Introduction

An average of 15.8 million gallons of fire retardant has been used in firefighting each year. Most of this retardant is released from the air. Aircraft are used to transport firefighting chemicals at the appropriate height and speed. The types of aircraft include:

- ❏ Fixed-wing multiengine airtankers.
- ❏ Fixed-wing single-engine airtankers.
- ❏ Helicopters with fixed tanks.
- ❏ Helicopters with suspended helibuckets.

The fire-retarding chemicals typically used in wildland firefighting are short-term and long-term retardants, foam, and water. The retardants may include a gum thickener.

The 10 principles for proper retardant application are:

1–Determine tactics, direct or indirect, based on fire characteristics and available resources.

2–Establish an anchor point and work from it (figure 1).

3–Use the proper drop height.

4–Apply the proper coverage levels.

5–Drop downhill and away from the sun.

6–Drop into the wind for the best accuracy.

7–Maintain an honest evaluation and effective communication between the ground and air.

8–Use direct attack when ground support is available or it is feasible to extinguish the fire.

9–Plan drops so that they can be extended or intersected effectively.

10–Monitor retardant effectiveness and adjust its use accordingly.

Figure 1—Airtanker establishing an anchor point.

Knowing the characteristics of the ground pattern obtained from a specific aircraft is an important component of proper retardant application (principles 1, 2, 4, and 9). Factors that influence the ground pattern of a retardant drop include:

- ❏ Drop height and drop speed.
- ❏ Flow rate of the liquid as it exits the tank.
- ❏ Volume of the liquid released.
- ❏ Tank geometry and venting.
- ❏ Gating system (the tank doors and release mechanism installed in an aircraft to release retardant).
- ❏ Rheological properties of the fire chemical (the flow characteristics of a fluid).
- ❏ Wind speed and direction.
- ❏ Temperature and relative humidity.
- ❏ Fuel type.
- ❏ Topography.
- ❏ Safety concerns of aircraft and ground personnel.
- ❏ Pilot proficiency.

Since the 1950's the Forest Service has used a procedure known as drop testing to quantify ground patterns. The procedure involves dropping fire chemicals from an airtanker flying over open cups arranged in a regularly spaced grid (figure 2). The cups are weighed before and after the drop to calculate the amount of retardant deposited in gallons per hundred square feet (gpc). These values are plotted onto a map of the grid. Points between cups are estimated, usually by an interpolation method that assumes uniform change between cups. Contour lines are made by connecting all points of equal coverage level. The length of each contour, referred to as line length, is calculated from observed and estimated data.

During a drop test, drops are made at varying drop heights, drop speeds, flow rates, volumes, and with different retardant materials to obtain a graphical and numerical picture of the ground patterns produced by the airtanker. Examining ground patterns provides information about the factors that influence the distribution of the drop (figure 3).

Some factors in a drop can be controlled, such as height, speed, flow rate, tank and gating system, and rheological (flow) properties of the retardant. Wind speed, wind direction, temperature, humidity, fuel type, and topography are among the factors affecting the ground patterns that cannot be controlled (Newstead and Lieskovsky 1985). Drop tests allow different tank and gating systems to be compared under similar conditions. Ground patterns can help managers learn the capabilities of an airtanker by determining the intervals between trail drops (figure 4). A trail drop is when door opening times are staggered to produce a long stream of retardant. An accurate set of ground patterns from an airtanker provides data to predict the time between releases needed for a successful trail drop.

This report will discuss factors affecting the ground pattern and give some historical background of the cup-and-grid method used to measure ground patterns. Additionally, new statistical tools will be presented that may improve the current cup-and-grid method.

Figure 2—The Dromader spray aircraft dropping water over a test grid.

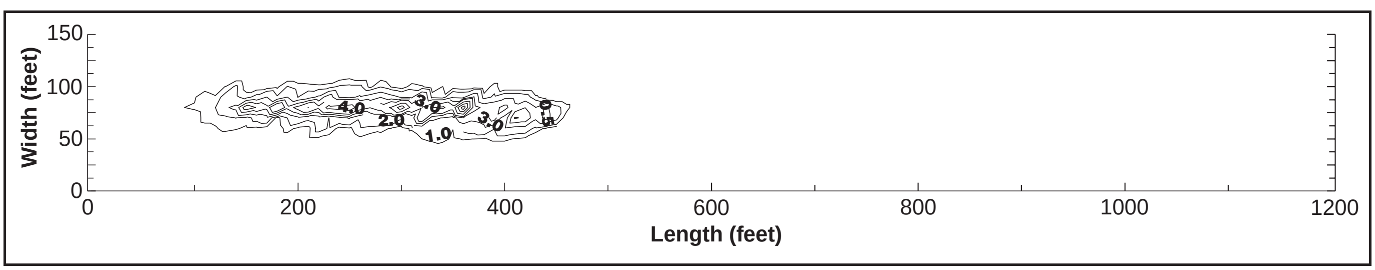


Figure 3—Drop pattern characteristics for the Marsh Turbo Thrush with a drop speed of 80 knots and a drop height of 31 feet.

