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Gum-Thickener Study—

Drop Test for Firefighting Operations, Marana, AZ

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Cover photos—Top: An S2T airtanker dropping retardant over the grid.
Lower left: A grid worker watching retardant fall on the grid.
Lower right: Grid workers watching a grid drop and preparing to pick up cups

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Drop Test for Firefighter Operations, Marana, AZ

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Contents

Summary

For many years, Wildland Fire Chemical Systems (WFCS) personnel of the U.S. Department of Agriculture, Forest Service, National Technology and Development Program have understood that increasing the rheological properties (recoverable viscosity and elasticity) of aerial-delivered retardants results in reduced drift under low wind conditions in a laboratory setting (Anderson and Wong: 1978; Anderson et al. 1974a, 1974b, 1976, 1977; George 1975, George et al. 1976; Swanson and Helvig 1973, 1974; Swanson et al. 1975). WFCS has also noted that, if the effective viscosities are too high, retardant tends to remain suspended in the fuel canopy and less retardant reaches the understory (George et al. 1970). If fire is carried through the canopy, retardant that stays primarily in the canopy is desirable. If, however, fire is carried by ground fuels, a retardant that stays in the canopy is undesirable.

Studies conducted during the 1970s compared high-viscosity (as measured by a Brookfield viscometer at a shear rate of 12 sec^{-1}), gum-thickened retardant to clay-thickened retardant and water. While these studies provided insight into effective viscosities, they didn't look at optimal levels of effective viscosities. In other words, these early studies did not address the question of how much gum thickener to add (Vandersall 1991).

This report looks at the ground distribution patterns of retardants (drop patterns) formulated with different amounts and types of gum thickener. As WFCS personnel, we gathered the data from 92 drops performed at Marana, AZ, using an S2T airtanker with a tank capacity of 1,200 gallons to release different retardants over a drop test grid. The S2T flew 150 to 250 feet above ground level (AGL) at 125 knots groundspeed. This comparison gave us data on how varying the amount of gum thickener affects line-length production and the continuity in drop patterns.

The firefighting chemicals used in the drop test included water and ammonium-phosphate-based retardants. We mixed the retardants to four thickness levels: unthickened, high viscosity (970 to 1,450 centipoise, cP), medium viscosity (530 to 950 cP), and low viscosity (123 to 234 cP). We took all viscosity measurements from this drop test using a Brookfield viscometer set at 60 revolutions per minute (r/min), measured at a shear rate of 12 sec^{-1} (USDA FS 2007). The Brookfield viscosity measurements indicated how much gum thickener was added. We included both guar- and xanthan-thickened retardant solutions in the study.

The results showed that, for tank controller dial settings (hereafter referred to as dial setting) 2 and 4, the addition of gum thickener mitigated the negative effects on the drop pattern from high altitudes, although there were diminishing returns when the viscosity of the retardant exceeded 700 cP to 800 cP. Adding gum thickener to achieve a viscosity level of 1,000 cP or higher did not add significantly to the line-length production and drop pattern continuity or recovery of the retardant.

All factors being equal, an 8 cP retardant exhibited the same amount of drift as a 1,295 cP retardant dropped from the same altitude. Also, a 179 cP retardant drifted less than a 700 and 1,305 cP retardant dropped from the same altitude.

Given the findings from our study, a ceiling of 700 cP to 800 cP may be considered appropriate for retardant using xanthan- or guar-gum thickeners. This study did not provide any information about the coating, clinging, and penetrating characteristics of the retardants. It also did not address the rate and magnitude of shear during discharge from the aircraft or wind conditions in excess of 10 miles per hour (mi/h). Finally, the study did not look at flow rates above 600 gallons per second (gal/s). Rather, it focused on the line-length production of aerial-applied retardants at dial settings 2 and 4. Employees in the field have concerns that high-viscosity, gum-thickened retardants (more than 1,000 cP) may impede the canopy penetration capabilities. This concern may overshadow the small gains obtained in drop pattern continuity and line-length production with higher viscosity retardants. WFCS recommends a canopy penetration study to further understand how viscosity affects the aerial application of these retardants.

Problem Statement

WFCS can make some general statements about how viscosity level affects line-length production based on information from past drop tests. However, previous studies involved many drop conditions, delivery systems, and different ranges of viscosity levels; each study had specific objectives rather than focusing on the type and amount of gum thickener.

Proposed Technology and Development Work

During January 2004, we proposed a drop test to collect data that would help answer rheological questions. As representatives of the U.S. Department of Agriculture, Forest Service, we worked with the California Department of Forestry (CDF) on the test. We used one delivery system (the S2T airtanker) at 125 knots and a full volume of 1,200 gallons. We varied altitude, flow rate, and firefighting chemical.

Test Location

WFCS performed the test at Marana, AZ, because the site has suitable facilities, test grid, and climate. We set up a temporary retardant mixing plant at the Pinal Park Airport and conducted the test between October 24 and November 17, 2005.

Primary Variables

Factors that contribute to the ground distribution pattern of an aerial drop include:

- Retardant properties, such as viscosity measured in centipoise (Brookfield viscometer measured at a shear rate of 12 sec^{-1}), density measured in grams per milliliter, and salt content measured with a refractometer
- Volume measured in gallons
- Windspeed measured in mi/h
- Wind direction measured in degrees clockwise off the nose of the aircraft
- Aircraft speed measured in knots
- Aircraft altitude measured in feet above the ground
- Flow rate of the chemical released from the aircraft tank measured in gal/s

We focused this drop test on the effect of viscosity imparted by guar- and xanthan-gum thickener on the ground distribution patterns during controlled drops from a single S2F Turbo Tracker (S2T), Tanker 93. We chose several retardants to represent the range of gum thickener in use over the last several years.

We selected a defined set of drop conditions (figure 1) to ensure that we included a reasonable range of conditions and settings in the test.

- Tank controller dial setting of 2, nearly equal to (≈) 253 gal/s
- Dial setting 4, ≈ 507 gal/s
- Drop altitudes of 175 and 250 feet

The airtankers dropped each retardant two or three times in rotation to ensure that weather patterns—both daily and through the month—influenced each drop in an equal way to ensure a representative sample.

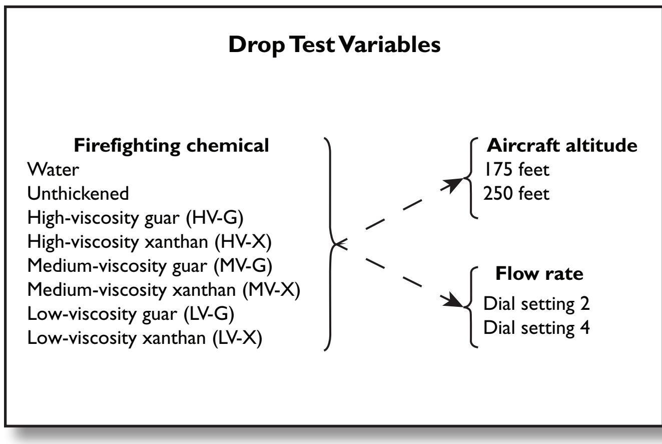

Figure 1—Drop test variables.

Products

Water—Readily available, this unthickened fire suppressant is more frequently applied from helicopters than fixed-wing airtankers, but still is an option.

Unthickened retardant—This fire retardant contains a small amount of clay in the concentrate that helps suspend the iron-oxide colorant. The clay imparts a small amount of viscosity to the concentrate, but no significant viscosity or elasticity to the mixed retardant. For this test, we added an iron-oxide colorant to the unthickened retardant.

Thickened retardant (guar gum)—This is a commercially available, high-viscosity fire retardant. The addition of guar gum imparts viscosity and elasticity to the concentrate (a dry powder that is added to water). For this test, we set the target centipoise range for high viscosity at 1,200 cP to 1,400 cP. Then, we diluted the high-viscosity retardant to provide medium-viscosity (target of 600 cP to 700 cP) and low-viscosity (target of 150 cP to 200 cP) versions of the retardant. The densities of the medium- and low-viscosity retardants were lower than the high-viscosity retardant because we diluted the mixed retardant with water to obtain the target viscosities. We also added a fugitive color to the guar-gum-thickened retardant.

Thickened retardant (xanthan gum)—This is a commercially available, low-viscosity fire retardant. The addition of xanthan gum imparts viscosity and elasticity to the concentrate, a liquid that is diluted with water at the time of use. For this test, we produced an experimental high-viscosity retardant by adding more xanthan gum to obtain a target viscosity in the range of 1,200 cP to 1,400 cP. We then diluted this formulation further to provide medium-viscosity (target of 600 cP to 700 cP) and low-viscosity (target of 150 cP to 200 cP) versions. The densities of the medium- and low-viscosity retardants were lower because we diluted the mixed retardant with water to obtain the target viscosities. We also added an iron-oxide colorant to the xanthan-gum-thickened retardants.

Israeli Chemical Limited (ICL) employees who work at full-service or portable airtanker bases during the fire season batch-mixed all retardants.

Mixing and Handling

ICL Performance Products LP (Phos-Chek retardants) supplied all retardants. ICL prepackaged the retardants in individual containers to be added to the prescribed amount of water required for a single airtanker load. We mixed a single 1,400-gallon batch of the high-viscosity retardant into the batch mixer and then loaded 1,200 gallons onto the airtanker. The additional 200 gallons provided enough volume to charge the pump and loading hose. We mixed three 1,200-gallon batches of the same retardant individually and loaded them onto the airtanker. These four loads constituted one replicate of the four drop conditions:

- Dial setting 2 at 175 feet
- Dial setting 2 at 250 feet
- Dial setting 4 at 175 feet
- Dial setting 4 at 250 feet

For each thickener type, we followed a set of four drops using the high-viscosity retardant with a set of four drops using the medium-viscosity retardant and, finally, a set of four drops using the low-viscosity retardant. At this point, we emptied the mix tank before mixing the next retardant. However, we didn't perform any additional rinsing. We believe this minimal amount of cross-contamination had no impact on results.

We set the order for mixing and loading fire retardants to minimize interactions, especially when known detrimental interactions might occur. We tested the fire retardants in the following order:

- Water (two of the drop conditions in the set of four)
- Guar-gum-thickened retardants
- Xanthan-gum-thickened retardants
- Water (the remaining two drop conditions in the set of four)
- Unthickened retardants

We measured the viscosity, density, and refractometer readings of each fire retardant from samples we collected while loading the aircraft.

Test Grid

The airtankers performed each drop over a grid of plastic cups that we arranged in columns and rows (figure 2). Following the drop, we recorded the weight of fire retardant in each cup and the location of each cup within the grid. The grid was 2,010 feet long and 225 feet wide with the center section dimensions at 15 by 15 feet. The grid widened toward the edges to 30 feet in the downrange direction. We spaced the first two rows 60 feet apart (table 1). The grid consisted of 114 rows of cups with 16 or 20 cups in each row, depending on the row. The grid contained 2,280 cups.

