technical note technical note

Cloud Sampling Instruments for Icing Flight Tests: (2) Cloud Water Concentration Indicators

Richard Jeck

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DOT/FAA/AR-TN06/30

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16. Abstract

This series of technical notes, "Cloud Sampling Instruments for Icing Test Flights," provides information and guidance for devices that are most commonly used for measuring cloud water and droplet sizes during aircraft certification test flights in natural icing conditions. Advice is given on the suitability, procedure, and precautions for using various instruments and on data analysis techniques. This technical note is devoted to the commercially available hot-wire devices for continuously measuring cloud water concentrations due to cloud droplets. The other technical notes in the series are:

- DOT/FAA/AR-TN06/29, Cloud Sampling Instruments for Icing Flight Tests: (1) Icing Rate Indicators
- DOT/FAA/AR-TN06/31, Cloud Sampling Instruments for Icing Flight Tests: (3) Cloud Droplet Sizers
- DOT/FAA/AR-TN06/32, Cloud Sampling Instruments for Icing Flight Tests: (4) Large Drop Sizers

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LIST OF ACRONYMS

ACO	Aircraft Certification Office
CFR	Code of Federal Regulations
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
FAA	Federal Aviation Administration
J-W	Johnson-Williams
LWC	Liquid water content

INTRODUCTION

Federal aviation regulations, such as Title 14 Code of Federal Regulations (CFR) 25.1419 "Ice Protection" require that, for aircraft being certificated for flight in icing conditions, flight tests be conducted in measured natural or simulated icing conditions. Different aircraft manufacturers have employed different types of instrumentation to measure the relevant icing cloud variables, primarily water content, droplet sizes, and temperature. The available instrumentation ranges from simple to complex, from old to new, and from relatively inexpensive to expensive. Most of the instrumentation comes from the cloud physics research community and requires a certain amount of knowledge and experience to ensure that the probes are properly installed, calibrated, and operated. In addition, all probe types can have subtle systematic errors that may be difficult to recognize by the inexperienced operator or data analyst.

The Federal Aviation Administration (FAA) Aircraft Certification Offices (ACO) have had little guidance on this type of instrumentation and, as a result of these complexities, have had to rely on aircraft manufacturers to supply presumably adequate instrumentation and technicians or to hire experienced contractors to install and operate suitable instrumentation and analyze the icing cloud data.

To help standardize policy and procedures among ACOs for icing certification projects, there was a need for official guidance on instrumentation for measuring the properties of icing conditions during natural icing test flights. This need was solidified as part of Task A.13.4 of the revised FAA Aircraft Icing Plan [1] of 2000, which calls for the FAA to develop certification guidance for measuring natural icing conditions.

The result was the following series of stand-alone technical notes—one for each type of instrument.

- DOT/FAA/AR-TN06/29, Cloud Sampling Instruments for Icing Flight Tests: (1) Icing Rate Indicators

- DOT/FAA/AR-TN06/30, Cloud Sampling Instruments for Icing Flight Tests: (2) Cloud Water Concentration Indicators

- DOT/FAA/AR-TN06/31, Cloud Sampling Instruments for Icing Flight Tests: (3) Cloud Droplet Sizers

- DOT/FAA/AR-TN06/32, Cloud Sampling Instruments for Icing Flight Tests: (4) Large Drop Sizers

The technical notes are intended to be a ready reference for ACOs, designated engineering representatives (DERs), aircraft manufacturers, and any other interested parties. They include advice on the suitability, procedure, and precautions for the most commonly used instruments for in-flight measurement of icing cloud variables. They also include advice on data quality assurance, data processing, and presentation of results.

The information and guidance was based on the author's own extensive experience with using the various instruments and analyzing the data from them. It was also based on information in the scientific and technical literature [1,3-5,10] and on the lessons learned during a comprehensive instrument comparison exercise conducted in 1998 in the Icing Research Wind Tunnel at the National Aeronautics and Space Administration Glenn Research Center near Cleveland, Ohio.

CSIRO "KING" SENSOR

The following is a description of the CSIRO "King" Liquid Water Content (LWC) Indicator.

- Classification: Electrical, hot-wire LWC sensor

- Manufacturer: Particle Metrics, Inc.
  5505 Airport Boulevard
  Boulder, Colorado 80301
  Telephone: 1-303-247-0411

- Purpose: To provide a direct, continuous measurement of LWC in clouds.

- Specifications:

  - LWC range: 0-1 g/m^3 or 0-6 g/m^3

  - Sampling rate: continuous

  - Physical size of probe: fork-shaped prongs on a 3-inch strut

  - Probe weight: about 2 pounds (1 kg)

  - Accessories needed: electrical control box, readout, chart recorder or data acquisition system

  - Cost of new system: $ 10,500

- Intended Use: Airborne cloud physics research

BACKGROUND.

This probe (shown in figure 1) was developed in the 1970s by Dr. Warren King and colleagues [3] at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. The probe is an improvement over the older Johnson-Williams (J-W) LWC probe in that it does not require a calibration box. It also offers more trouble-free performance characteristics. It gives a sensitive, continuous record of the LWC along the flight path, including fine-scale fluctuations in LWC along the way.

Until the year 2000, the commercial supplier of the King probe was Particle Measuring Systems of Boulder, Colorado. The present-day manufacturer is Particle Metrics, Inc.

This hot-wire device has been adopted by cloud physics research groups as a standard component of their instrument suite. It has often replaced the older J-W hot-wire probe previously in use.

PRINCIPLE OF OPERATION.

The sensor element is a thin copper wire wound around a 1.5-mm-diameter, 8-cm-long tube that is mounted between two prongs and crosswise to the airstream. The wire element is maintained at a constant elevated temperature of about 100°C by the electronics circuit. Cloud water droplets impinge on the heated wire and cool it. This causes an increase in electrical power to maintain the preset temperature. The increased power is directly proportional to the LWC in the airstream. The total power consumed by the sensor is output as an analog signal from 0 to 10 V for recording on a suitable data system.