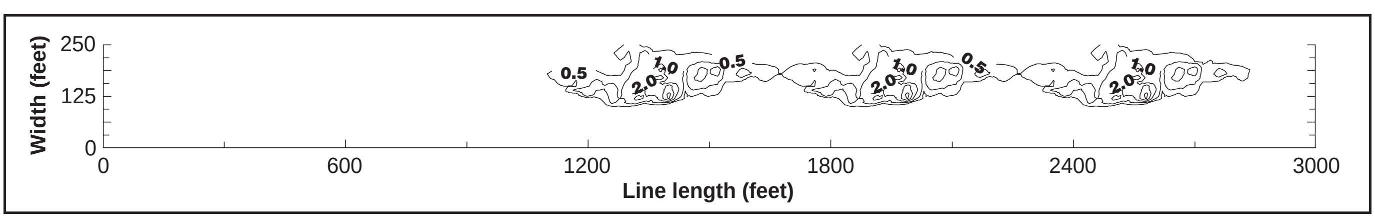


Figure 4—Computer simulation of a trail drop.

Mechanics of the Release

As an airtanker releases a load of retardant (figure 5), the fluid is distributed along the flight path. The characteristics of the drop (length, width, and coverage level) are a function of the height and speed of the aircraft, the flow rate and volume of the fluid exiting the tank, the rheological properties of the fluid, and the meteorological conditions (Swanson and Luedecke 1978).

The design of the tank and gating system directly affects the retardant flow rate. Relevant design elements include the size and shape of the door, the speed with which the door opens, and the geometry of the tank vents, baffling, cylinders, torque tubes, and other items inside the tank (figure 6, George and Blakely 1973). We have relied on the cup-and-grid method to understand how these factors influence the ground pattern.

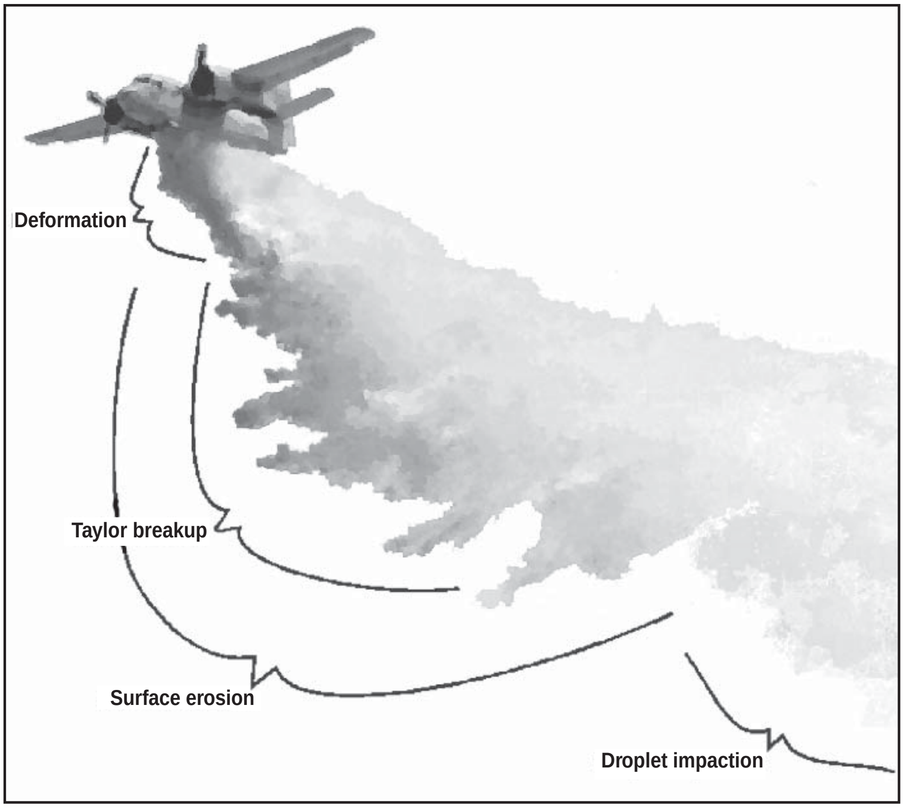


Figure 5—Distribution of fluid along the flight path.