Table 1—Row distance

Rows	Distance apart (feet)
1 to 3	60
3 to 9	30
9 to 105	15
105 to 114	30

A cup in row 2 represented a 60- by 15-foot section, or 900 square feet. A cup in row 4 represented a 30- by 15-foot section, or 450 square feet. A cup in row 90 represented a 15- by 15-foot section, or 225 square feet.

Flow Rate

We performed 44 drops at tank controller dial setting 2. The flow rates measured during the release over the grid ranged from 266 to 331 gal/s with a mean of 304 gal/s and a standard deviation of 11 gal/s, which was 4 percent of the mean. We performed a total of 48 drops at tank controller dial setting 4. The flow rates measured ranged from 503 to 590 gal/s with a mean of 552 gal/s and a standard deviation of 16 gal/s, which was 3 percent of the mean. Two drops (108 and 160) did not yield data.

The average in-flight flow rates of 304 and 552 gal/s were higher than the ground flow rates of 253 and 507 gal/s by about 45 to 55 gal/s. We measured flow rates using a level indicator. When you consider the factors influencing the liquid level during a drop, a discrepancy between average flow rates from ground testing and flight testing was not uncommon. We obtained ground flow rates from static testing the aircraft (Lovellette 2005).

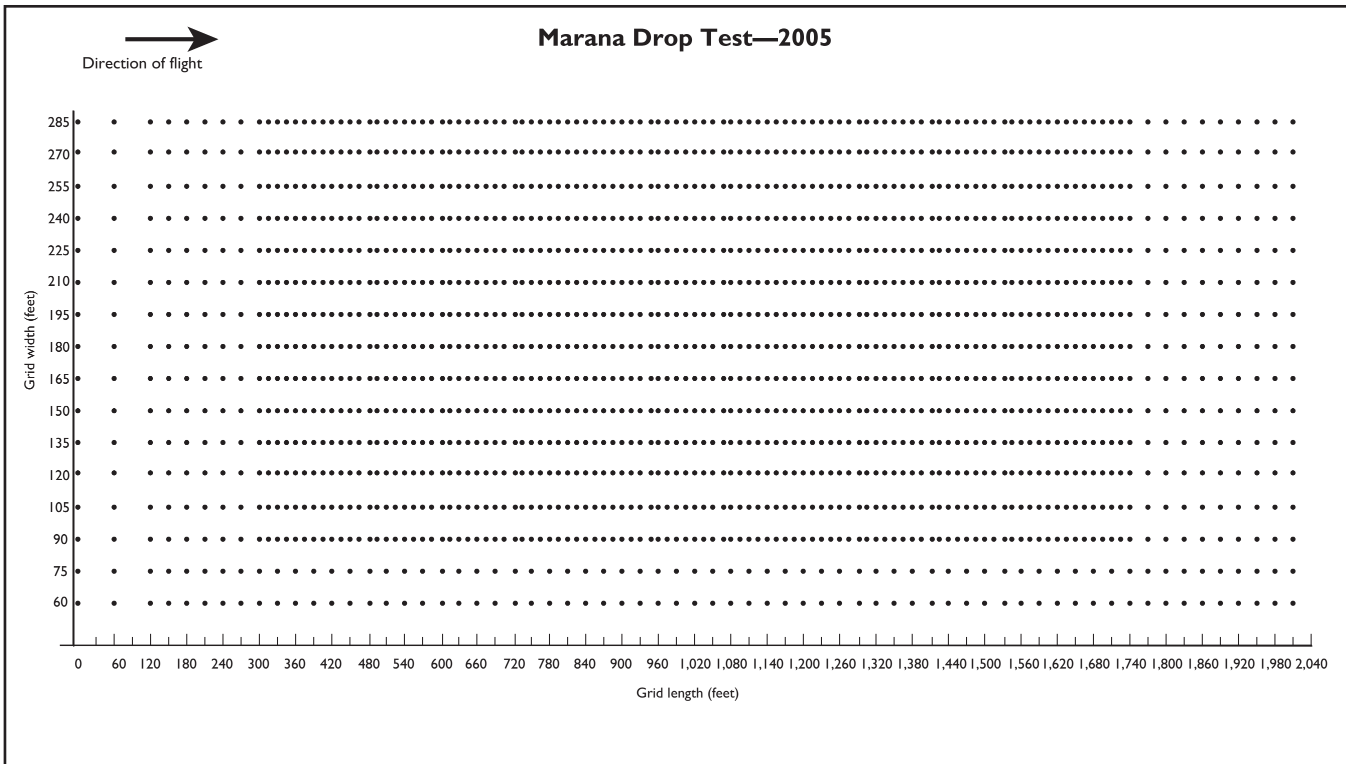

Figure 2—Drop test grid (not to scale).

Altitude

Aircraft altitude has an impact on the trajectory of the drop and therefore affects breakup of the retardant cloud (George and Blakely 1972). The pilot used the same flight path with a long approach to establish a level altitude and sustain it throughout the drop and to maintain a consistent altitude throughout the entire test.

Altitude and Speed

We used a Trimble Pro-XR Global Positioning System (GPS) unit to determine aircraft drop altitude and groundspeed and positioned the receiver antenna inside the aircraft cabin under an overhead window that provided a nearly 360-degree view of the sky. We used a Terra Sync software package and real-time Wide Area Augmentation System (WAAS). WAAS is a system of satellites and ground stations that provide GPS signal corrections, providing position accuracy within 3 meters, 95 percent of the time (Garmin Ltd.) <http://www8.garmin.com/aboutGPS/waas.html>. The GPS unit recorded aircraft position providing submeter accuracy at a rate of one reading per second while the aircraft was in flight.

A GPS operator held the unit while walking the perimeter of the grid before drop testing began, creating a ground-based file of grid position. We selected specific in-flight data points relating to aircraft position over the grid by overlaying the in-flight files with the ground-based file.

We calculated drop speed by dividing the distance between in-flight data points by the elapsed time between the same data points. We calculated drop altitude by correcting to the mean sea level (MSL) elevation of the aircraft belly and the MSL elevation of the ground and then subtracting the two values.

Video Coverage

We used four video cameras operating at 29.97 frames per second and a high-speed video camera operating at 250 frames per second to document the test drops.

In addition to GPS data, we also determined aircraft altitude using a Sony HyperHAD CCD video camera with a 7.5-millimeter (mm) fixed focal length lens. We took initial measurements of the aircraft at rest in 5-foot increments at 100 feet, moving back to 300 feet from the centerline (in front) of the aircraft while looking at the wingspan, and then perpendicular (from the side) to the aircraft for a measurement of the fuselage. We made a pixel count of the aircraft for each increment and then used the count as a scale for determining aircraft altitude from in-flight images.

We used a Sony mini-DV video camera with a wide-angle adapter pointed downrange and placed in the center of the last row to view the retardant cloud. A visual comparison could be made by keeping the camera orientation and location consistent throughout the drop test.

We located two of the four video cameras, including the high-speed video camera, on scaffolding 815 feet from the center of the grid, row 57. A Sony PD-170 mini-DV video camera tracked the aircraft as it passed over the grid to record a medium closeup of the drop characteristics throughout the entire drop.

We placed a Sony VX-1000 mini-DV video camera with a wide-angle adapter exactly at the centerline of the grid to record a wide perpendicular static view of the drops. This view captured changes in elevation of the aircraft throughout the drop as well as fire suppressant drop trajectory.

We placed a Photron Apex high-speed camera with a 200-mm lens on the scaffolding to record the breakup of the firefighting chemical on release.

Weather Data

Weather data collected during the drop test included windspeed, wind direction, temperature, and relative humidity. We placed a portable weather station 15 feet from the edge of the grid, in line with row 50. We placed the windspeed/direction instrument 20 feet above the ground and the temperature/relative humidity probes 15 feet above the ground.

We aligned the wind direction vane downrange in respect to the grid so that a direct headwind experienced by the aircraft measured zero degrees, a perpendicular wind from right (the 3 o'clock position for the pilot) to left measured 90 degrees, and a tailwind measured 180 degrees. Between drops, we collected data once per minute. At 10 to 15 seconds before each drop, we collected data at 1-second intervals for 90 seconds. We synchronized the internal clock with GPS time.

The windspeed and direction values in the summary tables (appendix A) are an average of 1-second readings recorded as the aircraft flew over the grid and the fire suppressant settled to the ground.

Compilation of Grid Data

We subtracted a tare weight of 45.5 grams from the recorded weight of each cup to determine the actual weight of fire retardant captured. The area of the cup opening was 28.27 square inches. The area of one cup represented 0.19635 square foot; dividing by 100 converts to 100 square feet. There are 3785.411 cubic centimeters (cc) in 1 gallon of water (H_20), so to convert grams of fire suppressant into gallons per hundred square feet (gal/100 ft^2), the equation is:

1 gallon per 3785.411 cc of H_20
× 1 grid cup per 0.0019635 of 100 ft^2
= 0.13454172 gallons per cc over 100 ft^2

0.13454172
× (grams of retardant in the grid cup
/ density of retardant (grams per cc))
= gal/100 ft^2

Line length in the downrange direction is considered an indicator of performance. We calculated the length in feet at each coverage level. We interpolated values between observed data calculated using a weighted average method called "kriging" to improve our line length measurements (appendix B). Separate "islands" of coverage were added together to get the total length of line (Suter 2002).

Graphing Method

Figure 3 illustrates how we displayed and analyzed data using drop 128. The direction of flight, indicated by the arrow, is left to right relative to the page and is the same for all patterns. The windspeed and direction is given with a compass. We quantified line lengths from contour patterns. The red contour line indicates 0.5 gal/100 ft^2 and greater (line is 1,133 feet long). The green contour line is 1 gal/100 ft^2 and greater (line is 855 feet long). The dark blue contour line is 2 gal/100 ft^2 and greater (line is 323 feet long when the separate islands of coverage are added together).

We used line length per 100 gallons dropped to compare patterns. This is referred to as "normalized" line length (USDA Forest Service 2006). For this example, the volume of retardant carried by the airtanker was 1,216 gallons. For the red contour line in figure 3, we divided the line length of 1,133 feet by the volume (1,133 / 1,216 = 0.93). We then multiplied 0.93 by 100 equaling 93 feet of normalized line. Table 2 lists the lengths of line measured per 100 gallons of water at the 0.5 and 1 gal/100 ft^2 coverage levels.

Figures 4 and 5 are graphs of the data showing length of line measured per 100 gallons of water dropped at different altitudes. These graphs depict the data in table 2.

