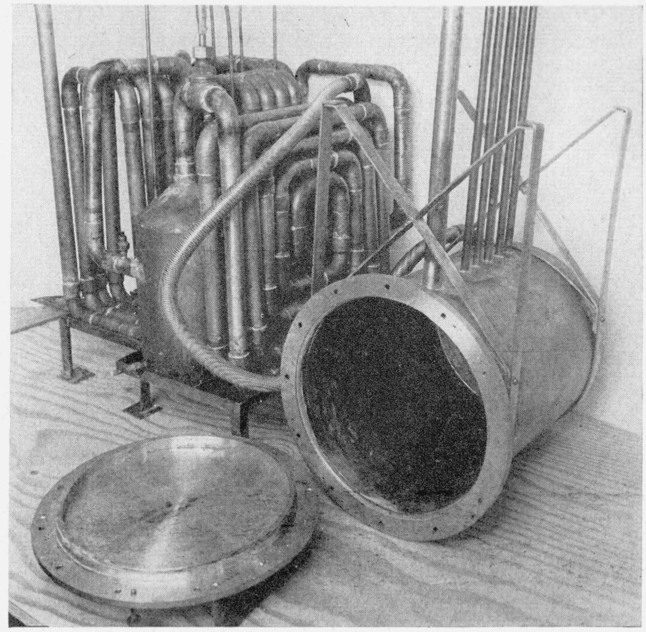

FIGURE 6. *Test chamber with cover removed.*

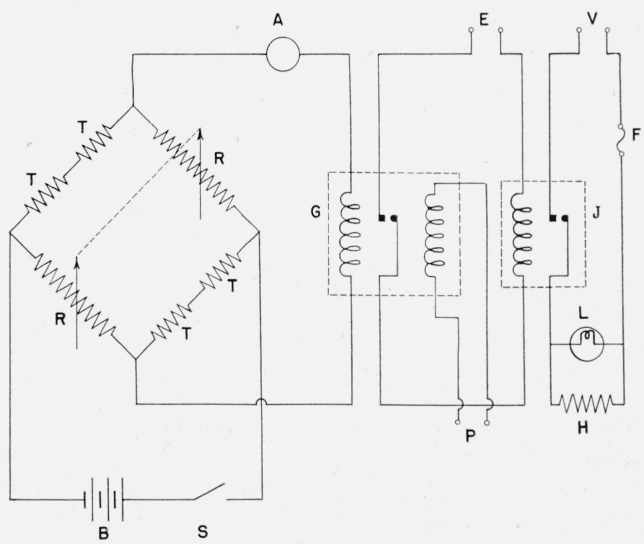

FIGURE 7. *Temperature control circuit.*

T, Thermistor; R, precision helical rheostat; B, 22½-v battery; S, battery switch; A, microammeter; G, ½ a galvanometer relay; P, input from pulsing circuit; F, fuse; J, power relay; E, input voltage for power relay coil; H, intermittent bath heater; V, input voltage for intermittent heater; L, pilot lamp.

the room air. The chamber is suspended from a counterweight system so that it can be easily raised above or immersed into the liquid bath, *B*. A length of flexible metal hose, between the test chamber, *A26*, and the final heat exchanger, *A25*, permits the test chamber to have the required motion.

The saturation pressure, P_s, is measured in the final saturator, *A22*, by gage *A23*, and the test pressure is measured in the test chamber by gage *A27*. These measurements are made with high-precision laboratory test gages that have been calibrated against the National Bureau of Standards pressure standards. For atmospheric or reduced pressures, a high-quality calibrated aneroid barometer is used. From atmospheric pressure up to 2 atm, a mercurial manometer is employed. The higher pressures are determined with either a 0- to 50-psig or a 0- to 200-psig Bourdon tube gage.