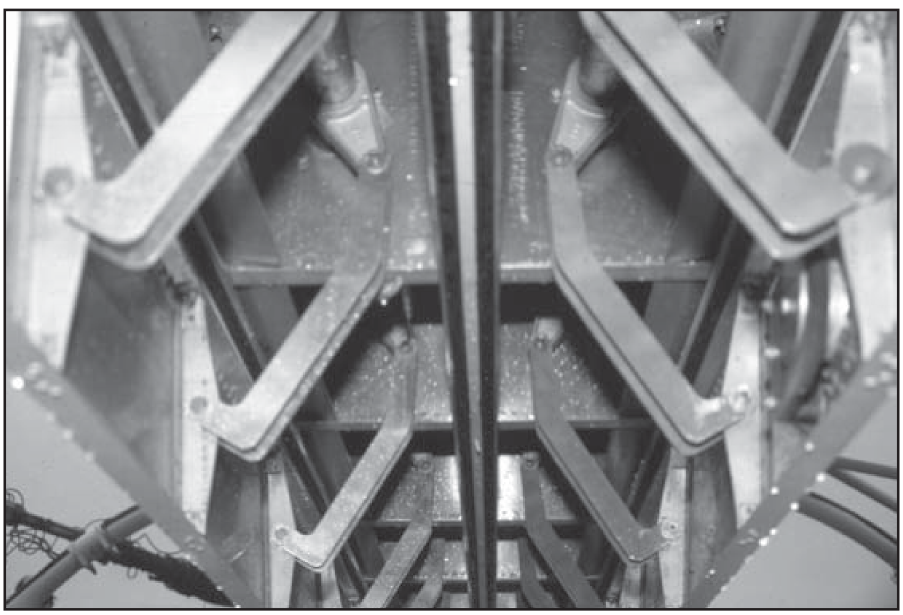


Figure 6—View of a tank and gating system showing baffling and torque arms, which produce clutter effect.

History of the Cup-and-Grid Method

Some of the first drop tests were conducted between 1955 and 1959 in California by the Pacific Southwest Forest and Range Experiment Station and the California Air Attack Coordinating Committee (Davis 1959). These tests were designed to answer six main questions.

- ❑ Does retardant viscosity affect drop behavior?
- ❑ Does retardant weight affect drop behavior?
- ❑ Do borate and bentonite have the same drop characteristics?
- ❑ How do airtanker height and speed affect the drop?
- ❑ How large should the gate be?
- ❑ Which is more important, airtanker carrying capacity or maneuverability?

The grid design for these tests consisted of 10-ounce paper cups sitting in a holder less than a foot off the ground (figure 7). Over a hundred cups were laid out in a geometric grid pattern. A Stearman biplane made the drops. Once the gpc was calculated, the values were plotted on graph paper. Contour plots were constructed by drawing lines between the points of equivalent gpc. Film was used to observe the airtanker's flight path in relation to the target. The film was also examined to determine retardant breakup, retardant drift, and the time from release to impact.

These early tests determined that:

- ❑ Increased viscosity reduces drift.
- ❑ Increasing the drop height increases the coverage area.
- ❑ Fall speed and drift are not increased by higher fluid weights.
- ❑ Borate and bentonite drop alike.
- ❑ Drift increases with both height and speed.

In 1959, Storey, Wendel, and Altobellis used the cup-and-grid method to investigate the retardant distribution and penetration patterns from a TBM airtanker in pine timber with and without understory. Hodgson drop tested a variety of aircraft in 1967. The grid dimensions were 480 by 172.5 feet, later increased to 570 by 202 feet. A total of 935 paper cups sat in can holders spaced at 15- by 7.5-foot intervals.

Figure 7—Paper cups being collected from the test grid. *—Photo courtesy of California Department of Forestry and Fire Protection. The fact that the California Department of Forestry and Fire Protection provided a photograph for this publication in no way implies the Department's endorsement of any theories or positions taken with this document.*

Points were estimated by linear interpolation. The report recommended closer cup spacing in the center of the grid where the coverage level tended to be heaviest.

Also during 1967 in Alberta, Canada, a University of Montana graduate student conducted a cup and grid test as part of his master's thesis. Joseph Grigel used a Snow Commander airtanker with a 250-gallon tank to drop Gelgard F, a short-term fire retardant, over an array of cups laid out in a grid format on the ground. Grigel went into more detail regarding methods and design. The objectives of the study as outlined by Grigel were to determine:

- ❑ The ground distribution patterns of Gelgard F retardant mixtures released from the Snow Commander airtanker onto an open area and a mature, well-stocked lodgepole-pine stand.
- ❑ The effect of release height and mixture viscosity on ground distribution patterns formed by Gelgard F retardant.
- ❑ The effect of tree canopy on the ground distribution patterns and recovery rates or the estimated amount of liquid that landed on the ground.

Grigel concluded that ground patterns were determined by height, speed, volume, gating system (as it contributes to flow rate), retardant properties, weather, and fuel or vegetation. A grid-within-a-grid layout was used. The inner grid consisted of cups spaced 7.5 feet apart, covering a 270- by 82.5-foot area (figure 8). An outer grid was built around the inner grid with 10- by 10-foot spacing. The outer grid was to catch any retardant that missed the inner grid. The entire grid, including the inner and outer portions, measured 350 by 142.5 feet (figure 9).