The following lists the advantages and disadvantages of the CSIRO King LWC Indicator:

- Advantages
  - Provides a good, continuous record of LWC in clouds
  - Probe and control/indicator system are small and convenient for use on any aircraft
  - Easy to use
- Disadvantages
  - LWC output signal subject to drift in flight
  - Probe, though heated, is subject to icing effects during long exposures
  - Although the probe is rugged, the sensing wire can break during flight causing a loss of important LWC data.

KNOWN SOURCES OF ERROR.

The performance of King LWC probes has been studied extensively [3, 4, and 5]. The principal sources of error are described below.

SIGNAL DRIFT. The probe design does not eliminate drifts in the output signal due to changes in air temperature during flight. An onboard attendant can manually adjust the baseline signal to read zero in the clear air just before cloud penetration. Otherwise, the data analyst must recognize these baseline drifts and compensate for them in the data processing.

The system is powered by the 28 Vdc electrical supply of the aircraft. The design of the electronics is such that the LWC calibration is sensitive to any changes in the supply voltage. Thus, a departure from 28 V will cause a proportional increase or decrease in the indicated LWC. This little-known effect can, if not accounted for, cause additional error in the recorded LWCs.

ICING EFFECTS. Although the probe is heated, prolonged exposures in icing conditions can result in some accumulation of ice on the prongs supporting the hot wire. This may affect the airflow past the hot wires and cause a false change in the LWC reading.

DROP SIZE SENSITIVITIES. The sensitivity of the probe begins to decrease for droplets larger than about 40-μm diameter. Therefore, the indicated LWC will be too small by some unknown factor when large drops are present. This should be kept in mind for flights through vigorous convective clouds and in drizzle or rain.

AIRSPEED EFFECTS. The control unit contains a knob for adjusting the system calibration to the existing airspeed. If this knob is not matched to the actual speed of the aircraft during sampling, then the indicated LWC will be off by a factor proportional to the size of the mismatch. This can be an uncorrectable error if the knob setting is not known for the data in question.

PROBE LOCATION CONCERNS. The probe is designed for mounting on a pylon or on the fuselage. In any case, the mounting location should not be where certain droplet sizes have been depleted or increased due to inertial sorting by the deflection of the airstream around the aircraft. This concern is discussed in references 6 and 7.

Another problem on single-engined, propeller driven airplanes is the difficulty in obtaining exposures outside of the propeller wash, unless the instrument is mounted under a wing outboard of the propeller(s).

Additional practical information and references are contained in Chapter 2, Vol. 1 of reference 8.

PRACTICAL RECOMMENDATION.

Have the system installed and operated by an experienced researcher or technician who is familiar with using it in flight and analyzing the results. An experienced operator should check the system before each flight, ride with the flight to monitor the signal and system performance, and to adjust the control settings as needed during the flight. All preflight checks and in-flight control settings, as well as any peculiarities, should be documented and dated in a flight observer's notebook.

DATA PROCESSING AND ANALYSES.

The raw output signal is an analog voltage that is proportional to the instantaneous LWC but will also include any baseline drifts or offset errors. To arrive at the true LWC values, the raw data must be corrected for baseline drifts and any other errors, offsets, or range settings that are known to be in effect.

CHART DISPLAYS. The signal may be recorded on a chart recorder for quick viewing. Examples of several LWC records are shown in figure 2. Corrected or adjusted data should look similar to figure 2, where the base is flat and the LWC scale is displayed.

TABULAR DISPLAYS. For digital recordings, the LWC signal is usually sampled at least once every second during flight. The digitized data can be easily tabulated and displayed in a computerized spreadsheet, but for nontrivial adjustments, such as a ramp correction to the baseline, some other computer software or code may be needed. A time-of-day scale is essential for most analyses.

Table 1 illustrates one way to display and analyze digitally recorded data. In this example, the LWC and other variables were sampled only every 5 seconds. This spreadsheet uses formulas in the cells to convert the LWC to an equivalent icing rate, severity, and cumulative ice depth on a selected aircraft component—in this case, the outer wing section of a Convair 640 (CV-640) airplane. This is one way to extract extra meaning from the LWC measurements and to rate the significance of the icing encounter. Reference 9 gives other examples for comparing LWC measurements to the probable maximum values of LWC in 14 CFR Part 25, Appendix C.

JOHNSON-WILLIAMS SENSOR

The following is a description of the Johnson-Williams (J-W) Liquid Water Content (LWC) Indicator.

- Classification: Electrical, hot-wire LWC sensor.

- Manufacturer: Science Engineering Associates, Inc.
  114C Mansfield Hollow Road
  P.O. Box 605
  Mansfield Center, CT 06250
  Telephone: 1-860-450-1717
  Website: www.scieng.com

- Purpose: To provide a direct, continuous measurement of LWC in clouds.

- Specifications:

  - LWC range: 0-3 g/m^3 in two selectable ranges, or 0-6 g/m^3 in three selectable ranges

  - Sampling rate: continuous

- Physical size of sensor: small open cylinder (1″ wide by 2″ long) on a 6-inch strut
- Sensor weight: about 1 pound (0.5 kg)
- Accessories needed: electrical control/readout, calibration unit, special cables, chart recorder or data acquisition system
- Cost of new system: $18,800

- Intended Use. Airborne cloud physics research.

BACKGROUND.

This sensor (shown in figure 3) was developed in the early 1950s by Mr. Carr Neel and others at the National Advisory Committee for Aeronautics (NACA) Ames laboratory. It was needed as a more convenient way to measure icing conditions than the labor intensive rotating multicylinder method then in use. It was the first practical means of measuring LWC in flight. It gives a sensitive, continuous record of the LWC along the flight path, including fine scale fluctuations in LWC along the way.

The sensor was first manufactured commercially in the late 1950s and 1960s by the Johnson-Williams division of the Bacharach Industrial Instrument Company, hence the name.

This new hot-wire device was so successful that it was rapidly adopted by cloud physics research groups as a standard component of their instrument suite and remains in widespread use today. The present-day manufacturer is Science Engineering Associates, Inc., as listed above. At this writing, the manufacturer is modernizing the electronics in preparation for offering an improved model.