The temperature of the liquid bath, *B*, can be adjusted to and closely regulated at any temperature from −40° to +40° C by a simple on-off thermostatting system. Stoddard solvent, which is used as the bath liquid so that low temperatures may be attained, is actively agitated by a centrifugal stirrer, *T6*, and is circulated from the bath, *B*, by a positive rotary displacement pump, *T2*, through a copper coil, *T1*, immersed in a mixture of dry ice and Stoddard solvent in bath *D* and back into bath *B*. By proper manual setting of a bypass valve, *T4*, and a control valve, *T5*, the rate of Stoddard solvent flow is adjusted so that the bath *B* tends to cool slightly. The desired bath temperature is established by resistances (coupled helical precision rheostats), *R*, in a Wheatstone bridge circuit, figure 7. Thermistors, *T*, with temperature coefficients of 4 percent/deg C, are employed as the temperature-sensitive elements. Any cooling disturbs the bridge balance, which is sensed by a galvanometer relay, *G*. A current of ½μa deflects the galvanometer pointer against a magnetic contact, actuating a power relay, *P*, and, in turn, intermittent bath heater, *H*. The operation of an electromagnetic plunger returns the pointer to a sensing position. If the bridge is unbalanced, the pointer will deflect and again throw on the heater; if the bridge is in balance, the pointer will remain in a null position. An electronic pulsing circuit, *P*, periodically triggers the plunger so that the pointer may sense the bridge balance.

3. Operation of Apparatus

The method of operation of this equipment is simple. The instrument, material, or device under investigation is inserted into the test chamber, the latter closed and immersed into the liquid bath. Distilled water is added to each saturator to an appropriate depth. Solid carbon dioxide is then added to the dry-ice bath, *D*. The temperature of the liquid bath is brought to and maintained at the desired value. Air from the high-pressure source is allowed to pass through the apparatus and the pressures in the saturators and test chamber adjusted to give any preselected relative humidity. The thermoregulator controlling the temperature of the air passing through the warm-up unit is set to maintain a temperature in the external saturator several degrees higher than in the liquid bath. When thermal equilibrium had been established in the components in the liquid bath, the pressure ratio indicates the correct relative humidity in the test chamber. Changing the relative humidity primarily involves adjusting the pressure regulators so that they will maintain a new pressure in the saturators. To maintain a constant air flow, a minor adjustment of the expansion valve is also made.

When atmospheric pressure is desired in the test chamber, the air emerging from the chamber is allowed to exhaust directly into the room. Elevated pressures in the chamber are obtained by throttling the flow from the chamber by means of the exhaust control valve, *A29*, figure 3. Reduced pressures in the chamber are achieved by attaching a vacuum source to the exhaust control valve and adjusting the valve to give the required reduced pressure.

In operating below freezing, one precaution must be observed. The level of the water in each saturator must be kept below the inlet nozzle, otherwise, on freezing, the opening will be sealed by ice.

The equipment may be operated continuously for 8 to 16 hr, after which the accumulated water in the dryer should be removed. Failure to do so may result in clogging of the dryer by ice and the reduction, or even complete stoppage, of air flow.

The removal of water from the dryer is accomplished in two steps. First the dry ice bath is raised to room temperature by a thermostat, *H1*, and heater, *H2*. Then suction is applied by vacuum source *V1* and room air drawn through the reversal valve, *A11*, and dryer until all the water has been evaporated. Overnight operation usually suffices to remove most of the water.

4. Performance and Accuracy

The psychrometric and dew-point methods of humidity measurement were used independently to evaluate the accuracy of the humidity produced by the equipment. A thermocouple wet-and-dry-bulb hygrometer was employed over a wide range of relative humidities and at temperatures from 0° to 30° C. A dew-point instrument having a thermocouple embedded just below the surface of a small (¼ in. in diameter) mirror for temperature measurement, manually controlled heating and cooling of the mirror, and visual observation through a telescope for dew and frost detection, was constructed and used to measure dew points from room temperature down to −27° C. A series of experiments was made in which the relative humidity measured by the above two methods was compared with the relative humidity given by the ratio of the test-chamber pressure to the saturator pressure. The results are shown in table 2. The average difference in percentage of relative humidity between the psychrometrically determined values and the apparatus values given by the pressure ratio is ±0.4 percent, and the average difference in percentage of relative humidity between the value determined by dew-point measurement, and the apparatus value given by the pressure ratio is ±0.6 percent. Similarly, the algebraic average differences are −0.2 and 0.0 respectively. It may be assumed that as there is no marked tendency for the differences to be either positive or negative, the air passing through the saturators emerges neither supersaturated or undersaturated.