Table 2 and figures 4 and 5 are three ways of looking at the same data. The scatter plots (figures 4 and 5) are used to show some general trends. These tables and plots are used to

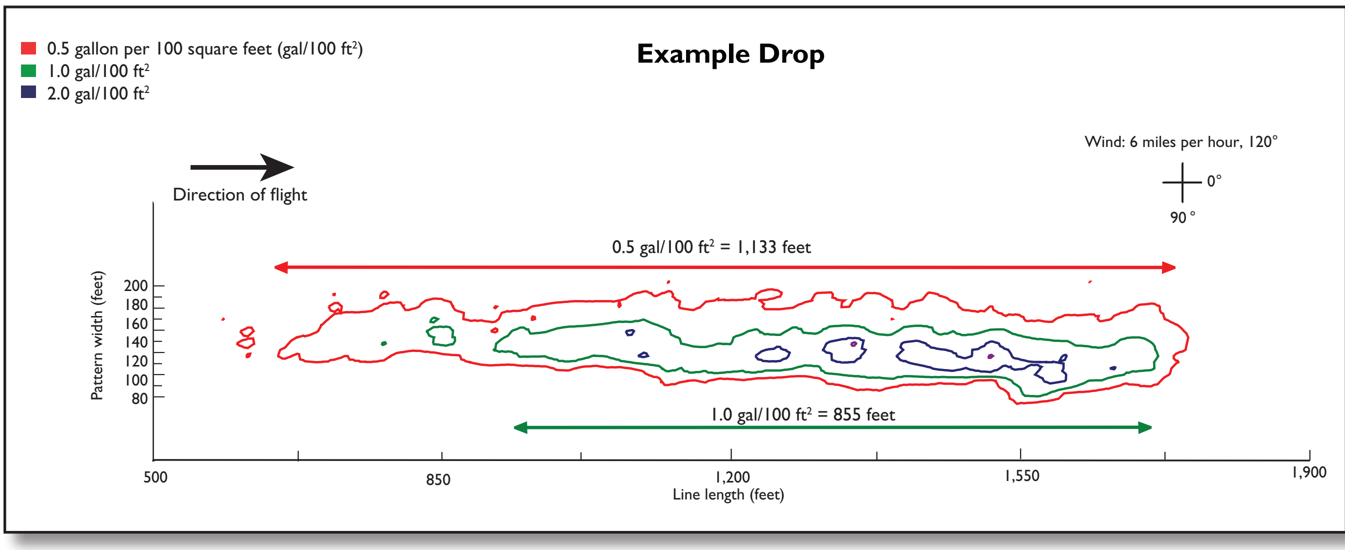

Figure 3—Ground deposition plot from drop 128: 1,216 gallons of water dropped from an altitude of 195 feet.

Table 2—Drop test data from six water drops using dial setting 2

Drop number	Fire suppressant	Volume gallons)	Percent recovered	Viscosity (centipoise)	Altitude (feet)	Wind-speed (miles per hour)	Wind direction (degrees)	Line length (feet per 100 gallons) coverage at 0.5 gallon per 100 square feet	Line length (feet per 100 gallons) coverage at 1.0 gallon per 100 square feet
102	Water	1,209	58	1	109	7	45	91	76
128	Water	1,216	67	1	195	6	120	93	70
129	Water	1,218	43	1	260	9	45	88	43
159	Water	1,207	42	1	264	6	250	84	16
165	Water	1,224	65	1	172	6	45	91	78
184	Water	1,190	69	1	306	3	80	91	67

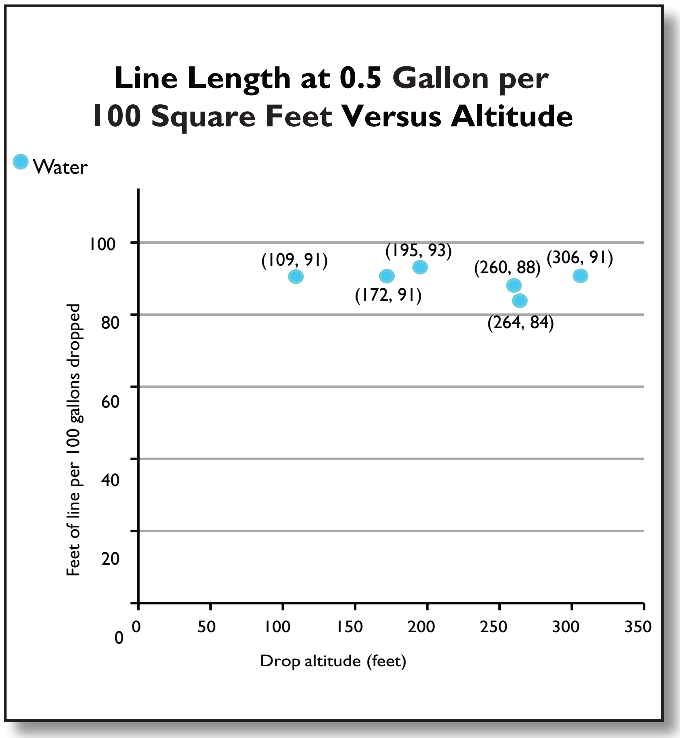

Figure 4—Normalized feet of line at 0.5 gallon per 100 square feet coverage level versus altitude. Altitude and line length are labeled here to indicate the correspondence between this chart and table 2.

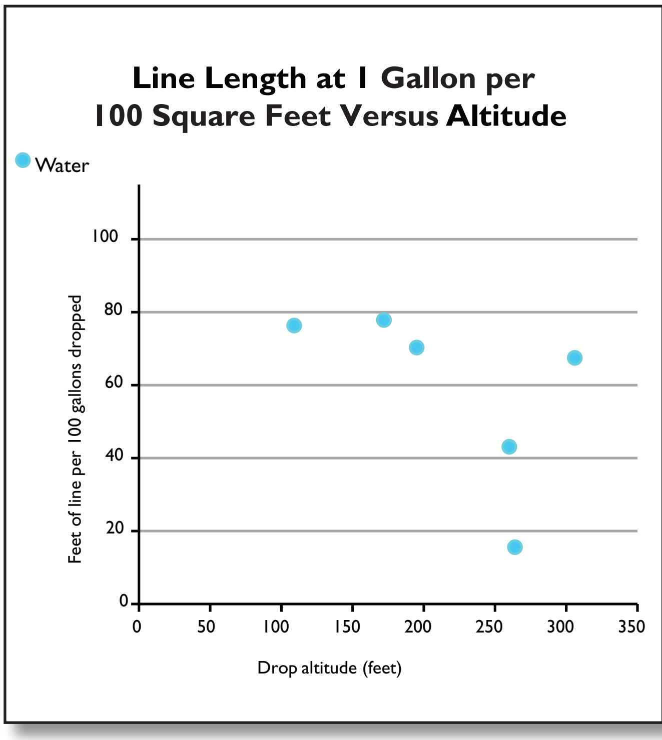

Figure 5—Normalized feet of line at 1 gallon per 100 square feet coverage level versus altitude.

make comparisons and identify trends. A full table of all the drops can be found in appendix A.

Data Evaluation

To evaluate the data, we examined two relationships: drop altitude versus line production and viscosity level versus line production. Figures 6 through 9 show dial setting 2 and figures 10 through 15 show dial setting 4. We then compared contour plots grouped by drop altitude and evaluated line-length production at different viscosity levels. Finally, we examined drift. We included percent of recovery and replicates in appendix C.

Line Production at Different Altitudes and Viscosity Levels

Table 3 shows data from 44 drops. We show graphs of these data in figures 6 through 9. We show altitude on the x-axis and feet of line (per 100 gallons dropped) on the y-axis.

Table 3—Drop test data from 44 drops using dial setting 2

Fire suppressant	Percent recovered	Viscosity (centipoise)	Altitude (feet)	Wind-speed (miles per hour)	Wind direction (degrees)	Line length (feet)	Line length (feet per 100 gallons)
						coverage at 0.5 gallon per 100 square feet	coverage at 0.5 gallon per 100 square feet
Water	58	1	109	7	45	1,095	91
Water	67	1	195	6	120	1,133	93
Water	43	1	260	9	45	1,073	88
Water	42	1	264	6	250	1,013	84
Water	65	1	172	6	45	1,110	91
Water	69	1	306	3	80	1,080	91
Unthickened	66	7	175	4	180	1,200	101
Unthickened	63	8	291	9	45	1,185	98
Unthickened	64	8	215	7	45	1,065	88
Unthickened	58	10	204	7	90	1,028	86
Unthickened	68	10	296	2	60	1,155	98
Unthickened	49	12	201	8	40	893	73
LV-G[1]	86	132	267	2	200	1,238	103
LV-G	88	144	195	2	30	1,200	102
LV-G	94	152	238	6	30	1,253	104
LV-G	90	160	187	6	45	1,208	99
LV-X[2]	76	173	178	3	120	1,155	96
LV-X	80	178	269	5	60	1,095	91
LV-X	94	181	195	1	220	1,215	101
LV-X	90	186	269	1	60	1,230	101
LV-X	69	187	209	7	70	1,200	98
LV-X	75	193	263	7	45	1,125	92
MV-G[3]	84	705	191	6	80	1,155	96
MV-G	73	760	145	8	90	1,170	96
MV-G	81	800	216	8	20	1,155	96
MV-G	89	950	268	9	45	1,260	104
MV-X[4]	85	555	182	1	30	1,170	97
MV-X	82	560	281	7	30	1,200	98
MV-X	79	560	232	4	180	1,170	96
MV-X	79	575	197	6	40	1,253	104
MV-X	78	595	294	6	40	1,125	89
MV-X	89	620	165	9	45	1,043	86
HV-G[5]	82	1,150	172	8	60	1,163	96
HV-G	88	1,275	115	5	50	1,133	93
HV-G	83	1,375	281	5	30	1,088	90
HV-G	83	1,390	220	6	20	1,155	95
HV-G	92	1,405	260	5	50	1,163	96
HV-G	83	1,450	158	6	20	1,163	96
HV-X[6]	89	1,250	239	2	230	1,283	106
HV-X	88	1,250	195	2	270	1,193	98
HV-X	88	1,250	205	6	20	1,238	103
HV-X	82	1,255	265	10	30	1,230	102
HV-X	93	1,305	213	2	90	1,185	97
HV-X	91	1,400	259	3	60	1,193	98

[1] Low-viscosity guar [2] Low-viscosity xanthan [3] Medium-viscosity guar [4] Medium-viscosity xanthan [5] High-viscosity guar [6] High-viscosity xanthan

Figures 6 through 9 show line lengths per 100 gallons dropped at different drop altitudes using dial setting 2. We show five firefighting chemicals with the different symbols explained in the legend.

The first plot (figure 6), at the 0.5 gal/100 ft^2 coverage level, shows there was very little difference in line lengths among the five different chemicals dropped. Altitude didn't seem to influence line lengths at this coverage level.