PRINCIPLE OF OPERATION.

A calibrated resistance wire is mounted crosswise in a cylindrical tube with the wire axis perpendicular to the airstream. The wire element is connected electrically as one arm in a balanced bridge circuit. Cloud water droplets impinge on the heated wire and are evaporated. The cooling effect of the evaporating droplets decreases the electrical resistance of the wire, causing the bridge to become unbalanced. The magnitude of the unbalance is a function of the LWC of the airstream.

A second resistance wire, mounted with its axis parallel to the airstream direction and hence not subject to water drop impingement, is connected as an adjacent arm of the bridge. This wire serves to compensate for variations in air speed, altitude, and air temperature. The output of the bridge is, therefore, proportional to the rate of impingement of water on the sensing wire. This signal is converted to concentration of water per unit volume of air by means of an adjustment for true air speed.

The following lists the advantages and disadvantages of the J-W LWC sensor.

- Advantages
  - Provides a good, continuous record of LWC in clouds
  - Sensor and control/indicator system are small and convenient for use on any aircraft
  - Sensor is rugged and withstands the rigors of airborne use
  - Easy to use
- Disadvantages
  - LWC output signal subject to drift in flight
  - Sensor, though heated, is subject to icing effects during long exposures
  - System should have constant attention by experienced operator during flight

KNOWN SOURCES OF ERROR.

The performance of J-W LWC sensors has been studied extensively [10 and 4]. Many of the operational problems are subtle ones that require an experienced operator to recognize or anticipate. The principal sources of error are described below.

SIGNAL DRIFT. The sensor design attempts to eliminate drifts in the output signal due to changes in air temperature during flight. Nevertheless, drifts equivalent to as much as a few tenths of a g/m^3 still commonly occur with changes in altitude. During flight, an onboard attendant can manually adjust the baseline signal to read zero in the clear air just before cloud penetration. Otherwise, the data analyst must recognize these baseline drifts and compensate for them in the data processing.

During slant passes through clouds, for example, this baseline reading may be different before and after the pass. In this case, the postflight data analyst usually subtracts the drift in ramp-like fashion with distance through the cloud.

The system is powered by the 400-Hz, 115-V electrical supply of the aircraft. The design of the J-W electronics is such that the LWC calibration is sensitive to any changes in the supply voltage. Thus, a 10% departure from 115 V will cause a 10% increase or decrease in the upper limit of the selected LWC range. This little-known effect can, if not accounted for, cause additional error in the recorded LWCs.

ICING EFFECTS. Although the sensor is heated, prolonged exposures in icing conditions can result in some accumulation of ice on the cylindrical housing. This can affect the airflow past the hot wires in the cylinder and cause a false change in the LWC reading. Usually the effect is to lower the apparent value of the LWC, so if the J-W-indicated LWCs are gradually but steadily

decreasing contrary to all other observations, then the operator or analyst should investigate the possibility that icing has eroded the J-W signal.

CALIBRATION UNCERTAINTIES. The manufacturer supplies a device for checking the calibration of the system. It is a resistance box with two selectable resistors representing full-scale LWC on each of two scales. The accuracy or reliability of these substitute calibrations is unknown. There is no independent way to calibrate the sensors except by (1) operating the device in a LWC-calibrated, spray-equipped wind tunnel or (2) comparing measurements with other sensors or sensors simultaneously exposed during flight. Otherwise, the user is forced to blindly rely on the manufacturer's calibration and calibration checking device alone. Careful comparison tests in spray-equipped wind tunnels have revealed that some sensors from different users were unknowingly out of calibration and that sensors were not necessarily interchangeable between systems [10]. Therefore, the calibration record for each sensor should be provided to the data analyst.

DROP SIZE SENSITIVITIES. The sensitivity of the sensor begins to decrease for droplets larger than about 30-μm diameter. Therefore, the indicated LWC will be too small by some unknown factor when large drops are present. This should be kept in mind for flights through vigorous convective clouds and in drizzle or rain.

AIRSPEED EFFECTS. The control unit contains a knob for adjusting the system calibration to the existing airspeed. If this knob is not matched to the actual speed of the aircraft during sampling, then the indicated LWC will be off by a factor proportional to the size of the mismatch. This can be an uncorrectable error if the knob setting is not known for the data in question.

INSTALLATION EFFECTS. Past experience has shown that if the sensor mount to the aircraft has become a little corroded or there is otherwise a poor electrical grounding connection, then the output signal can be noisy or otherwise affected. This requires a particular alertness to these possibilities on the part of the installer, operator, and data analyst.

SENSOR LOCATION CONCERNS. The J-W sensor is designed for convenient mounting on the fuselage, usually toward the nose where the pitot and air temperature sensors are located. Otherwise, a fuselage location farther aft can result in sampling an airstream in which certain droplet sizes have been depleted or increased due to inertial sorting by the deflection of the airstream around the nose of the aircraft. This concern has been discussed in references 6 and 7.

Another problem on single-engined, propeller-driven airplanes is the difficulty in obtaining exposures outside of the propeller wash, unless the instrument is mounted under a wing outboard of the propellers.

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REFERENCES

1. "Aircraft Ice Detectors and Icing Rate Measuring Instruments," Aerospace Information Report AIR4367, Society of Automotive Engineers (SAE), 1995, www.SAE.org.

2. Anon, "FAA In-Flight Icing Plan, Revision A," FAA report FAA-AIR-99-06, April 2000, Federal Aviation Administration, 800 Independence Ave., SW, Washington, DC 20591.

3. King, W.D., Parkin, D.A., and Handsworth, R.J., "A Hot-Wire Liquid Water Device Having Fully Calculable Response Characteristics," *J. Applied Meteorology*, **17**, 1978, pp. 1809-1813.

4. Baumgardner, D., "An Analysis and Comparison of Five Water Droplet Measuring Instruments," *J. Applied Meteorology*, **22**, 1983, pp. 891-910.