Table 2. *Summary of calibration*

Date of run	Nominal ambient bath temperature	Relative humidity produced by pressure-humidity apparatus	Relative humidity measured by—		Difference in relative humidity between pressure-humidity apparatus and—	
			Dew-point hygrometer	Psychrometer	Dew-point measurement	Psychrometric measurement
	° C	%	%	%	%	%
3-28-51	23.5	96.1	----	96.2	-----	−0.1
		90.1	----	91.1	-----	−1.0
		81.6	----	82.3	-----	−0.7
		74.4	----	75.2	-----	−.8
		59.6	----	59.7	-----	−.1
		50.1	----	50.5	-----	−.4
		38.0	----	38.4	-----	−.4
		25.1	----	25.4	-----	−.3
3-28-51	9.7	92.9	----	92.4	-----	+.5
		79.8	----	79.8	-----	.0
		61.0	----	61.0	-----	.0
		49.5	----	49.3	-----	+.2
		37.2	----	37.0	-----	+.2
		24.6	----	24.2	-----	+.4
3-28-51	30.4	92.6	----	92.9	-----	−.3
		78.3	----	78.6	-----	−.3
		59.6	----	59.7	-----	−.1
		49.2	----	49.4	-----	−.2
		37.0	----	37.2	-----	−.2
		24.9	---	24.8	-----	+.1
4-6-51	24.7	97.9	96.7	----------	+1.2	-----
		88.8	88.7	----------	+0.1	-----
		77.6	75.9	----------	+1.7	-----
		77.4	77.9	----------	−0.5	-----
		54.8	55.4	----------	−.6	-----
		36.9	37.3	----------	−.4	-----
		23.0	23.9	----------	−.9	-----
4-16-51	6.0	96.9	97.0	96.9	−.1	0.0
		90.6	92.1	91.4	−1.5	−.8
		77.9	78.6	78.5	−0.7	−.6
		57.7	58.5	58.2	−.8	−.5
		42.7	42.9	42.6	−.2	+.1
4-18-51	6.0	96.2	96.3	94.7	−.1	+1.5
		53.9	54.7	53.8	−.8	+0.1
		36.6	36.6	36.7	.0	−.1
		28.3	28.4	28.8	−.1	−.5
		23.2	23.1	23.5	+.1	−.3
4-19-51	−4.8	96.8	97.1	----------	−.3	-----
		86.0	86.7	----------	−.7	-----
		74.7	74.7	----------	.0	-----
4-24-51	−9.6	76.4	75.9	----------	+.5	-----
		68.3	68.2	----------	+.1	-----
		54.1	53.5	----------	+.6	-----
4-25-51	−19.8	96.3	95.6	----------	+.7	-----
		88.0	89.1	----------	−1.1	-----
		78.7	78.2	----------	+0.5	-----
		66.4	65.0	----------	+1.4	-----
		56.7	55.6	----------	+1.1	-----
				Arithmetic avg	±0.6	±0.4
				Algebraic avg	.0	−.2

The relative-humidity range obtainable is limited by the range of ratios of test-chamber pressure to saturator pressure. The maximum saturator pressure that can be employed with this apparatus is about 150 psi. When the test chamber is maintained at its maximum pressure (about 2 atm), the minimum relative humidity is about 20 percent. At atmospheric pressure, a relative humidity as low as 10 percent is readily produced, and at a reduced pressure of ½ atm, the minimum relative humidity decreases to 5 percent.

The temperature range of the equipment extends from −40° to +40° C. The upper end is limited by the flash point of the bath liquid (Stoddard solvent). However, by substituting water for Stoddard solvent as the bath liquid, the upper end of the temperature range may be extended to about 90° C.

The accuracy with which any desired relative humidity may be established is a function of the uniformity of temperature in the apparatus, particularly in the final saturator and the test chamber. The relative humidity in the test chamber will be equal to the pressure ratio of the test chamber to final saturator only if these two units are at the same temperature. The distribution of temperature within the saturators, test chamber, and surrounding liquid bath was explored by means of thermocouples, located at the inlet, outlet, and in the water of each saturator, near the front and rear of the test chamber, and at four separate points within the liquid of the bath. As an indication of the variations in temperature that may exist in the apparatus, data are presented in table 3 of the average temperatures at various locations for three 2-hour runs at different ambient temperatures. It may be seen that the differentials are of minor magnitude, especially between the final bath saturator and the test chamber.