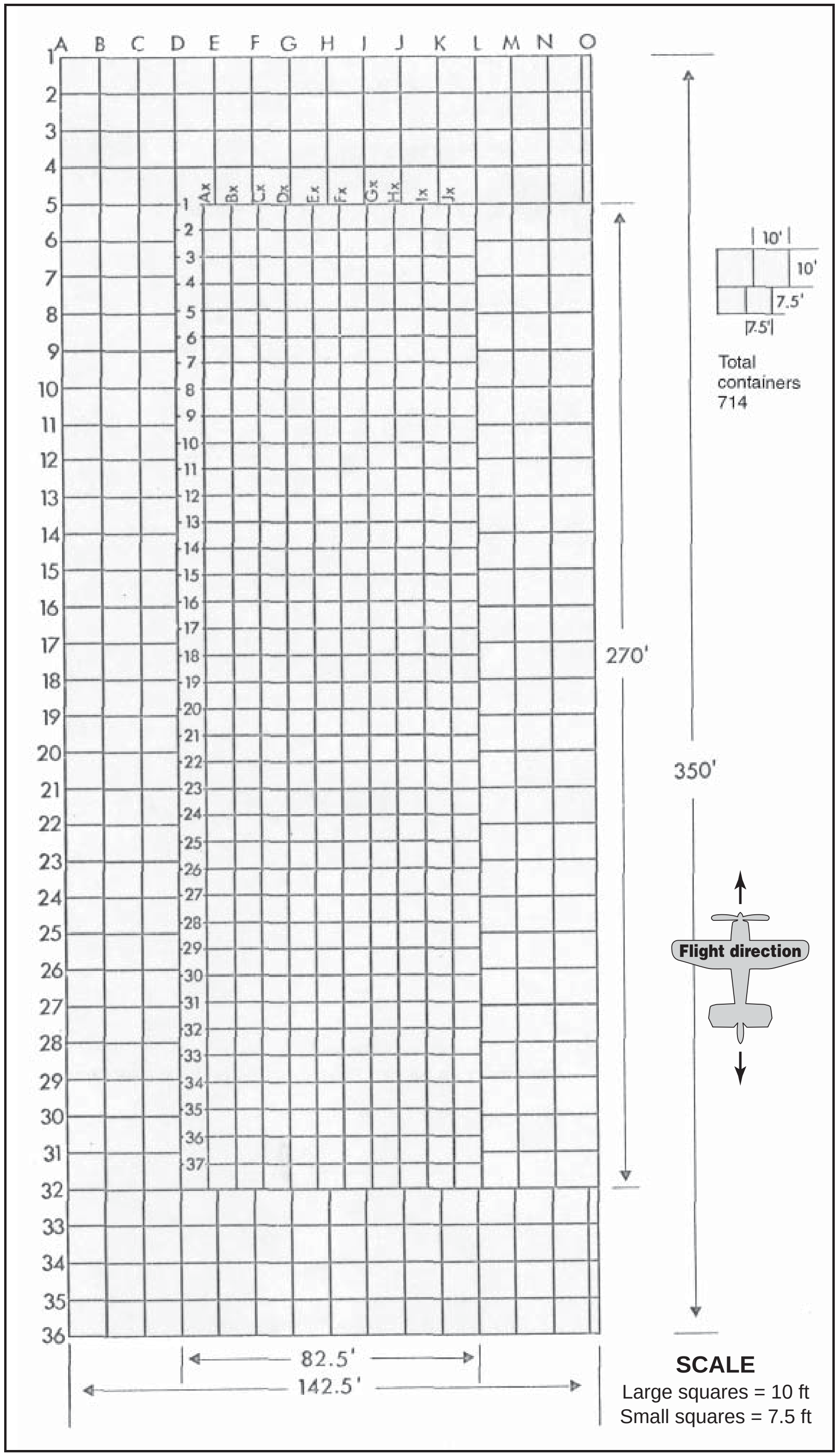


Figure 8—Diagram of Grigel's test grid. *—Courtesy of Joseph Grigel.*

Figure 9—Grigel's test grid set up in an open field. *—Photo courtesy of Joseph Grigel.*

It was assumed that each cup on the grid would represent one-half the distance to the adjacent containers. Linear interpolation was used to estimate points. Grigel noted some principal sources of error:

❑ Evaporation of water in the cup before weighing.

❑ Variation in the cup lid weights.

❑ Cup and can missing or not mounted vertically during the drop.

❑ Splashing of drop material.

❑ Human error.

The cup-and-grid method was examined more closely in 1973 (figure 10) at the Intermountain Forest and Range Experiment Station's Northern Forest Fire Laboratory in Missoula, now the Missoula Fire Sciences Laboratory (George and Blakely 1973). Two main questions were addressed:

❑ What is the accuracy or variation for a particular grid point?

❑ Is the overall grid spacing and sampling adequate?