5. King, W.D., et al., "Icing Wind Tunnel Tests on the CSIRO Liquid Water Probe," *J. Atmospheric and Oceanic Technology*, **2**, 1985, pp.340-352.

6. Drummond, A.M. and MacPherson, J.I., "Aircraft Flow Effects on Cloud Drop Images and Concentrations Measured by the NAE Twin Otter," *J. Atmospheric and Oceanic Technology*, **2**, 633 ff, 1985.

7. Norment, H.G., "Additional Studies of the Effects of Airplane Flowfields on Hydrometeor Concentration Measurements," Technical Report AFGL-TR-76-0187 Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts 01731, 1976.

8. Heinrich, A. et al., "Aircraft Icing Handbook," FAA Report DOT/FAA/CT-88/8-1, March 1991.

9. Jeck, R.K., "Icing Design Envelopes (14 CFR Parts 25 and 29, Appendix C) Converted to a Distance-Based Format," Technical report DOT/FAA/AR-00/30, April 2002.

10. Strapp, J.W. and Schemenauer, R.S., "Calibrations of Johnson-Williams Liquid Water Content Meters in a High-Speed Icing Tunnel," *J. Applied Meteorology*, **21**, 1982 pp. 98-108.

11. Jeck, R.K., "A History and Interpretation of Aircraft Icing Intensity Definitions and FAA Rules for Operating in Icing Conditions," FAA report DOT/FAA/AR-01/91, November 2001.