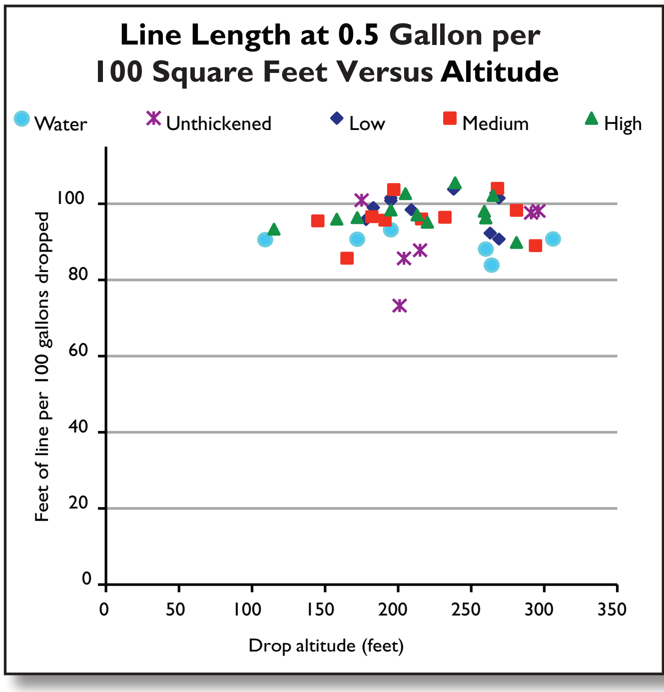

Figure 6—Normalized feet of line at 0.5 gallon per 100 square feet coverage level versus drop altitude.

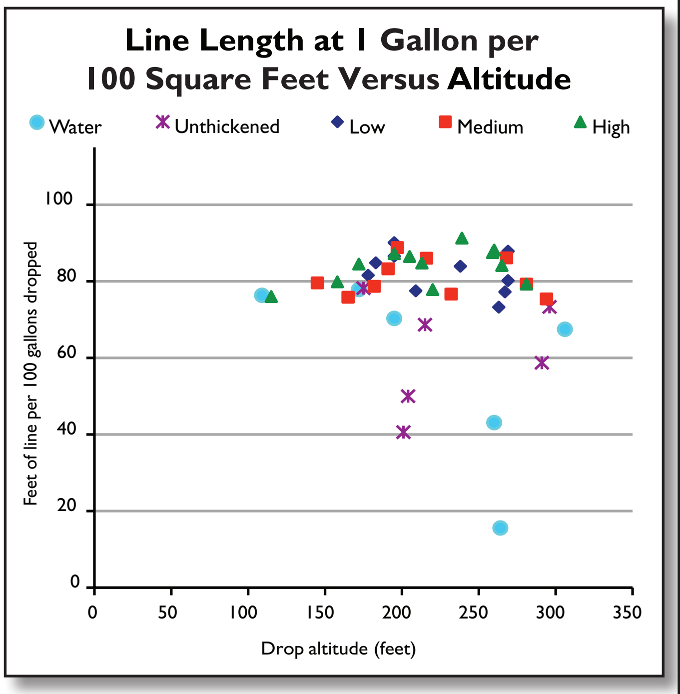

Figure 7—Normalized feet of line at 1 gallon per 100 square feet coverage level versus drop altitude.

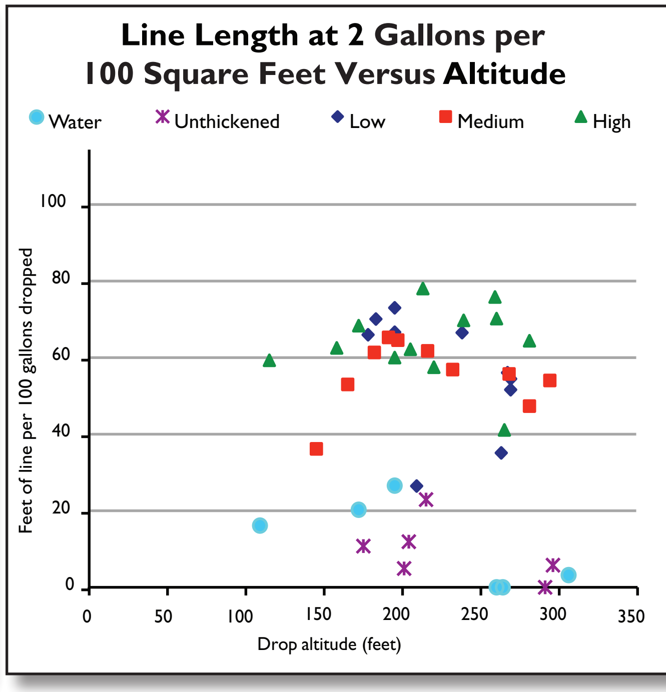

Figure 8—Normalized feet of line at 2 gallons per 100 square feet coverage level versus drop altitude.

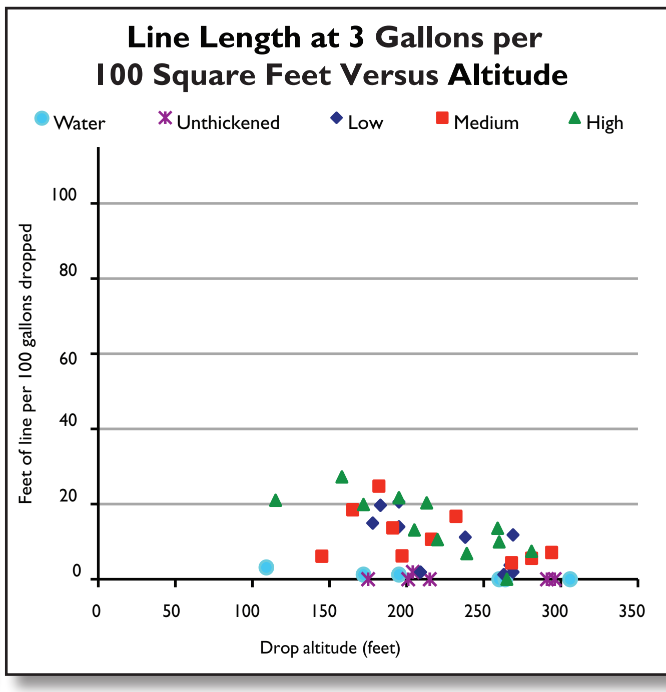

Figure 9—Normalized feet of line at 3 gallons per 100 square feet coverage level versus drop altitude.

Water and unthickened retardants had shorter line lengths than thickened retardants at the 1 gal/100 ft^2 coverage level and higher (figures 7 through 9). This difference became more distinct as the coverage level increased.

Three thickened retardants performed the same at the 0.5 and 1 gal/100 ft^2 coverage level. The high-viscosity retardant began to produce longer line lengths at the 2 gal/100 ft^2 coverage level. The differences between high, medium, and low viscosity were negligible at 3 gal/100 ft^2. We found two trends: line lengths decreased as drop altitude increased and thickened retardants performed better than unthickened retardants. Otherwise, the amount of gum didn't seem to have an effect at these coverage levels.

This may mean at dial setting 2, which should optimize line-length production at the 2 gal/100 ft^2 coverage level, the addition of gum to the retardant improved performance; but high and even medium amounts of gum did not necessarily increase line-length production over low amounts of gum.

Next, we examined the same relationship; line lengths versus drop altitudes at dial setting 4 using the data in table 4. The results were similar among the six scatter plots (figures 10 through 15).

Table 4—Drop test data from 46 drops using dial setting 4

Fire suppressant	Percent recovered	Viscosity (centipoise)	Altitude (feet)	Wind-speed (miles per hour)	Wind direction (degrees)	Line length (feet)	Line length (feet per 100 gallons)
						coverage at 0.5 gallon per 100 square feet	coverage at 0.5 gallon per 100 square feet
Water	37	1	170	10.0	60	825	69
Water	66	1	245	3.0	30	863	71
Water	73	1	199	6.0	45	840	69
Water	57	1	227	5.0	60	758	62
Water	77	1	289	4.0	40	810	67
Water	71	1	190	6.0	30	720	60
Unthickened	68	7	306	9.0	45	780	64
Unthickened	65	7	287	6.0	280	735	62
Unthickened	79	8	214	5.0	70	788	65
Unthickened	51	8	286	3.0	30	878	74
Unthickened	67	9	277	5.0	240	735	60
Unthickened	74	10	185	3.0	350	825	69
LV-G[1]	87	123	253	2.0	180	900	74
LV-G	86	128	199	5.0	120	825	68
LV-G	92	148	258	0.5	120	893	73
LV-G	95	214	122	6.0	30	848	70
LV-X[2]	78	169	180	4.0	70	795	67
LV-X	93	170	209	1.0	300	840	69
LV-X	67	178	317	5.0	45	765	64
LV-X	84	179	190	3.0	220	870	72
LV-X	84	180	216	4.0	90	885	73
LV-X	87	192	243	3.0	60	833	69
LV-X	83	234	269	6.0	45	750	62
MV-G[3]	90	700	192	5.0	60	870	72
MV-G	89	710	121	4.0	20	885	73
MV-G	81	750	180	6.0	35	825	68
MV-G	91	750	285	6.0	60	863	71
MV-X[4]	72	535	186	13.0	270	735	60
MV-X	79	575	251	1.0	90	735	60

Table 4—Drop test data from 46 drops using dial setting 4

Fire suppressant	Percent recovered	Viscosity (centipoise)	Altitude (feet)	Wind-speed (miles per hour)	Wind direction (degrees)	Line length (feet) coverage at 0.5 gallon per 100 square feet	Line length (feet per 100 gallons) coverage at 0.5 gallon per 100 square feet
MV-X	86	605	212	6.0	45	773	63
MV-X	85	700	190	4.0	120	795	65
HV-G[5]	82	970	179	8.0	60	878	73
HV-G	88	1,050	152	3.0	300	855	70
HV-G	89	1,255	212	5.0	60	863	72
HV-G	80	1,280	258	9.0	130	825	68
HV-G	87	1,315	157	6.0	40	788	67
HV-G	75	1,445	314	7.0	60	720	60
HV-X[6]	91	1,235	211	6.0	45	878	73
HV-X	88	1,300	255	1.0	290	870	71
HV-X	89	1,300	200	2.0	320	870	71
HV-X	90	1,305	199	3.0	90	833	68
HV-X	91	1,310	246	4.0	60	833	69
HV-X	71	1,400	273	13.0	135	788	65

[1] Low-viscosity guar [2] Low-viscosity xanthan [3] Medium-viscosity guar [4] Medium-viscosity xanthan [5] High-viscosity guar [6] High-viscosity xanthan

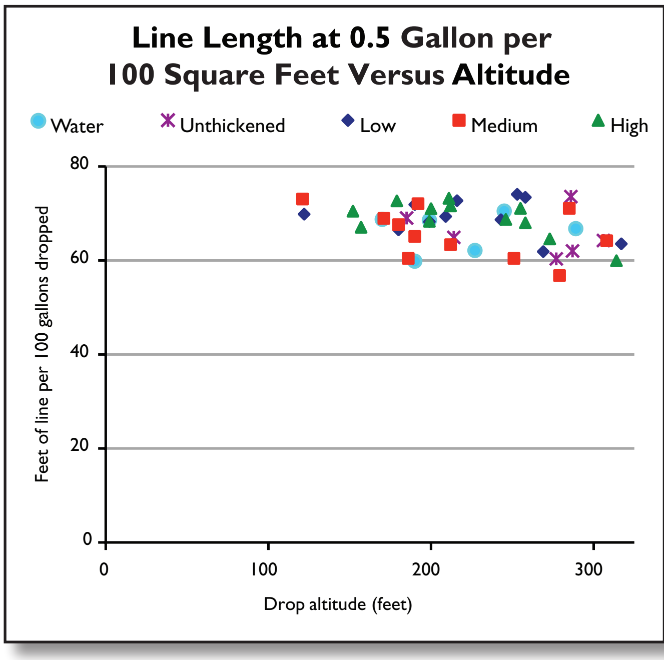

Figure 10—Normalized feet of line at 0.5 gallon per 100 square feet coverage level versus drop altitude.