In addition to an inner grid of closely spaced cups and an outer grid of more widely spaced cups, nine tables with nine cups each were placed in the inner grid. The nine cups were within an area of 20 by 20 inches. They were used to provide a measure of variation around a single sample point. This arrangement used the four surrounding grid points to provide a value to compare to the predicted value for the point. In addition, holes were cut in the tops of the three tables and deep cans were positioned so their tops were the same height as the cups (figure 11). These were used to determine if a significant amount of retardant was splashing out of the cups. Contour plots were calculated "using a method of linear proportioning." A vertical distribution test was conducted to determine retardant's penetration through the tree canopy and its retention on fuels.

The grid system was evaluated by plotting the observed mean concentration in gpc from the inner grid area against the observed mean concentrations from the table data. The observations were found to be highly correlated. Proportioning points for prediction purposes produced an error of less than ±0.5

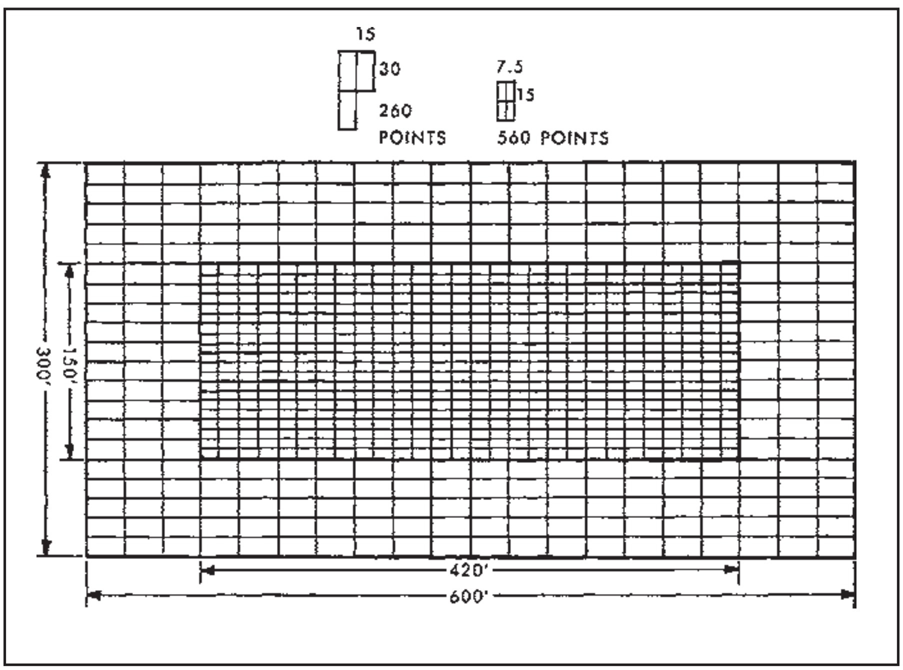


Figure 10—Diagram of George and Blakely's test grid.

Figure 11—Table of nine cups for measuring variation around a single sample point.

For these tests, cups were mounted on stakes at 10- by 10-foot intervals for the inner grid and up to 60- by 20-foot intervals for the outer grid. Grid size ranged from 250 by 600 feet up to 250 by 3,000 feet, depending on the volume dropped (figure 13).

Aircraft drop height and drop speed were measured using video analysis, a global positioning system (gps), and a radar altimeter. Video proved to be the most accurate and reliable. Four liquids were used: water, a 0.6-percent foam solution, gum-thickened retardant, and water-like retardant (figures 14 and 15). Flow-rate settings varied depending on the system. For example, the Bambi helibuckets were tested with only one flow-rate setting. Some airtankers were tested with up to as many as nine selectable flow-rate settings.

gpc. Variation was examined by plotting the standard deviation for the table concentrations against the mean gpc for each table. Levels up to 3 gpc would result in a standard deviation of 0.2 gpc or less.

D. H. Swanson and A. D. Luedecke used ground patterns in their 1978 paper, *Tank Design Guide for Fire Retardant Aircraft*, to compare the effects of different factors on the drop. Ground patterns obtained from the cup-and-grid method along with film showed that the most efficient drop occurs when the majority of the retardant's forward momentum has stopped before the retardant reaches the ground. These findings helped determine the proper drop height (figure 12).

In the 1990's the Forest Service conducted an extensive series of drop tests on a wide variety of retardant delivery systems. The systems tested included a number of helitankers and multiengine and single-engine fixed-wing airtankers. Drop-test data from each system were assembled into drop-test data books.

Figure 12—An example of retardant reaching the ground before forward momentum has stopped.