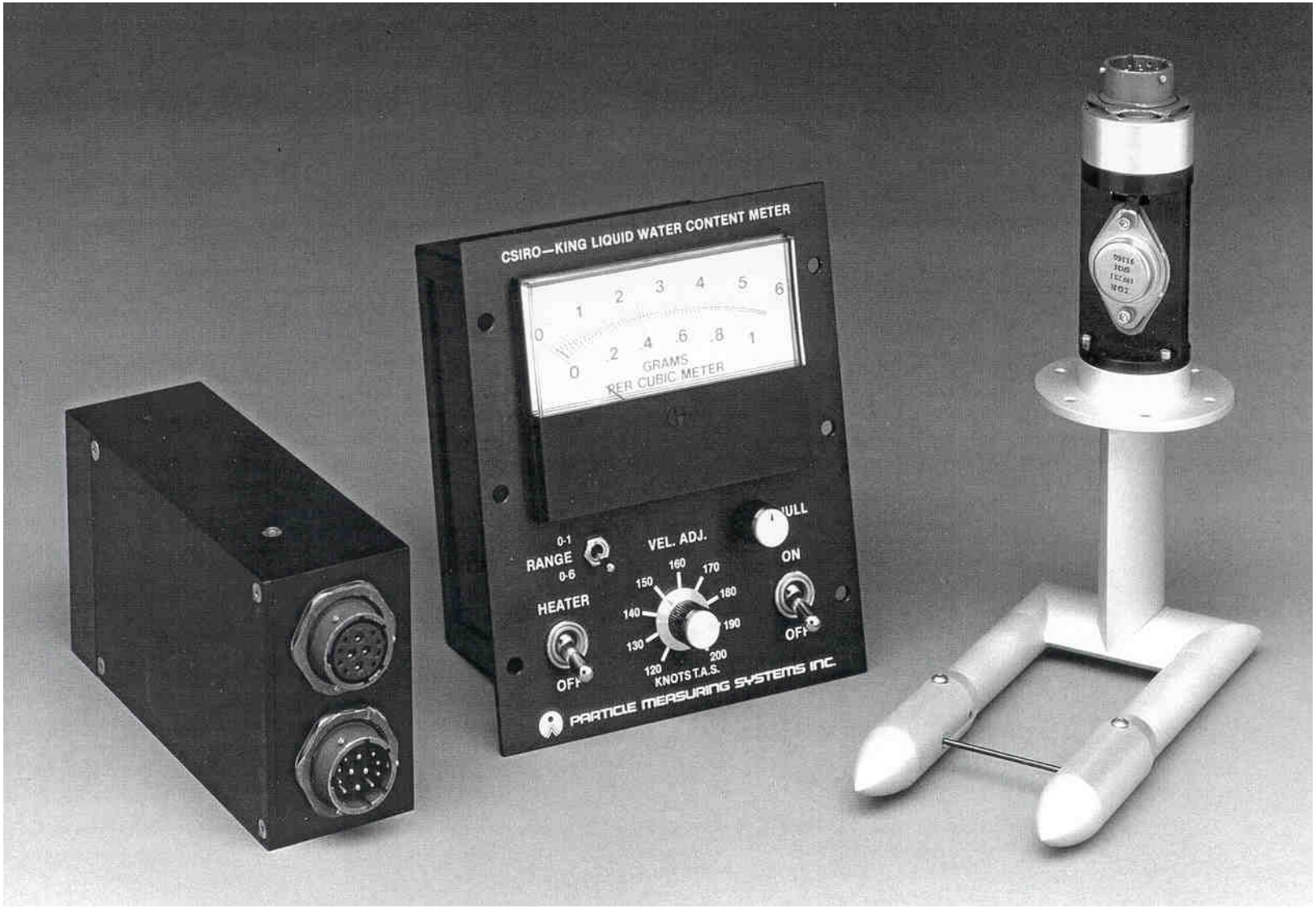


FIGURE 1. THE CSIRO “KING” LWC SENSING SYSTEM

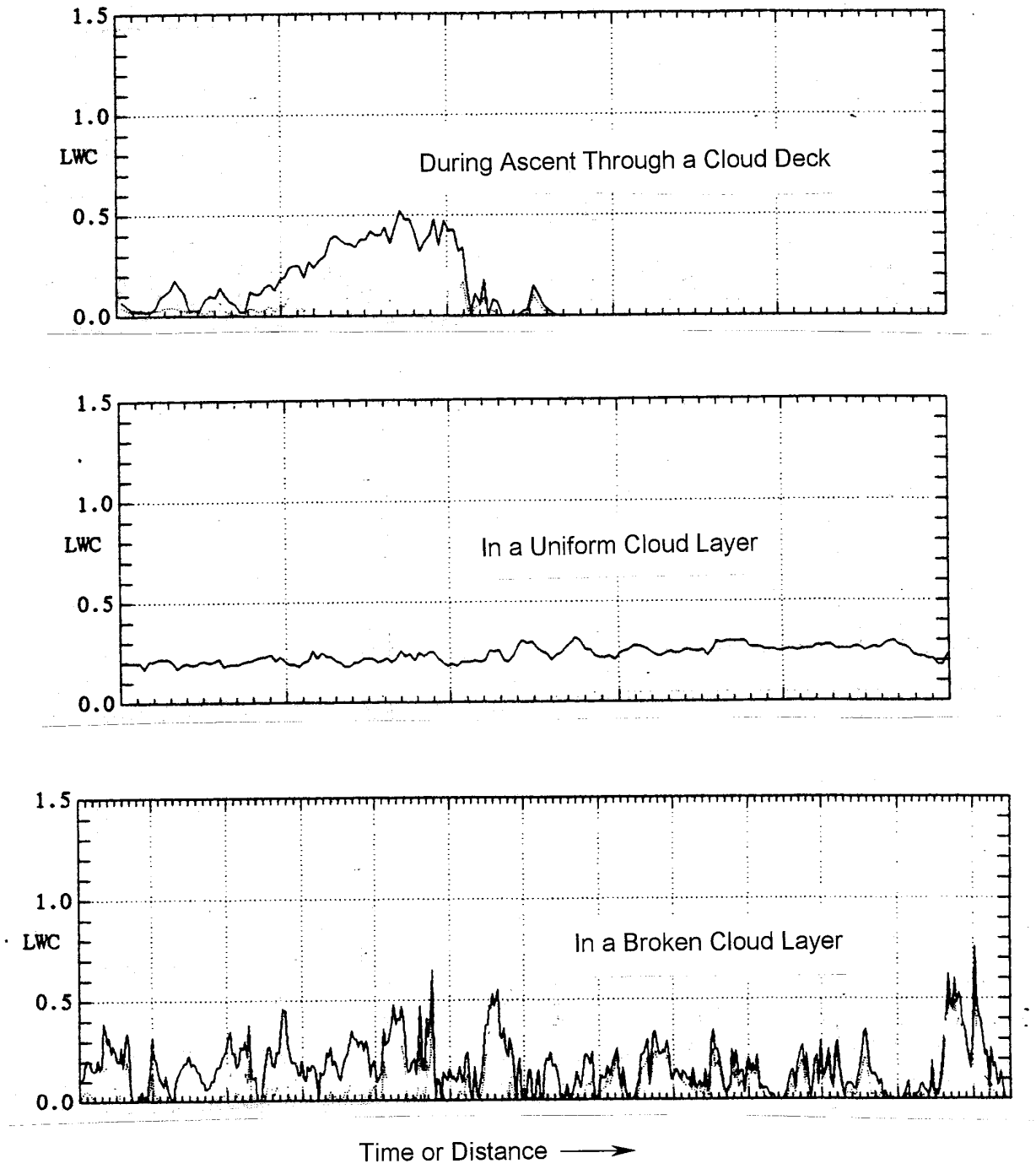
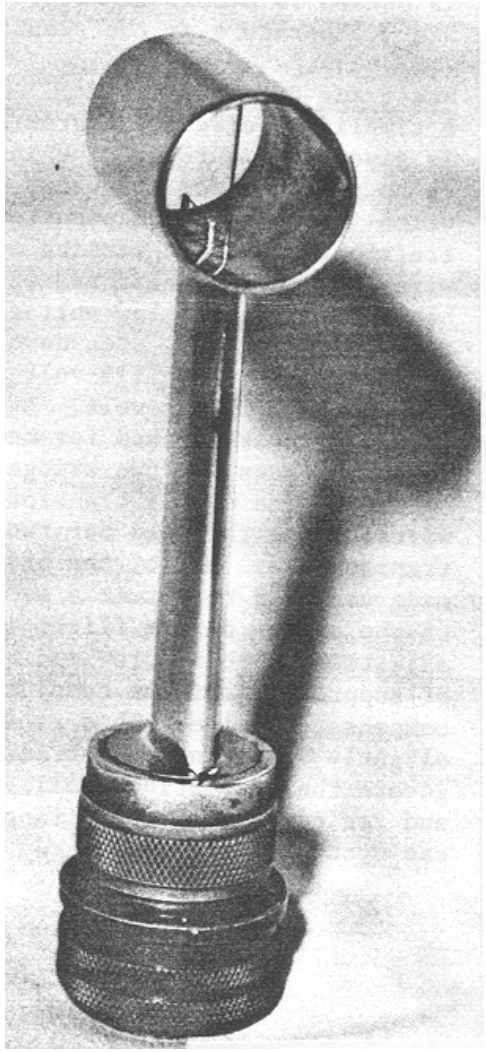