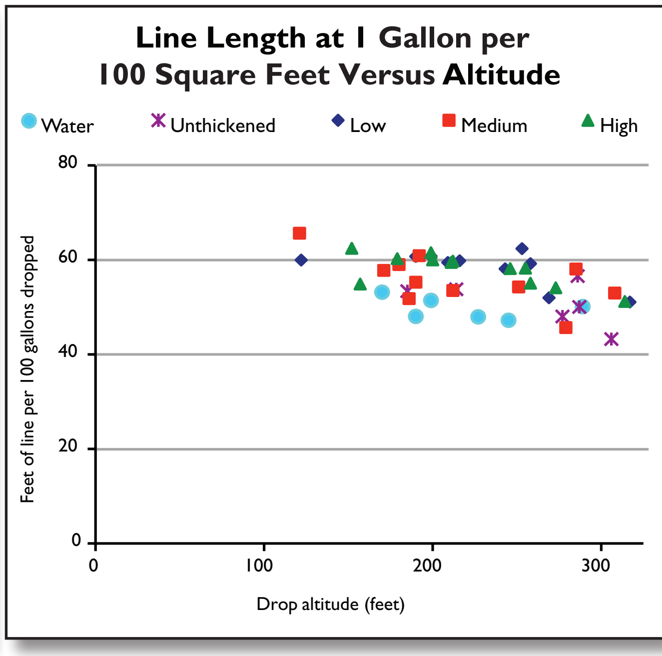

Figure 11—Normalized feet of line at 1 gallon per 100 square feet coverage level versus drop altitude.

There seemed to be no difference between gum-thickened retardants and unthickened retardants at lower coverage levels. As coverage levels increased, we began to see some trends: gum-thickened retardants began to perform better and drop altitude had an effect on line length. At dial setting 4, higher coverage levels were obtained overall. Again, we found no strong evidence of any real improvement in line-length production using high-viscosity over medium- and low-viscosity retardants.

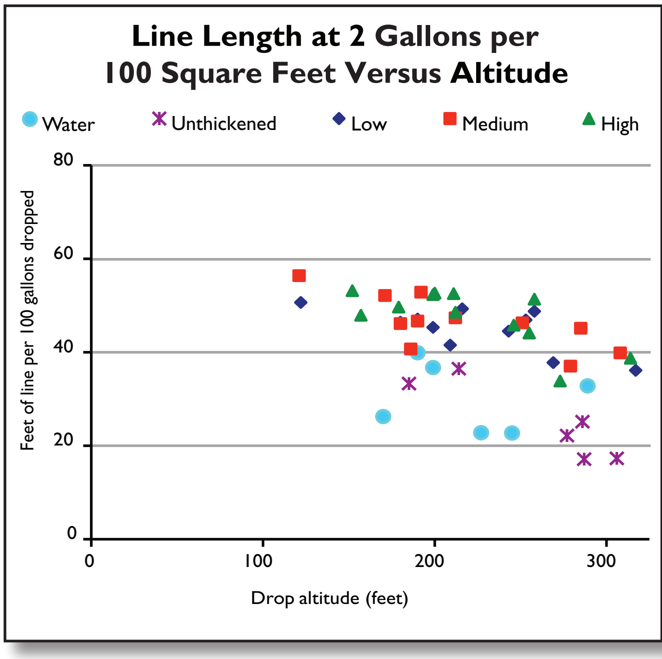

Figure 12—Normalized feet of line at 2 gallons per 100 square feet coverage level versus drop altitude.

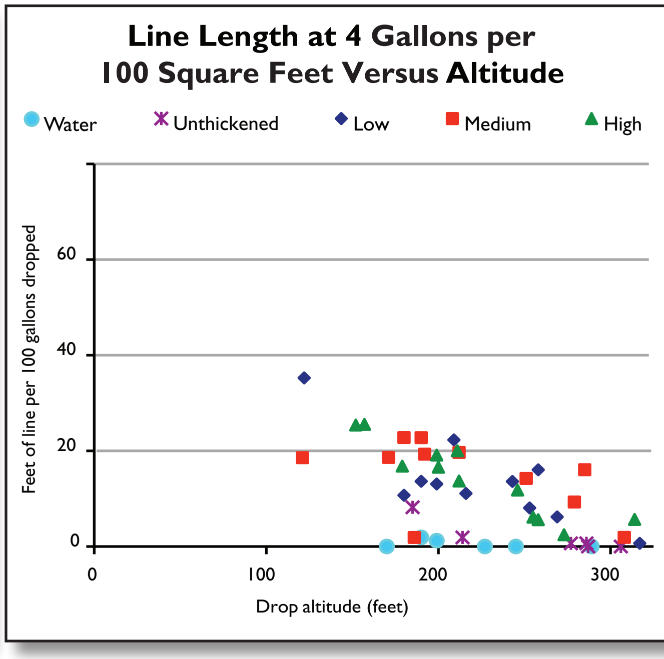

Figure 14—Normalized feet of line at 4 gallons per 100 square feet coverage level versus drop altitude.

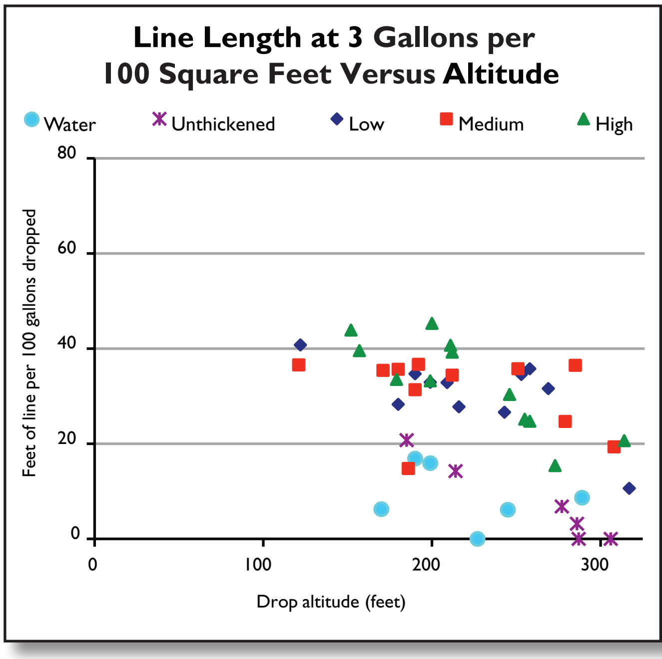

Figure 13—Normalized feet of line at 3 gallons per 100 square feet coverage level versus drop altitude.

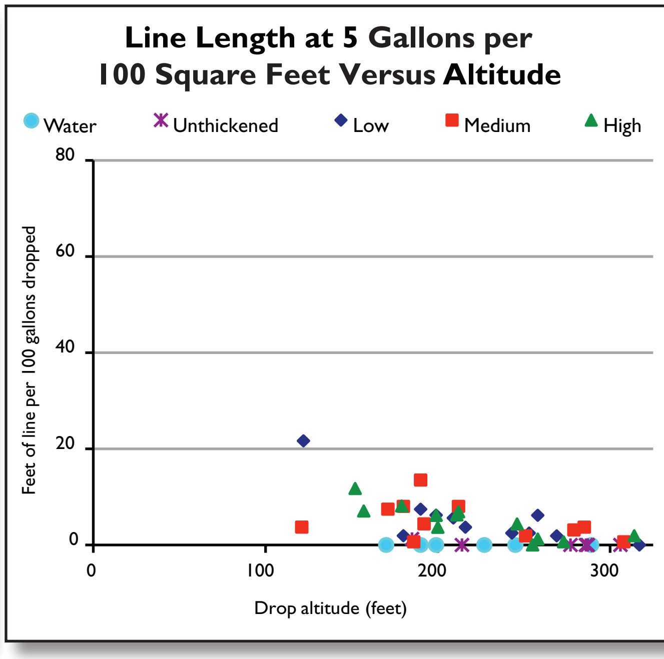

Figure 15—Normalized feet of line at 5 gallons per 100 square feet coverage level versus drop altitude.

Holding all variables equal, adding gum to unthickened retardant seemed to improve line-length production, but continuing to increase the amount of thickener didn't necessarily result in a significant improvement in that performance at dial settings 2 and 4.

Contour Plots

Figures 16 and 17 show two plots from drops at dial setting 4 at roughly the same altitude. The contours start with 1 gal/100 ft^2 at the gray line, 2 gal/100 ft^2 at the blue line, 3 gal/100 ft^2 at the red line, and so forth. A headwind is zero degrees and winds at 90 degrees come from the pilot's right side. The water drop in figure 16 was wider at the 2 gal/100 ft^2 coverage level and had a longer continuous line than the unthickened retardant pattern in figure 17. The unthickened retardant drop contained more than 3 gal/100 ft^2, but it was concentrated at one end of the drop, whereas the water drop was more evenly distributed. The unthickened retardant contained higher coverage levels overall, increasing up to 6 gal/100 ft^2, where water coverage levels increased to only 4 gal/100 ft^2.