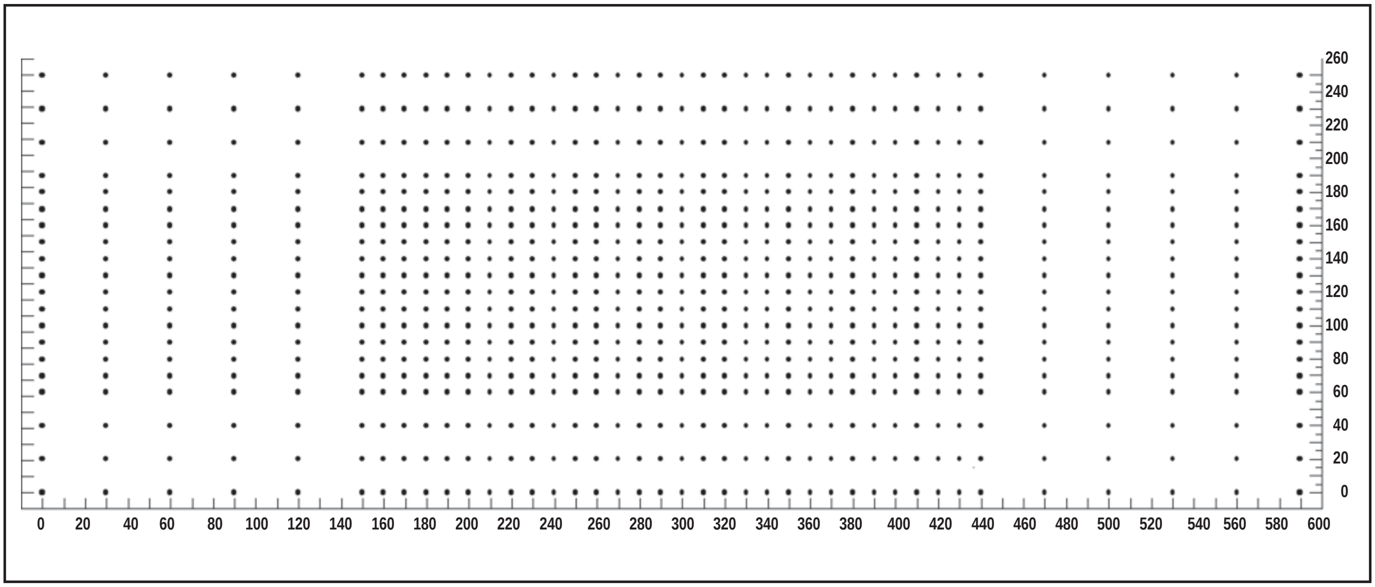


Figure 13—A 600-foot test grid from a 1999 drop test.

Figure 14—Foam dropped on the test grid.

Figure 15—Retardant dropped on the test grid.

Wind speed and direction were measured using a portable weather station adjacent to the drop site. Instrumentation was mounted 20 feet above the ground. The weight of retardant in each cup and the location of each cup within the grid were recorded. Linear interpolation was used to estimate unknown values (values between cups). Contour patterns were made with computer software (figure 16).

As with previous drop tests, ground patterns differed depending on aircraft height and speed, type of retardant or suppressant, flow rate, and wind conditions.

Drop testing over a regularly spaced array of cups has allowed researchers to measure the line length, width, and area, and to calculate the coverage level of the ground pattern. This has improved our knowledge of how height, speed, volume, tank geometry, flow rate, meteorological conditions, and retardant properties influence ground patterns. Yet data regarding the accuracy of the cup and grid method are sparse.