FIGURE 2. EXAMPLES OF SOME LWC RECORDS



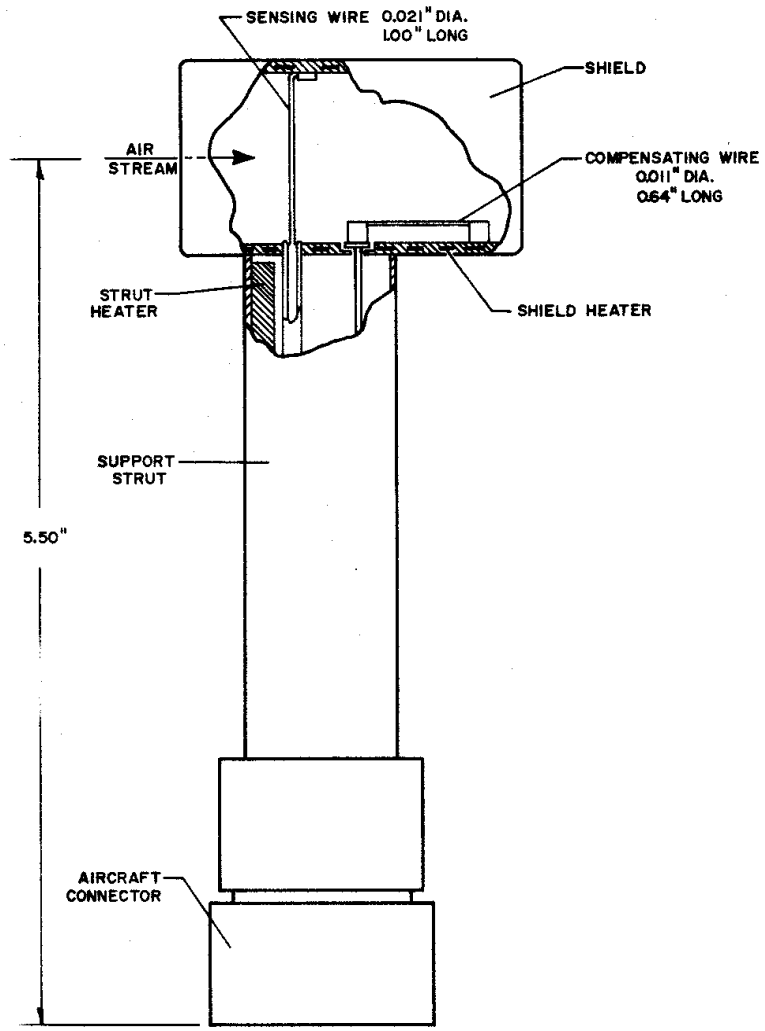


FIGURE 3. PHOTOGRAPH AND DRAWING OF THE “J-W” HOT-WIRE LWC SENSOR (SHOWN 80% FULL SCALE)

TABLE 1. EXAMPLE OF AN INFORMATIVE TABULAR DISPLAY OF LWC DATA

	A	B	C	D	E	F	G	H	I	J
1	**Suggested Data Presentation for LWC Sensor**									
2	Notes:	1) Icing rate on a clean, unheated component computed from formula:								
3				Rate (mm/min) = (A)x(LWC)x(Beta)x(TAS)x(25.4 mm/inch),						
4		where	Beta =	0.35	for a Convair CV-640 outer wing section* at about 200 kt TAS,					
5		and	A =	0.0016	* (NACA 23015 with chord=1.40 m)					
6		2) Other user input:								
7			dt(sec) =	5	for the data in this example.					
8										
9	(User Input)		Nominal Icing Rate on Clean, Unheated Component					(User Input)		
10		Measured	(Convair CV-640 outer wing section*)				Pres			Cum.
11	Time	LWC	Icing Rate	Icing	Running Avg	Cum. Icing	Alt	OAT	TAS	Distance
12	(hh:mm:ss)	(g/m3)	(mm/min)	Intensity**	(mm/min)	Depth (mm)	(k Ft)	(degC)	(kt)	(nmi)
13	122530	0.00	0.00	None	0.00	0.00	16.8	-23.1	213	0.3
14	122535	0.01	0.03	Trace	0.02	0.00	16.8	-23.5	214	0.6
15	122540	0.03	0.09	Trace	0.04	0.01	16.9	-23.2	215	0.9
16	122545	0.01	0.03	Trace	0.04	0.01	16.8	-23.1	214	1.2
17	122550	0.02	0.06	Trace	0.04	0.02	16.8	-23.3	218	1.5
18	122555	0.05	0.15	Light	0.07	0.03	16.8	-23.1	217	1.8
19	122600	0.02	0.06	Trace	0.08	0.04	16.8	-23.1	218	2.1
20	122605	0.04	0.12	Light	0.09	0.05	16.8	-23.4	218	2.4
21	122610	0.06	0.19	Light	0.12	0.06	16.8	-23.6	217	2.7
22	122615	0.07	0.22	Light	0.15	0.08	16.8	-23.6	217	3.0
23	122620	0.10	0.31	Light	0.18	0.11	16.8	-23.6	217	3.3
24	122625	0.15	0.46	Moderate	0.26	0.14	16.8	-23.6	217	3.6
25	122630	0.11	0.34	Light	0.30	0.17	16.8	-23.6	218	3.9
26	122635	0.08	0.25	Light	0.31	0.19	16.8	-23.6	216	4.2
27	122640	0.07	0.22	Light	0.31	0.21	16.8	-23.6	217	4.5
28	122645	0.08	0.25	Light	0.30	0.23	16.8	-23.6	217	4.8
29	122650	0.07	0.22	Light	0.25	0.25	16.8	-23.6	216	5.1
30	122655	0.07	0.22	Light	0.23	0.27	16.8	-23.6	217	5.4
31	122700	0.07	0.22	Light	0.22	0.29	16.8	-23.6	217	5.7
32	122705	0.07	0.22	Light	0.22	0.30	16.8	-23.6	218	6.0
33	122710	0.07	0.22	Light	0.22	0.32	16.8	-23.6	218	6.3
34	122715	0.07	0.22	Light	0.22	0.34	16.8	-23.6	219	6.6
35	122720	0.07	0.22	Light	0.22	0.36	16.8	-23.6	217	6.9
36	122725	0.06	0.18	Light	0.21	0.37	16.8	-23.6	216	7.2
37	122730	0.04	0.12	Light	0.19	0.38	16.8	-23.6	215	7.5
38	122735	0.05	0.15	Light	0.18	0.40	16.8	-23.6	216	7.8
39	122740	0.07	0.21	Light	0.18	0.41	16.8	-23.6	214	8.1
40	122745	0.08	0.24	Light	0.18	0.43	16.8	-23.6	215	8.4
41	122750	0.10	0.31	Light	0.21	0.46	16.8	-23.6	218	8.7
42	122755	0.11	0.34	Light	0.25	0.49	16.8	-23.6	218	9.0
43	122800	0.12	0.37	Light	0.30	0.52	16.8	-23.6	217	9.3
44	122805	0.11	0.34	Light	0.32	0.55	16.8	-23.6	215	9.6
45	122810	0.14	0.43	Moderate	0.36	0.58	16.8	-23.6	216	9.9
46	122815	0.14	0.43	Moderate	0.38	0.62	16.8	-23.6	215	10.2
47	122820	0.15	0.46	Moderate	0.41	0.66	16.8	-23.6	216	10.5
48	122825	0.20	0.61	Moderate	0.45	0.71	16.8	-23.6	216	10.8
49	122830	0.19	0.58	Moderate	0.50	0.76	16.8	-23.6	215	11.1
50	122835	0.17	0.52	Moderate	0.52	0.80	16.8	-23.8	215	11.4
51	122840	0.21	0.65	Moderate	0.56	0.85	16.8	-23.7	217	11.7
52	122845	0.22	0.69	Moderate	0.61	0.91	16.8	-23.8	219	12.0
53	122850	0.23	0.71	Moderate	0.63	0.97	16.8	-23.7	217	12.3
54	122855	0.23	0.71	Moderate	0.65	1.03	16.8	-23.6	216	12.6
55	122900	0.26	0.80	Moderate	0.71	1.10	16.8	-23.6	217	12.9
56	122905	0.27	0.83	Moderate	0.75	1.17	16.8	-23.6	216	13.2
57	122910	0.27	0.82	Moderate	0.77	1.23	16.8	-23.6	214	13.5