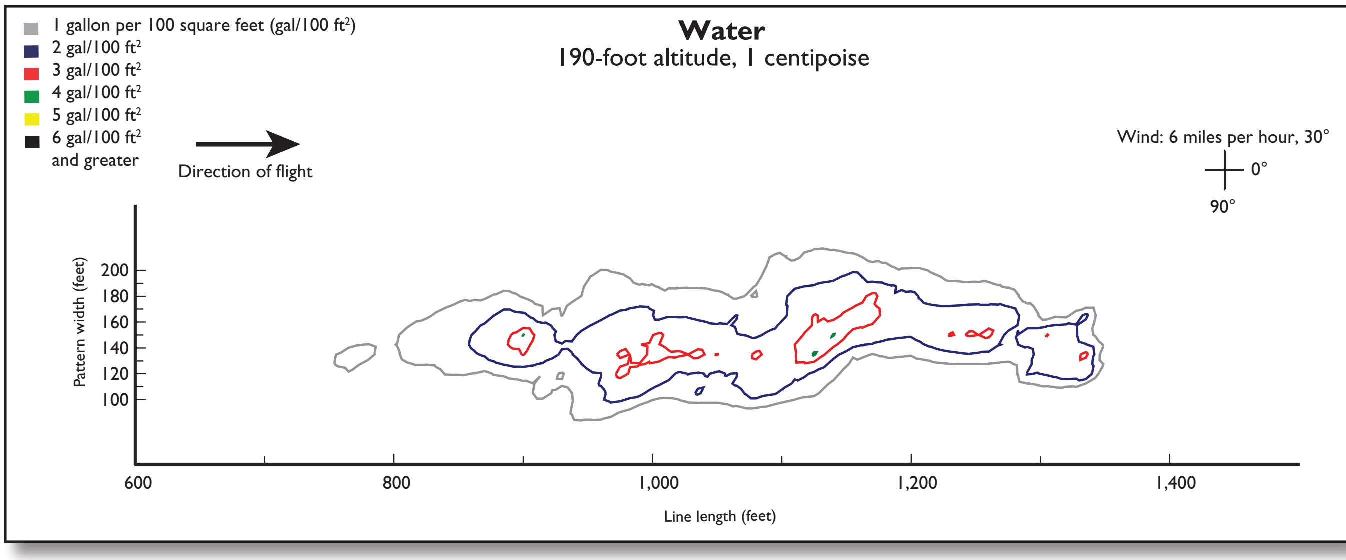

Figure 16—Contour plot of drop 190: unthickened retardant, dial setting 4, 190-foot altitude, 129 knots groundspeed.

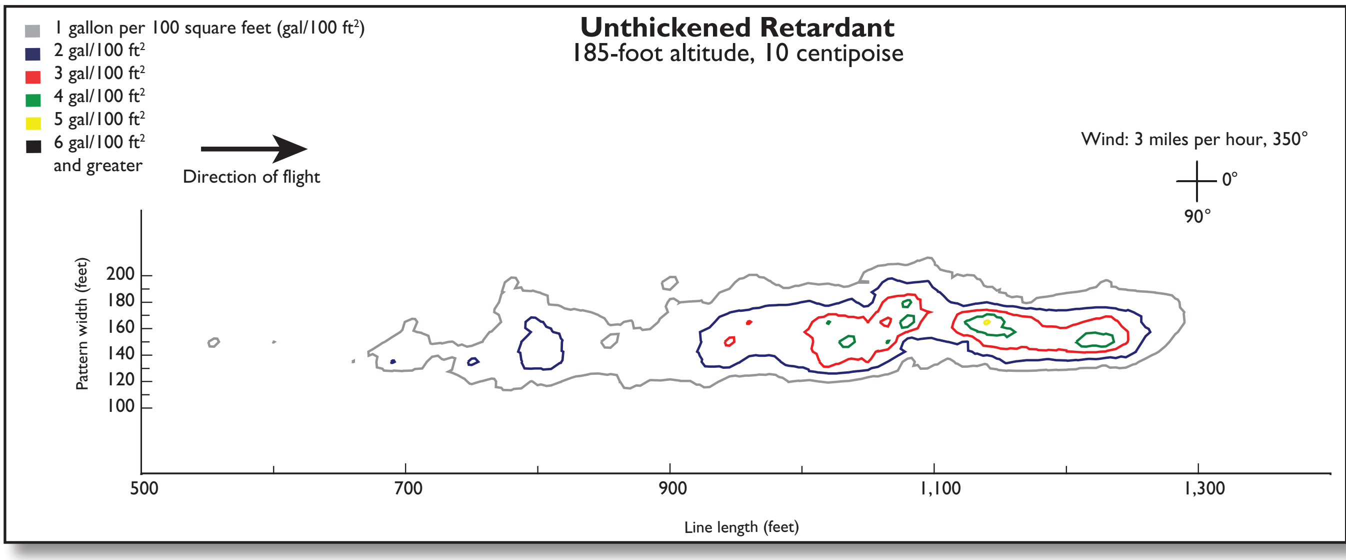

Figure 17—Contour plot of drop 163: unthickened retardant, dial setting 4, 185-foot altitude, 135 knots groundspeed.

Figures 18 and 19 show that thickened retardants had longer line lengths at each coverage level compared to water and unthickened products, as we would expect. Although at 1 gal/100 ft^2, line lengths only differed by about 23 feet. The high-viscosity drop (figure 19) contained coverage levels up to 10 gal/100 ft^2, while the low-viscosity drop (figure 18) only reached 5 gal/100 ft^2. This may be because more of the low-viscosity drop broke up into fine droplets and drifted off the grid. Also, we found more continuous, unbroken 2 and 4 gal/100 ft^2 areas with high-viscosity retardant. At the 180-foot altitude, high-viscosity retardant (970 cP) outperformed low-viscosity retardant (169 cP).

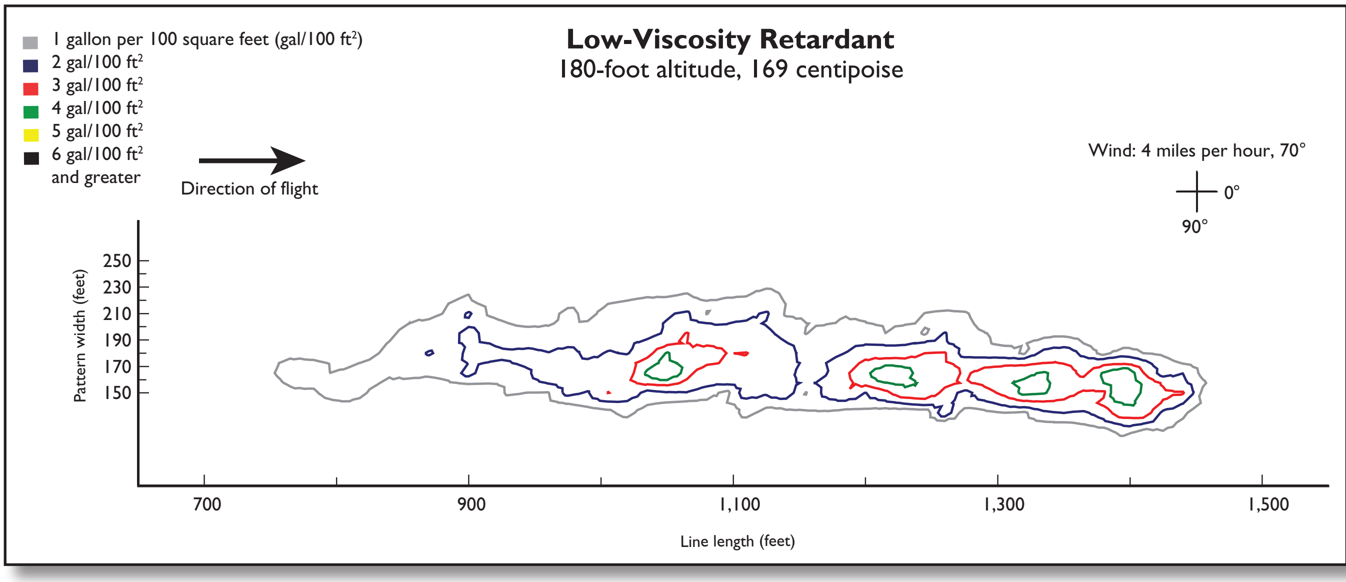

Figure 18—Contour plot of drop 192: low-viscosity xanthan, dial setting 4, 180-foot altitude, 131 knots groundspeed.

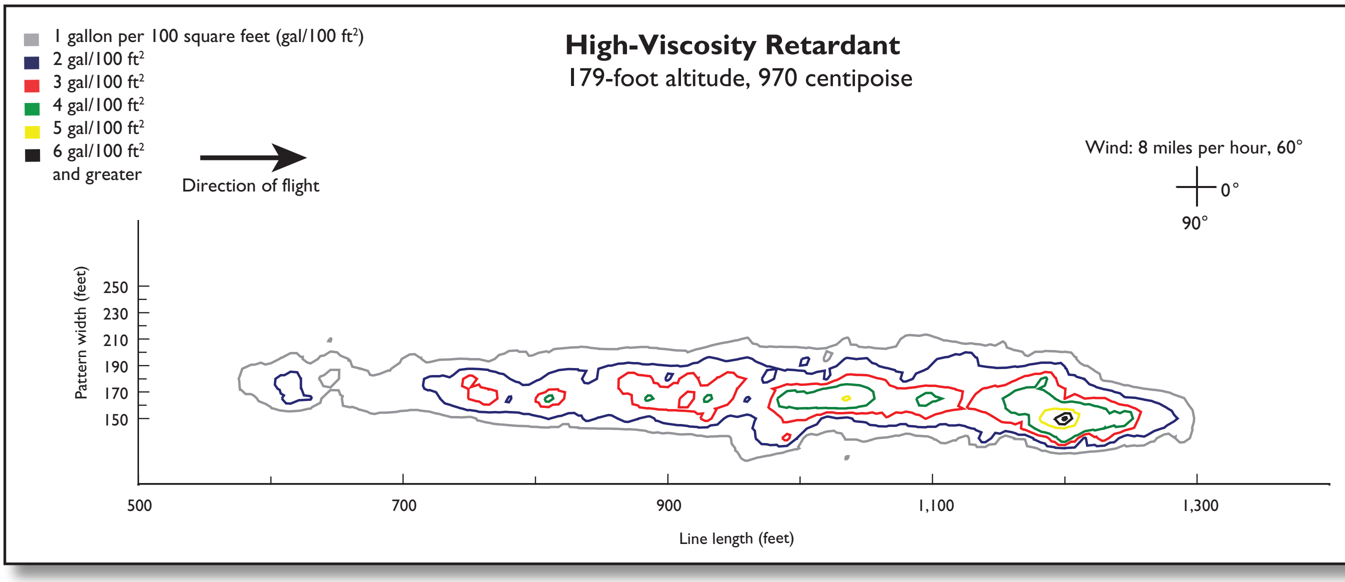

Figure 19—Contour plot of drop 135: high-viscosity guar, dial setting 4, 179-foot altitude, 134 knots groundspeed.

The next four plots (figures 20 through 23) are contour plots from drops at dial setting 4 and altitudes above 285 feet. Water performed better than unthickened retardant, which was surprising. It may be that at these drop altitudes the drops were so broken up that the cloud became very sensitive to small differences in windspeed that we were unable to measure. Figure 20 shows a drop that appears to have been affected by a crosswind, which can have the effect of pushing droplets back into the bulk of the cloud on the windward side of the drop.