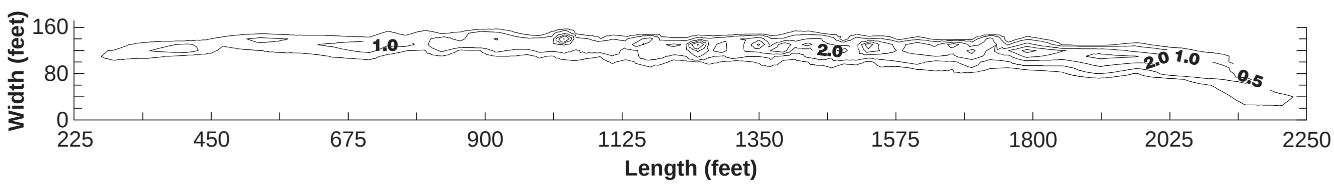
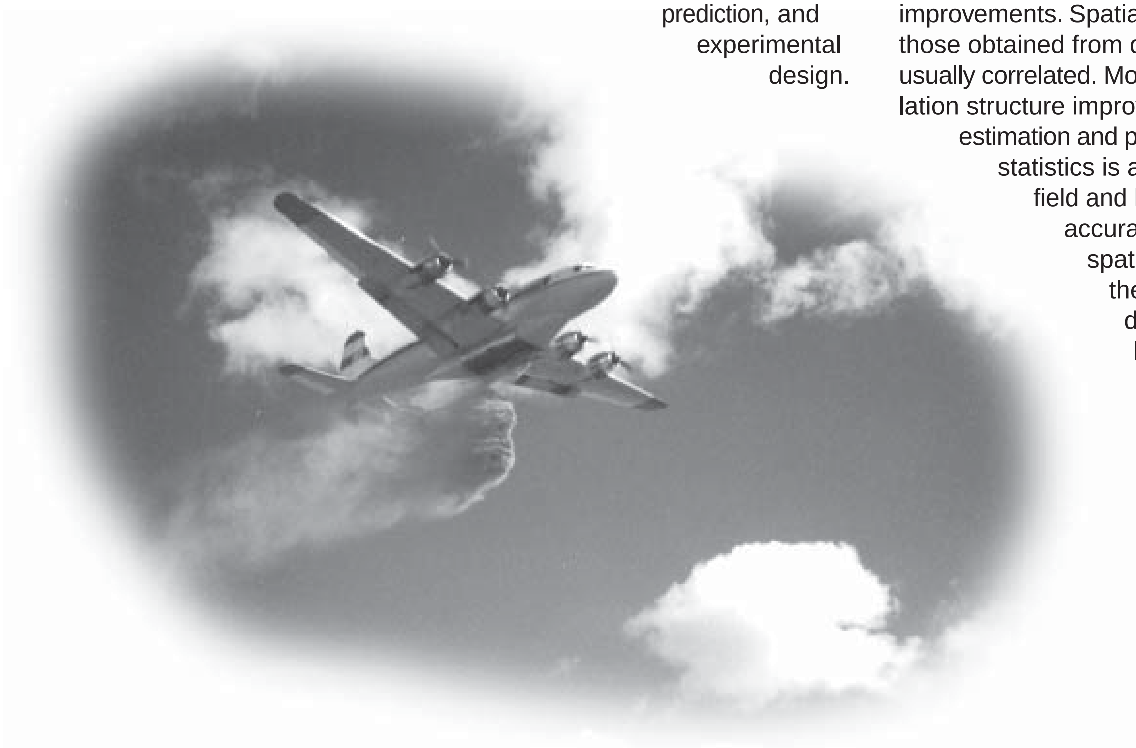


Figure 16—Drop pattern characteristics for the Sims 2,000-gallon helibucket with a drop speed of 83 knots and a drop height of 119 feet.

Alternative Methods of Analysis

Aside from the tests conducted by George and Blakely, very little work has been done to determine appropriate cup spacing and grid dimensions needed for an unbiased, efficient sampling method. Linear interpolation, often in one direction, has been frequently employed to estimate unknown values. Because ground patterns are three dimensional, it may be more appropriate to treat these data as spatial, and to use spatial statistical tools for estimation, prediction, and experimental design.



Spatial statistical methods take into account the location of an observation as well as the value of the observation to obtain more accurate estimates of unknown values (Isaaks and Srivastava 1989). This information is used to build a model for prediction and sampling improvements. Spatial data such as those obtained from drop tests are usually correlated. Modeling this correlation structure improves accuracy of estimation and prediction. Spatial statistics is a relatively new field and has proven more accurate for estimating spatial data. Using these methods for drop testing may lead to a greater understanding of our aerial capabilities and improve our wildland firefighting.

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Glossary

Airtanker—Fixed-wing aircraft certified by the Federal Aviation Administration as being capable of transporting and delivering fire retardant solutions.

Anchor Point—An advantageous location, usually a barrier to fire spread, to start constructing a fireline. The anchor point is used to minimize the chance of being flanked by the fire while the line is being constructed.

Baffling—Partitions placed in tanks to reduce shifting of the water load and to give the tank greater structural integrity.

Bambi bucket—A collapsible helibucket slung below a helicopter, typically used to dip water from a variety of water sources for fire suppression.

Bentonite—A clay slurry, short-term fire retardant whose effectiveness depends primarily on the water it holds.

Breakup—The dispersion of retardant, foam, or water in the air after it is released from a tank or bucket.

Borate—One of the first long-term fire retardants. Its use was discontinued in the 1960's.

Constant-flow airtankers—Airtankers that use doors to control the flow rate.

Contour plots—A graphical picture on which the characteristics of a surface are shown by contour lines. In drop testing, the contour line is a line that joins points of equal coverage level on a surface.

Conventional airtankers—Airtankers that divide the retardant load into isolated compartments. The release system is designed to open the doors of these compartments in sequence, producing a line of retardant.

Correlated—When two or more things are mutually related. In statistics, correlation refers to interdependence between two or more variables.

Coverage level—A recommended amount of retardant (in gallons) applied to a specific area (100 square feet) of surface. Coverage level 2 represents 2 gallons of retardant per hundred square feet of surface.

Cup-and-grid method—A procedure incorporating containers set in a regular, defined pattern to measure deposition patterns created by the aerial release of fire-retarding chemicals.

Direct attack—Any treatment applied directly to burning fuel to stop combustion.

Drift—The effect of wind on retardant or suppressant drops.

