**Table 1 Absorption of ozone and iodine[a]**

| Materials | | Oils |
|---|---|---|
| Ozone | Iodine | Ozone |
| Glass | Glass | Watch oil |
| Acetate | Polystyrene | Apiezon A oil |
| Nylon | Acetate | Florube oil |
| Polyethylene | Polyethylene | Silicon oil |
| Polyvinyl chloride | Perspex | |
| | Polyvinyl chloride | |
| | Nylon | |

[a]The columns show the materials in order of suitability for use with the bubbler. The material absorbing least heads the column.

The best lubricating oil for the pump was, surprisingly, a simple watch oil.

In the final manufacture of the bubbler and pump, great care is taken to keep all the components clean, and certain treatments are carried out to help further reduce losses. The pumps and polyethylene tubing are stored in a permanent ozone atmosphere, and the lubricating oil is regularly ozonized by bubbling ozone through it for several hours. Iodine absorption losses are reduced by iodization of the bubbler reaction cell. It is filled with potassium iodide solution, and ozone is bubbled through it to form iodine. This is not removed electrochemically, and the walls of the cell are allowed to absorb the iodine.

These treatments proved very effective. Ozonesondes treated this way and stored in conditions similar to those at an ozonesonde station were found to have ozone losses ranging from 0 to 7%. As a result, the total ozone losses in an ozonesonde sounding are assumed to be $4 \pm 4\%$.

### Accuracy of the Bubbler Ozonesonde

In addition to the ozone and iodine losses just mentioned, there are errors involved in monitoring the airflow rate during the ozonesonde sounding. These errors are $\pm 6\%$, giving a total possible error of $\pm 10\%$ before telemetry, which may introduce further errors. However, analysis of more than fifty ozonesonde flights in England suggests that the errors are probably less.

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# Trailing Vortices of Jet Transport Aircraft during Takeoff and Landing

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Recently, emphasis has been placed on determining the minimum safe separation intervals of aircraft during approach, landing, and takeoff from busy airports. One of the limiting factors governing the separation interval is the wing trailing vortex velocity field of the lead aircraft. This vortex velocity field affects the separation interval somewhat as the type and size vary of the lead and following aircraft. In addition, the movements of the trailing vortices result in different exposure paths for the following aircraft, depending on whether a takeoff or landing is being conducted. Multiple runway layouts involve considerations of trailing vortex movement. Parallel runways require sufficient lateral separation to prevent trailing vortices generated over one runway from interfering with operations at the adjacent runway. Intersecting runways are continuously subject to trailing vortex interference. For example, a long main runway, reserved for very large airplanes, may intersect several short runways used for general aviation operations, and therefore the very large airplane trails vortices over all the intersecting runways used by light aircraft. The induced effects of the trailing vortices have become more serious with the advent of the large jet transport aircraft capable of creating very strong vortices. Recently, several cases of litigation have been noted in which it was claimed that fatal airplane crashes were the result of taking off into a trailing vortex velocity field generated by large jet transports.

The danger of trailing vortices to light planes during takeoff and landing has been attested to by almost all of the Douglas Aircraft Company pilots, flying light twin-engined aircraft into airports used by large jet transports. In particular, jet transport training operations where the light aircraft follow the large transport, making touch-and-go landings, results in trailing vortices occurring along the entire runway. Numerous causes of uncontrollable 90° to 180° rolls in 6000-lb aircraft have been experienced by Douglas Company pilots encountering trailing vortices, and the usual experience has been that the vortex velocity field will force the aircraft out of the vortex in a few seconds. As the aircraft may be inverted when coming out of the vortex, encountering vortices near the ground must be avoided.

In order to obtain quantitative information on the behavior of trailing vortices of jet transports near the ground, the Systems Research and Development Service of the Federal Aviation Agency sponsored a test program, and this note will present data from this program on the movement and decay of wing trailing vortices from Douglas DC-8 jet transport aircraft during takeoff and landing in low wind conditions. The complete test program and data are detailed in Ref. 1. Existing theory will be used to show the degree of correlation with the test data. The difference in wing configuration for the DC-8 during takeoff and landing results in a large increase in flap-end vorticity during landing. Information on the number of trailing vortices will be presented for both configurations. The test program was conducted in two parts. Each of the parts and its results will be described separately.