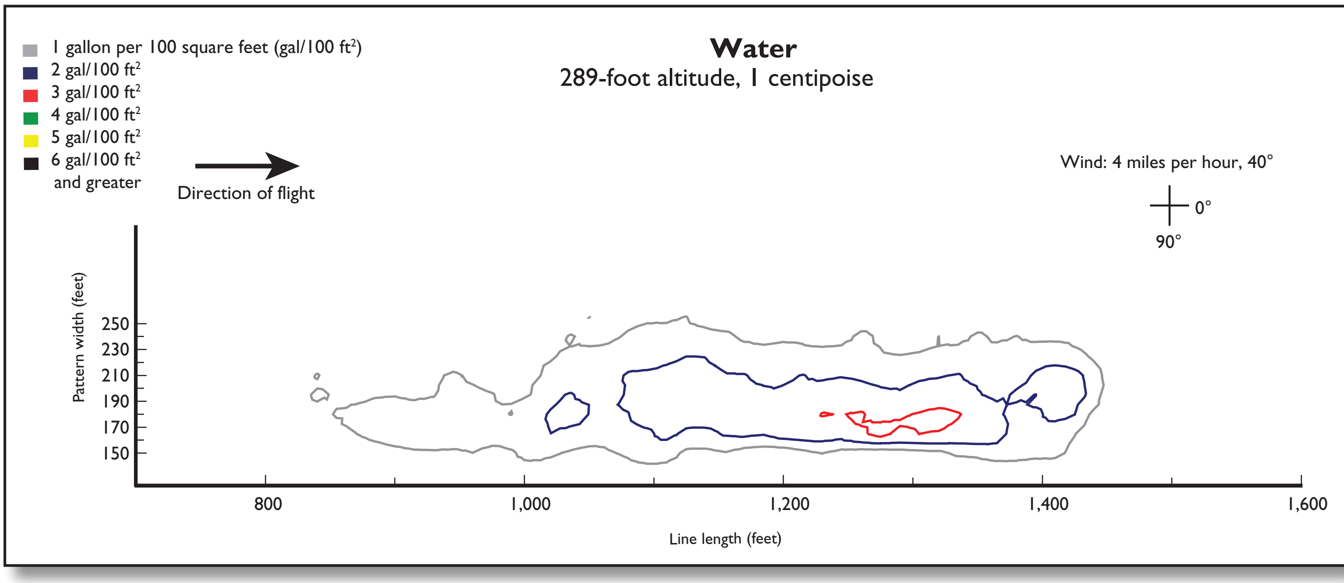

Figure 20—Contour plot of drop 183: water, dial setting 4, 289-foot altitude, 129 knots groundspeed.

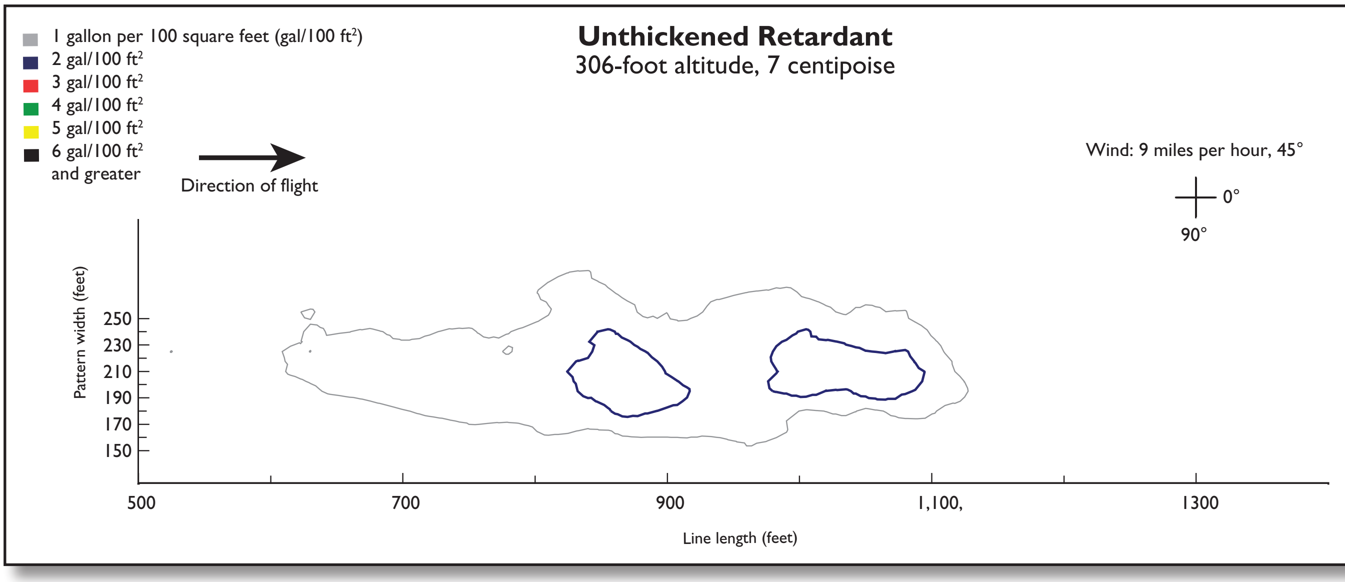

Figure 21—Contour plot of drop 131: unthickened retardant, dial setting 4, 306-foot altitude, 130 knots groundspeed.

Figures 22 and 23 compare the line-length production of a high- and low-viscosity retardant at 317 and 314 feet, respectively. The two drops were roughly the same length at the 1 gal/100 ft^2 coverage level, but the high-viscosity retardant produced a longer line length at 3 gal/100 ft^2 and greater.

Table 5 contains data from a medium-viscosity retardant drop and a high-viscosity retardant drop at 190 and 199 AGL respectively. Figures 24 and 25 show contour plots of these two drops. Increasing viscosity from 700 to 1,305 cP created an increase in line-length production at the 1, 2, and 3 gal/100 ft^2 coverage levels, but at the 4, 5, and 6 gal/100 ft^2 coverage levels, the higher viscosity retardant did not perform as well as the medium. The continuity of line also appeared to be better with medium-viscosity retardant.

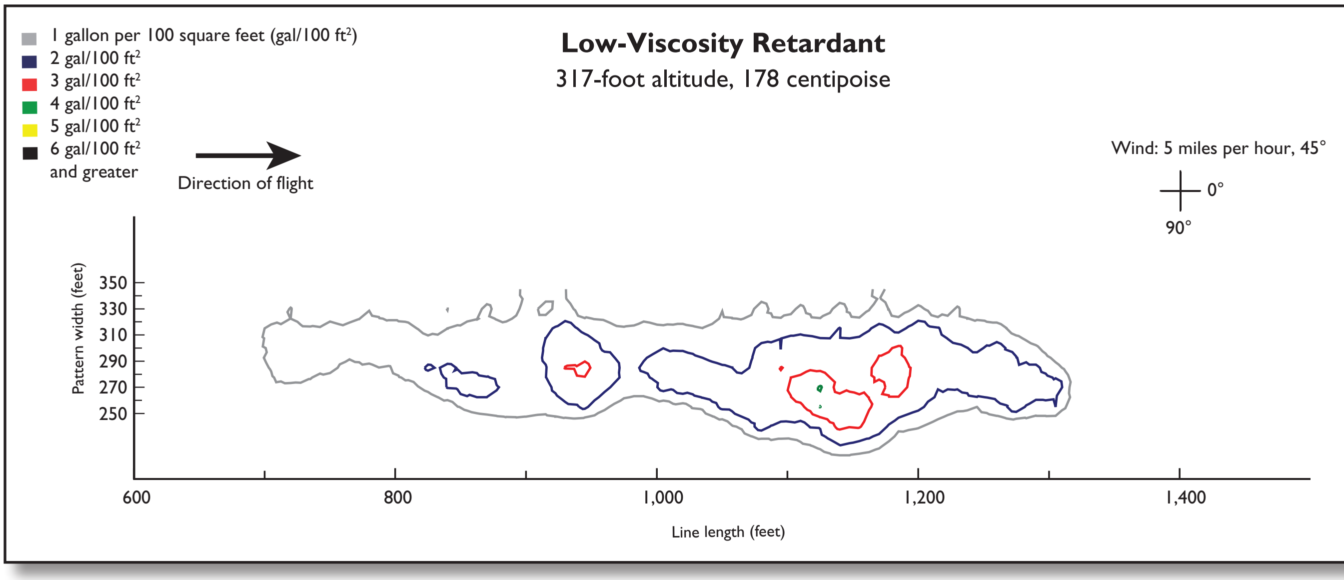

Figure 22—Contour plot of drop 182: low-viscosity xanthan, dial setting 4, 317-foot altitude, 123 knots groundspeed.

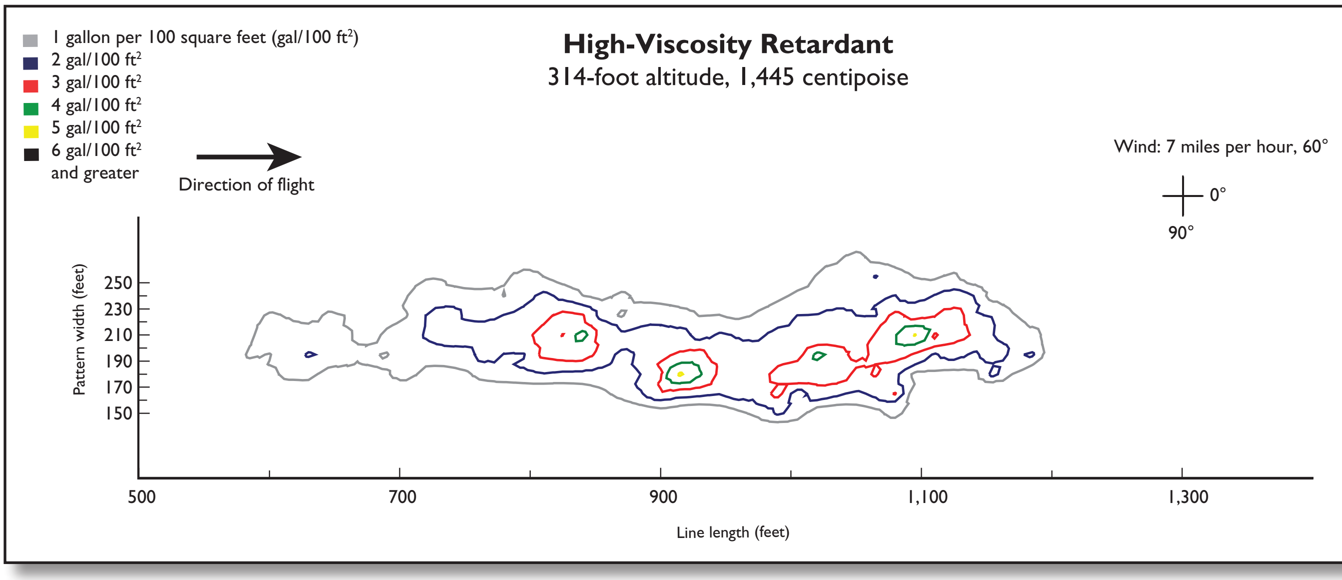

Figure 23—Contour plot of drop 189: high-viscosity guar, dial setting 4, 314-foot altitude, 130 knots groundspeed.