TABLE 1. EXAMPLE OF AN INFORMATIVE TABULAR DISPLAY OF LWC DATA (Continued)

	A	B	C	D	E	F	G	H	I	J
58	122915	0.28	0.86	Moderate	0.80	1.31	16.8	-23.6	217	13.8
59	122920	0.28	0.86	Moderate	0.84	1.38	16.8	-23.6	216	14.1
60	122925	0.28	0.86	Moderate	0.85	1.45	16.8	-23.7	217	14.4
61	122930	0.27	0.83	Moderate	0.85	1.52	16.8	-23.6	215	14.7
62	122935	0.29	0.90	Moderate	0.86	1.59	16.8	-23.6	217	15.0
63	122940	0.30	0.93	Moderate	0.87	1.67	16.8	-23.7	217	15.3
64	122945	0.31	0.95	Moderate	0.89	1.75	16.8	-23.6	215	15.6
65	122950	0.29	0.88	Moderate	0.90	1.82	16.8	-23.6	214	15.9
66	122955	0.32	0.98	Moderate	0.93	1.90	16.8	-23.6	215	16.2
67	123000	0.31	0.96	Moderate	0.94	1.98	16.8	-23.7	218	16.5
68	123005	0.31	0.96	Moderate	0.95	2.06	16.8	-23.6	218	16.8
69	123010	0.31	0.96	Moderate	0.95	2.14	16.8	-23.6	218	17.1
70	123015	0.31	0.96	Moderate	0.96	2.22	16.8	-23.6	217	17.4
71	123020	0.30	0.92	Moderate	0.95	2.30	16.8	-23.7	215	17.7
72	123025	0.30	0.92	Moderate	0.94	2.38	16.8	-23.6	215	18.0
73	123030	0.27	0.83	Moderate	0.92	2.45	16.8	-23.8	215	18.3
74	123035	0.27	0.83	Moderate	0.89	2.51	16.8	-23.6	215	18.6
75	123040	0.29	0.89	Moderate	0.88	2.59	16.8	-23.6	216	18.9
76	123045	0.29	0.88	Moderate	0.87	2.66	16.8	-23.6	213	19.2
77	123050	0.26	0.79	Moderate	0.84	2.73	16.8	-23.8	214	19.5
78	123055	0.28	0.86	Moderate	0.85	2.80	16.8	-23.6	215	19.8
79	123100	0.24	0.72	Moderate	0.83	2.86	16.9	-23.6	210	20.1
80	123105	0.22	0.65	Moderate	0.78	2.91	17.1	-24.0	207	20.4
81	123110	0.19	0.54	Moderate	0.71	2.96	17.3	-24.3	198	20.7
82	123115	0.17	0.46	Moderate	0.64	3.00	17.5	-24.8	191	20.9
83	123120	0.12	0.32	Light	0.54	3.02	17.7	-25.5	186	21.2
84	123125	0.11	0.29	Light	0.45	3.05	17.8	-25.7	185	21.5
85	123130	0.07	0.19	Light	0.36	3.06	17.9	-26.0	187	21.7
86	123135	0.11	0.30	Light	0.31	3.09	17.9	-26.1	190	22.0
87	123140	0.09	0.24	Light	0.27	3.11	17.9	-26.2	191	22.2
88	123145	0.03	0.08	Trace	0.22	3.11	17.9	-26.3	195	22.5
89	123150	0.05	0.14	Light	0.19	3.13	18.0	-26.1	199	22.8
90	123155	0.07	0.20	Light	0.19	3.14	18.0	-26.3	202	23.1
91	123200	0.08	0.24	Light	0.18	3.16	18.0	-26.4	207	23.4
92	123205	0.08	0.24	Light	0.18	3.18	18.0	-26.1	212	23.7
93	123210	0.09	0.28	Light	0.22	3.21	18.0	-26.1	217	24.0
94	123215	0.06	0.19	Light	0.23	3.22	18.0	-26.1	220	24.3
95	123220	0.02	0.06	Trace	0.20	3.23	17.9	-26.1	221	24.6
96	123225	0.02	0.06	Trace	0.17	3.23	17.9	-25.9	219	24.9
97	123230	0.04	0.12	Light	0.14	3.24	17.9	-26.4	218	25.2
98	123235	0.01	0.03	Trace	0.09	3.25	17.9	-26.7	218	25.5
99	123240	0.00	0.00	None	0.06	3.25	17.9	-26.7	220	25.8
100	123245	0.00	0.00	None	0.04	3.25	17.9	-26.7	221	26.1
101	123250	0.00	0.00	None	0.03	3.25	17.9	-26.6	223	26.4
102	123255	0.00	0.00	None	0.01	3.25	17.9	-25.9	225	26.7
103	1-minute cloud gap		0.00	None	0.00	3.25				26.7
104	123355	0.00	0.00	None	0.00	3.25	18.0	-25.6	219	27.0
105	123400	0.01	0.03	Trace	0.01	3.25	18.0	-25.7	219	27.3
106	123405	0.03	0.09	Trace	0.03	3.26	18.0	-26.1	220	27.6
107	123410	0.02	0.06	Trace	0.04	3.26	18.0	-26.1	221	27.9
108	123415	0.01	0.03	Trace	0.04	3.26	17.9	-26.1	220	28.2
109	123420	0.03	0.09	Trace	0.06	3.27	17.9	-26.2	221	28.5
110	123425	0.03	0.09	Trace	0.08	3.28	17.9	-26.1	222	28.9