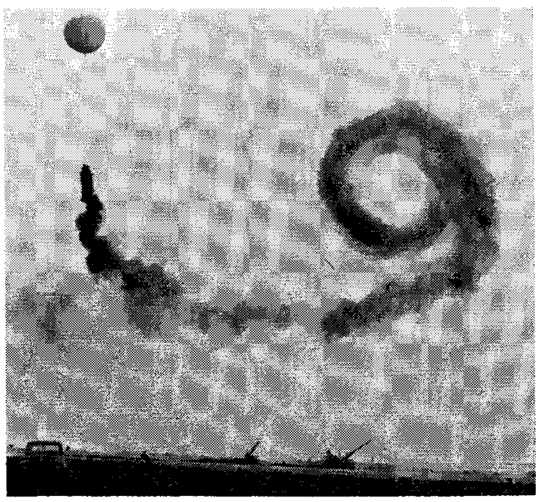

Fig. 1 Wing trailing vortex visualization.

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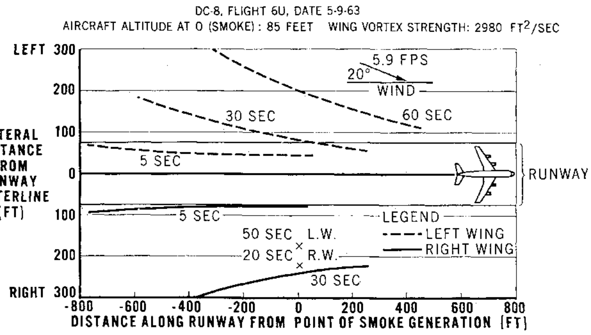


**Fig. 2 Theoretical location of trailing vortices near the ground.**

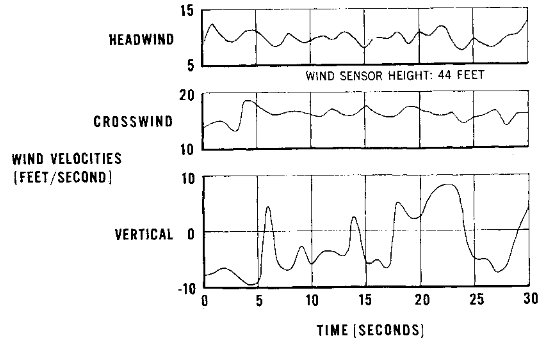


**Fig. 4 Ambient wind velocities prior to takeoff.**

### Trailing Vortex Movement near the Ground

Tests were performed to determine the general movement of the rolled-up trailing vortices during low wind conditions. Commercial airline operations were utilized to provide the trailing vortices. The vortices were generated by Douglas DC-8 aircraft with gross weights from 176,000 to 217,000 lb, taking off and passing overhead at heights of 85 to 292 ft. The method used to visualize and therefore locate the vortices was to suspend a smoke generator from a helium-filled weather balloon at the height predicted for the core center of the vortex (about 50 ft). The equipment was located 150 ft off the centerline of the runway, and the smoke generator was actuated after the aircraft had passed the observation point. The aircraft position was determined from camera data, and color movies were obtained of the smoke patterns. Hand-held velometers were used to obtain the wind velocities at the 5-ft level. The rolled-up trailing vortices were made clearly visible by the smoke, as shown in Fig. 1. During a landing approach, the far-wing vortex movement was slow enough to alloy a large quantity of smoke to be introduced into the vortex core center. Immediately, a thin filament of smoke moved very rapidly along the vortex axis in the direction of the aircraft at approximately the speed of the aircraft in accordance with viscous vortex theory.

The available theory on the initial position and subsequent movement of rolled-up trailing vortices was utilized to determine correlation with the observed vortices. The problem is complicated because of the change in altitude of the vortex-generating airplane. The vortices then generated along the runway are influenced by the ground to a varying degree and therefore move at different horizontal velocities along the runway. A further consideration is the vertical wind velocity gradients present near the ground. All these factors were incorporated in a digital computer program, and the theoretical positions of the vortices were calculated for the takeoff vortices observed. A typical presentation of the theoretical movement of the trailing vortices is shown in Fig. 2. The observed movement, in the vertical plane of the smoke generator and perpendicular to the runway centerline, as measured from the movie films, is shown in Fig. 3. The opposite wing vortices were identified by the differences in rotation of the vortex. The measured winds influenced the results greatly because the wind velocities were the same order of magnitude as the vortex movement velocities. The observed lateral position of the vortex cores for periods up to 65 sec after aircraft passage, deviated a maximum of about 330 ft from the calculated positions. In cases where a vortex appeared on the opposite side of the runway compared with the theoretical position, which occurred several times with the far wing vortices, it is considered that observed wind directions or velocities were in error. Limiting heights above the ground for the vortex core were found to be about 40 ft, which is 16 ft below the asymptotic height predicted by the theory for the Douglas DC-8 aircraft. A limited examination of the trailing vortex system with the landing approach configuration of the DC-8 (with 50° flap deflection) showed a total of two trailing vortices of the same type seen during the takeoffs.