Drop test—A test of a fire chemical delivery system flying over a cup-and-grid matrix to determine the coverage level producted for each drop type.

Fire retardant—Any substance, except plain water, that by chemical or physical action reduces the flammability of fuels or slows their rate of combustion.

Fire suppressant—An agent that is directly applied to burning fuel to extinguish the flaming and glowing phases of combustion.

Flight path—Track of an aircraft over the earth's surface.

Flow rate—The rate at which the retardant exits a tank or bucket, usually expressed in gallons per second.

Foam—The aerated bubble structure created by forcing air into a water solution containing a foam concentrate. Foam may be produced by suitably designed equipment or by cascading a water solution containing a foam solution at high velocity through the air.

Gate—Refers to the door area and release mechanism of a tank.

Gelgard F—A firefighting gel. Gels modify the physical properties of water, especially its ability to cling to fuel. Gels rely on the moisture they contain to reduce or inhibit combustion.

Ground pattern—The characteristics of a ground pattern of fire-retarding chemicals, including length, width, area, and coverage level expressed in gallons per hundred square feet.

Gum-thickened retardant—Any firefighting product containing a thickener. The thickener increases the product's elasticity.

Helicopter buckets—A container suspended below a helicopter, usually used for dipping water for firefighting.

Helitanker—A helicopter equipped with a fixed-tank or a bucket-type container that is used for aerial delivery of water or retardants.

Line building—Constructing a fireline. Aircraft drop retardant or suppressant in overlapping lines to help ground crews build fireline.

Line length—The length, usually expressed in feet, of a ground pattern. Line length is used to relate the length of different coverage levels within a ground pattern.

Linear interpolation—Estimation of a value of a variable between two known values that assumes uniform change between the two known values.

Recovery rates—The estimated amount of retardant recovered from the cup and grid method compared to the amount of retardant dropped, expressed as a percentage of total gallons dropped.

Retardant—see *fire retardant*.

Retardant mass—The total volume of retardant released from the aircraft.

Rheological properties—Those properties, including viscosity and elasticity, affecting the flow characteristics of a fluid. These properties affect the behavior of the retardant as it is dropped from an airtanker.

Short-term fire retardant—A formulation added to water to modify its physical properties, improving its drop characteristics or its ability to cling to fuel. The retardant relies on the moisture it contains to reduce or inhibit combustion. It is ineffective once its moisture has evaporated.

Spatial statistics—Statistical methods for spatial data. Typically, these data fall into three categories: lattice data, geostatistical data, and spatial point patterns.

Tank and gating system—Tank, doors, and release mechanism installed in aircraft to release a drop.

Torque tubes—A hydraulically or pneumatically powered, rotating shaft that opens and closes the tank's doors.

Tree canopy—The layer containing the crowns of the tallest vegetation present (living or dead), usually above 20 feet.

Understory—Low-growing vegetation under a stand of trees. Also the portion of trees in forest stands below the forest canopy.

Venting—The openings in the tank vents used to allow air into the tank.

Viscosity—A measure of a fluid's resistance to flow. With foam, an indication of the foam's ability to spread over and cling to fuels and to itself.

Water-like retardant—Unthickened products or thickened products that do not have elasticity.

Wildland fire—A fire in wildland.

About the Author

Ann Suter is a statistician for the Missoula Technology and Development Center, Wildland Fire Chemical Systems. She joined the Forest Service in 1997 after serving 2 years as a Peace Corps Volunteer in Jamaica, where she worked on reforestation and soil erosion control. She holds a master's degree in international development from the American University.

Library Card

Suter, Ann. 2000. Drop testing airtankers: a discussion of the cup-and-grid method. Tech. Rep. 0057-2868-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center. 14 p.

Presents the development of drop tests from the 1950's through the 1990's as a method of quantifying ground patterns from aerial-retardant drops. During a drop test, drops are made at varying drop heights, drop speeds, flow rates, and volumes, and with different retardant materials to obtain a graphical and numerical picture of the ground patterns produced by the airtanker. Examining ground patterns provides information about the factors that influence the distribution of the drop. The report discusses the methods used to measure and describe ground patterns and proposes a spatial statistical method for increased efficiency and accuracy. Includes a glossary of technical terms.

Keywords: airtankers, coverage levels, drop tests, ground pattern, history, line length, rheology, spatial statistics, tank and gating systems

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USDA FS, Missoula Technology & Development Center
Building 1, Fort Missoula
Missoula, MT 59804-7294
Phone: 406–329–3978
Fax: 406–329–3719
E-mail: wo_mtdc_pubs@fs.fed.us

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For further technical information, contact Ann Suter at:

USDA Forest Service, MTDC (Wildland Fire Chemical Systems)
5775 Highway 10 West, P.O. Box 8089
Missoula, MT 59807
Phone: 406–329–4815
Fax: 406–329–4811
Lotus Notes: Ann Suter/WO/USDAFS
E-mail: asuter@fs.fed.us