TABLE 1. EXAMPLE OF AN INFORMATIVE TABULAR DISPLAY OF LWC DATA (Continued)

	A	B	C	D	E	F	G	H	I	J
111	123430	0.05	0.16	Light	0.09	3.29	17.9	-26.3	222	29.2
112	123435	0.06	0.19	Light	0.11	3.31	17.9	-26.7	223	29.5
113	123440	0.09	0.28	Light	0.16	3.33	17.9	-26.2	221	29.8
114	123445	0.10	0.31	Light	0.21	3.36	17.9	-26.1	220	30.1
115	123450	0.11	0.34	Light	0.26	3.39	17.9	-26.1	220	30.4
116	123455	0.15	0.47	Moderate	0.32	3.43	17.9	-26.1	220	30.7
117	123500	0.12	0.37	Light	0.36	3.46	18.0	-26.1	217	31.0
118	123505	0.12	0.36	Light	0.37	3.49	18.2	-26.2	209	31.3
119	123510	0.03	0.09	Trace	0.33	3.49	18.4	-26.8	206	31.6
120	123515	0.02	0.06	Trace	0.27	3.50	18.6	-27.1	202	31.9
121	123520	0.00	0.00	None	0.17	3.50	18.7	-27.3	195	32.1
122	123525	0.00	0.00	None	0.10	3.50	18.8	-27.6	196	32.4
123	123530	0.00	0.00	None	0.03	3.50	18.8	-27.6	198	32.7
124	123535	0.00	0.00	None	0.01	3.50	18.9	-27.9	201	33.0
125										
126										
127		** Icing Intensities defined as:								
128		**Trace**: 1/4-inch accumulation in 1 hour or longer (less than 0.1 mm/min), (less than 1/4-inch per hour),								
129		**Light**: 1/4-inch accumulation in 15-60 minutes (0.1 - 0.4 mm/min), (1/4 to 1 inch per hour),								
130		**Moderate**: 1/4-inch accumulation in 5-15 minutes (0.4 - 1.3 mm/min), (1 to 3 inches per hour),								
131		**Heavy**: 1/4-inch accumulation in less than 5 minutes (more than 1.3 mm/min), (more than 3 inches per hour).								

Explanation of the procedure and of the formulas in the columns of table 1.

1. User pastes recorded values of data into the columns for Time, LWC, Altitude, OAT, and TAS,
2. Formulas for nominal icing rate and cumulative exposure distance will automatically compute the corresponding values for those columns. The nominal icing rates are a way to put the data in perspective and to evaluate the significance of the icing encounter.
3. The formulas operate as follows:
   - The nominal icing rate on a user-selectable wing section, tailplane, or other component of interest is computed from the formula:
     Icing Rate (mm/min) = (A)x(LWC)x(Beta)x(TAS)x(25.4 mm/inch),
     where Beta is the peak collection efficiency for cloud droplets on the component of interest at the airspeeds shown in the TAS column, and the constant (A) varies from 0.0009 to 0.0014, depending on the component and the airspeed.
     (See the Appendix in Ref. 11 for an introductory explanation and examples for other airplanes.)
     The values for Beta can be easily obtained from LEWICE or similar droplet impingement codes.
     Beta depends mainly on the leading edge radius of the component and on the airspeed and the droplet sizes in the icing cloud.
     If droplet size is not measured, a standard size of 15 microns can be assumed for the median volume diameter (MVD).
     The components will be for the actual aircraft under test. The CV-640 outer wing is shown only as an example.
     (These computations of nominal icing rate and accumulation DO NOT account for any incomplete freezing and reduced ice accretion when the total air temperatures are near or above 0 degC.
     In this case the computed nominal amounts will be greater than actual amounts on the airplane component.
   - Column C computes the Icing Rate according to the formula above.
   - Column D converts the numerical icing rate in column C to an icing intensity according to the definitions given above.
   - Column E computes a 5-sec running average of the icing rate on the component.
   - Column F estimates a cumulative ice accretion depth on the component for which ice accretion is being computed. It assumes:
     (a) continual accretion (no de-icing) during the encounter.
     (b) a constant value for Beta. (This assumption is good for up to 1/4-inch (6.4 mm) of ice accretion.
     After that, Beta may begin to change somewhat and the estimated ice accumulation will be less accurate.)
   - Column J computes the cumulative distance traveled in the exposure, based on the TAS values given in column I.

Formulas used in the columns:

Col. C: A*LWC*Beta*TAS*(25.4)
where LWC and TAS are taken from columns B and I, respectively, in the same row
and Beta and “A” are the values entered in cells D4 and D5, respectively, by the user.

Col D: IF(IcingRate>1.27,”Heavy”,IF(IcingRate>0.423,”Moderate”,IF(IcingRate>0.106,”Light”,IF(Icing Rate>0,”Trace”,”None”))))
where Icing**Rate** is the adjacent value computed in column E.

Col E: AVERAGE(R[-4]C[-2]:RC[-2])

Col F: IcingRate*(dt/60)+R[-1]C
where dt is the sampling rate entered in cell D7 by the user.

Col. J: (TAS/3600)*dt, where TAS is the adjacent value in column I.

Version of May 7, 2005. Prepared by Richard Jeck, Research Physicist/Meteorologist, Flight Safety Research Section (ATO-P R&D)
FAA William. J. Hughes Technical Center, Atlantic City International Airport, New Jersey 08405.