During the tests, when the aircraft passes the observation point at altitudes of about 100 ft, a strong lateral wind gust was felt by the observers. This was sometimes interpreted as the tangential velocity field of the vortex, and the smoke generators were actuated immediately for fear of losing the vortex. In every case of this type, the vortex was observed, with the smoke a few seconds later, meaning that a separate phenomenon was occurring. It is considered that the lateral wind gust originated from the pressure field under the aircraft as it passed by.

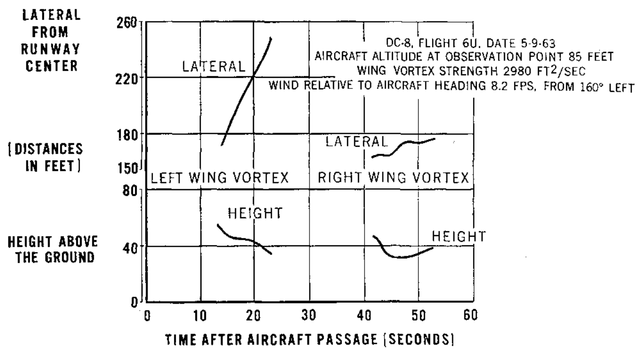


**Fig. 3 Measured location of trailing vortices near the ground.**

### Trailing Vortex Strength and Velocity Decay

The strengths (in terms of tangential velocities) and decay of trailing vortices were measured by two methods, the first of which utilized color movies of the observed vortices described previously. Discontinuities in the smoke patterns were followed for periods up to 2 sec. A velocity transducer was used to measure directly the vortex strength for the second method. A Flow Corporation Dynamic Wind Vector Indicator, which is a three-axes drag-force gage, measured the

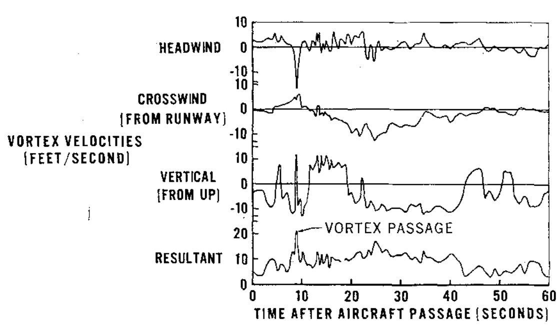


**Fig. 5 Wind and vortex velocities recorded during takeoff with steady wind removed.**

**Table 1 DC-8 takeoff trailing vortex decay**

| Flight | Time after aircraft, sec | Vortex radius measured, ft | Tangential velocity, fps Measured | Tangential velocity, fps Theoretical |
|---|---|---|---|---|
| 1U | 21 | 17 | 9 | 17 |
| 2U | 17.5 | 10.5 | 14 | 16.3 |
| 3U | 20.5 | 7.8 | 16.4 | 12.7 |
| 3U | 22 | 11.2 | 8.8 | 15.2 |
| 3U | 41 | 6.7 | 10.4 | 7.4 |
| 4U | 17.3 | 8 | 21 | 14.9 |
| 5U | 58 | 7.5 | 9 | 7 |
| Wind velocity sensor tests | | | | |
| 2 | 9 | ... | 34[a] | 23 |
| 3 | 9 | ... | 24[a] | 26 |
| 1 | 12 | ... | 21[a] | 18 |

[a] Peak velocities recorded and compared with peak theoretical values.

dynamic pressure due to the velocity. Difficulties were encountered in filtering out the ambient wind fluctuations. An example of the wind fluctuations measured at a height of 44 ft prior to the aircraft passage is shown in Fig. 4. The steady wind components were subtracted from the transducer readings, and a typical time history of the velocities recorded is shown in Fig. 5.

Theoretical methods based on the solution of the equations of motion for a free vortex and a matching of the radial velocities between the viscous core and the outer vortex were used to determine the degree of correlation obtained with the observed values. In addition, assumed values of atmospheric turbulence in terms of eddy viscosity were used in the theoretical calculations. Table 1 presents the measured tangential velocities along with the comparable theoretical values. The degree of velocity correlation is affected by the proximity of the measured values to the outer edge of the core, because at this point the velocity decay equation deviates most from the theoretical picture. The initial radius of the vortex core is calculated to be 11 ft. It is noted from Table 1 that the tangential velocities of actual trailing vortices, for periods up to 1 min after aircraft passage, approximate the magnitude predicted by the available viscous decay theory.

## Summary

This test program determined that wing trailing vortex positions were extremely sensitive to low-level wind conditions, including vertical velocity gradients, and that the existing theories can predict the approximate behavior of the vortices near the ground. It is concluded from the test results that the location of trailing vortices near the ground cannot be accurately predicted on the basis of routine wind data furnished by the control tower.

## Reference

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