Table 3. *Temperature distribution*

Location	Temperature		
Initial bath saturator:	° C	° C	° C
Air inlet	9.55	23.33	30.24
Air outlet	9.57	23.30	30.25
Water	9.66	23.29	30.30
Intermediate bath saturator:			
Air inlet	9.63	23.35	30.45
Air outlet	9.65	23.36	30.44
Water	9.63	23.29	30.39
Final bath saturator:			
Air inlet	9.64	23.39	30.48
Air outlet	9.65	23.40	30.44
Water	9.66	23.36	30.43
Test chamber:			
Front	9.64	23.35	30.40
Rear	9.61	23.35	30.37
Bath:			
Side of test chamber	9.64	23.38	30.40
Expansion valve	9.64	23.39	30.40
Rear of test chamber	9.61	23.39	30.39
Bottom	9.58	23.38	30.39

The constancy of bath temperature is of importance, for quite often materials or hygrometers under investigation are temperature dependent. The control system has effectively regulated the bath at temperatures from −40° to +40° C. For periods of time of 2 to 5 hours, average fluctuations of 0.02 to 0.05 deg. have been observed.

5. Discussion

This equipment has been used successfully for calibration testing and research. The working space of 1 ft^3 is ample for most instruments, materials, and devices that have to be completely immersed in an atmosphere of known relative humidity. There is no theoretical limitation on the size of the test chamber that may be employed with this type of equipment; a larger sized chamber would simply require a larger surrounding liquid bath. Neither is there any limitation on the geometry of the test chamber. A cylinder was chosen in this case for ease of construction, but any other space configuration can be substituted. Even in the present design, the cylindrical test chamber can be uncoupled from the setup, and, within the limitation of the available bath space, any other size, shape, or design of chamber can be attached.

Occasionally air of known or preestablished dew point is required at a place or instrument remote from the test chamber. The desired dew point can be readily produced by the apparatus, and all or part of the air from the test chamber can be piped wherever needed. The only limiting factor involves the temperature of the ambient air, which must not drop below the dew point of the air flowing through the transmission tubing, because condensation may occur in the lines.

The range of relative humidities obtainable with this type of equipment may be extended to much lower values by using a higher pressure source. A 250-psig compressor, operating between 150 to 200 psig, is used in the present design and provides relative humidities that are sufficiently low for most purposes. Much higher pressures would necessitate components capable of withstanding those high pressures. Similarly, for flows in excess of 5 ft^3/min, a compressor having a larger volume capacity would be required.

The rapidity with which the relative humidity may be changed depends primarily on the time involved in adjusting the pressure regulator, which controls the saturation pressure. Minor adjustments of the expansion valve and the exhaust control valve may be required after the major pressure adjustment has been made. These operations can easily be executed within 30 sec. At low rates of flow, the limiting factor ceases to be the time required for performing the above mechanical operations and becomes, instead, the time involved in purging air of one relative humidity, with air of another relative humidity. The component with the maximum air volume is the test chamber. It has a space of about 1 ft^3, so that the purging time depends upon the rate of air flow through this 1-ft^3 volume.

6. Summary

An apparatus of versatility and convenience for producing atmospheres of known relative humidity has been developed and constructed at the Bureau. It operates on the "two-pressure principle," whereby air is saturated at a high pressure and expanded to a lower pressure, the relative humidity at the lower pressure being the ratio of the lower to higher pressure, provided the operation is performed at constant temperature.

Important parameters can be varied and controlled over wide ranges: relative humidity from 10 to 98 percent; temperature from $-40°$ to $+40°$ C; flow up to 150 liters/min; test-chamber pressure from ½ to 2 atm. The relative humidity can easily be changed from one value to another within 30 sec.

Independent checks on the accuracy of the relative-humidity production with the psychrometric and dew-point methods have yielded average agreements of ± 0.4 to ± 0.6 percent. As the latter methods of measurement are probably no more accurate than about ± 0.5 percent, it is reasonable to assume that the apparatus produces relative humidities that are known to at least ± 0.5-percent relative humidity.

WASHINGTON, December 12, 1951