Table 5—Line length in feet per 100 gallons

Coverage level (GPC)	Line length (feet per 100 gallons dropped)	
	Medium viscosity (700 centipoise)	High viscosity (1,305 centipoise)
1	55	62
2	47	52
3	31	33
4	23	19
5	14	6
6	5	1
7	1	0

Considering the 10 contour plots (figures 16 through 25), higher viscosity solutions appeared to improve coverage levels and provide better continuity of pattern at high drop altitudes. At lower altitudes, medium-viscosity retardants seemed to do well. Adding gum thickener seemed to make a difference, but the optimum amount to impart optimum viscosity still has not been determined. Unthickened retardant did not seem to perform any better than water. In some cases, it performed worse. All other factors being equal, altitude had a significant impact on coverage level and quality of drop pattern; probably more than any other factor.

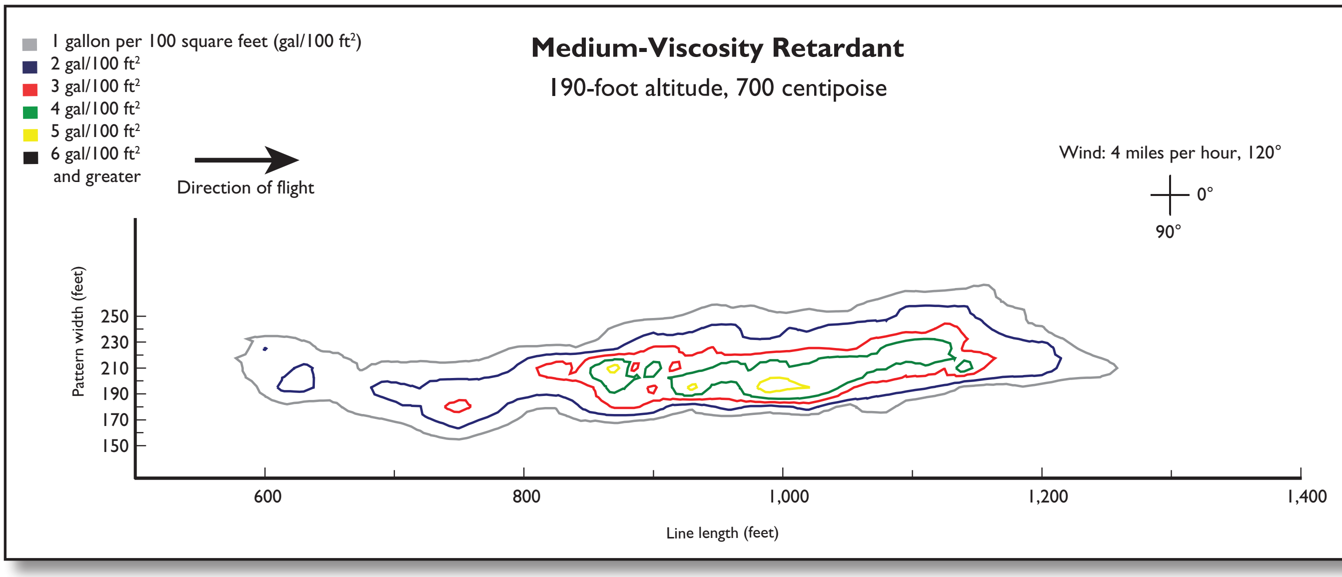

Figure 24—Contour plot of drop 120: medium-viscosity xanthan, dial setting 4, 190-foot altitude, 138 knots groundspeed.

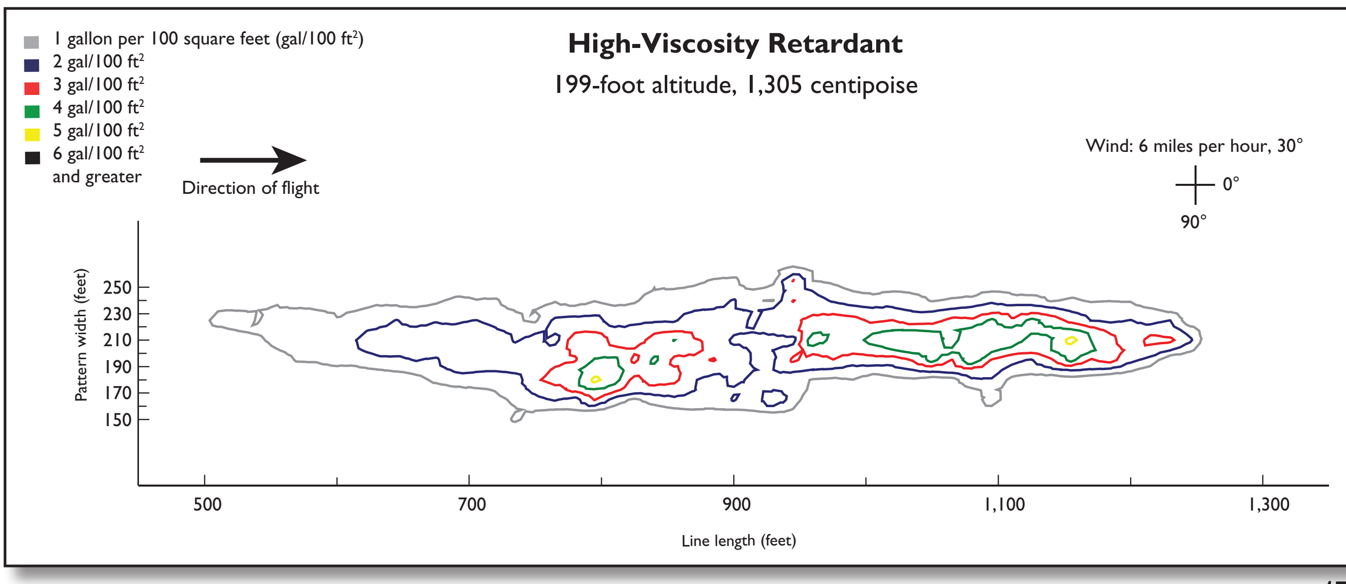

Figure 25—Contour plot of drop 150: high-viscosity xanthan, dial setting 4, 199-foot altitude, 133 knots groundspeed.

Viscosity Versus Normalized Retardant Line-Length Production

To investigate further, we compared viscosity levels to length of line. The next set of graphs show viscosity levels on the x-axis in centipoise and normalized retardant line-length production (length of retardant line per 100 gallons dropped) expressed on the y-axis in feet.

Figure 26 shows an altitude of about 195 feet (190 feet to 200 feet) at dial setting 4.

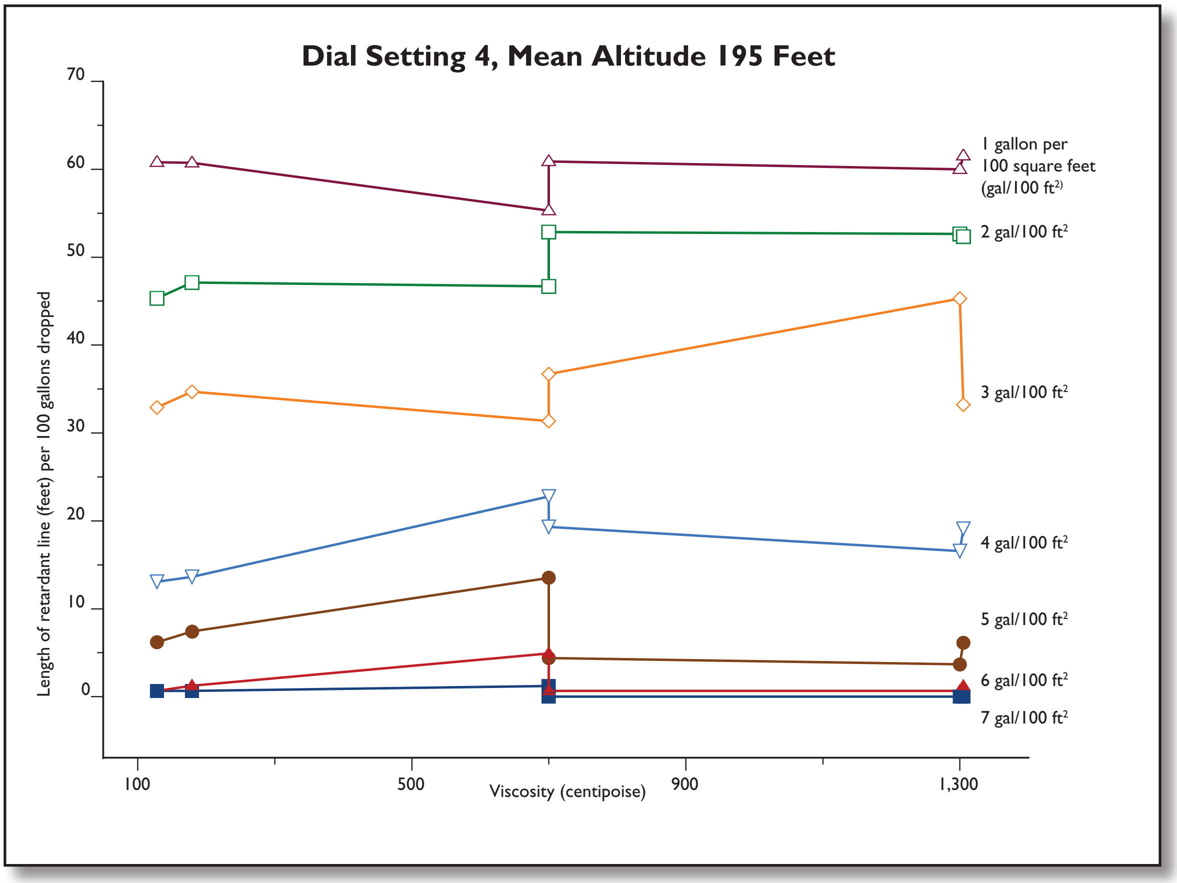

Figure 26—Six drops: dial setting 4, altitudes between 190 and 200 feet, varying viscosity levels. The different colors denote different gallons per 100 square foot levels.

Figure 27 shows an enlargement of the 1 gal/100 ft^2 line from figure 26 to better display the data. Figure 27 shows six data points from six different drops. On the first drop, we used retardant at 128 cP and achieved 61 feet per 100 gallons at the 1 gal/100 ft^2 coverage level for a data point of (128, 61). On the second drop, we used retardant at 179 cP and achieved 61 feet per 100 gallons at the 1 gal/100 ft^2 coverage level for a data point of (179, 61).

The next four data points are (700, 55), (700, 61), (1,300, 60), and (1,305, 62).

In figure 26, the viscosity at 700 cP produced the longest line length over most coverage levels. The high-viscosity drop produced the longest line length at one coverage level (3 gal/100 ft^2) out of the seven coverage levels shown.

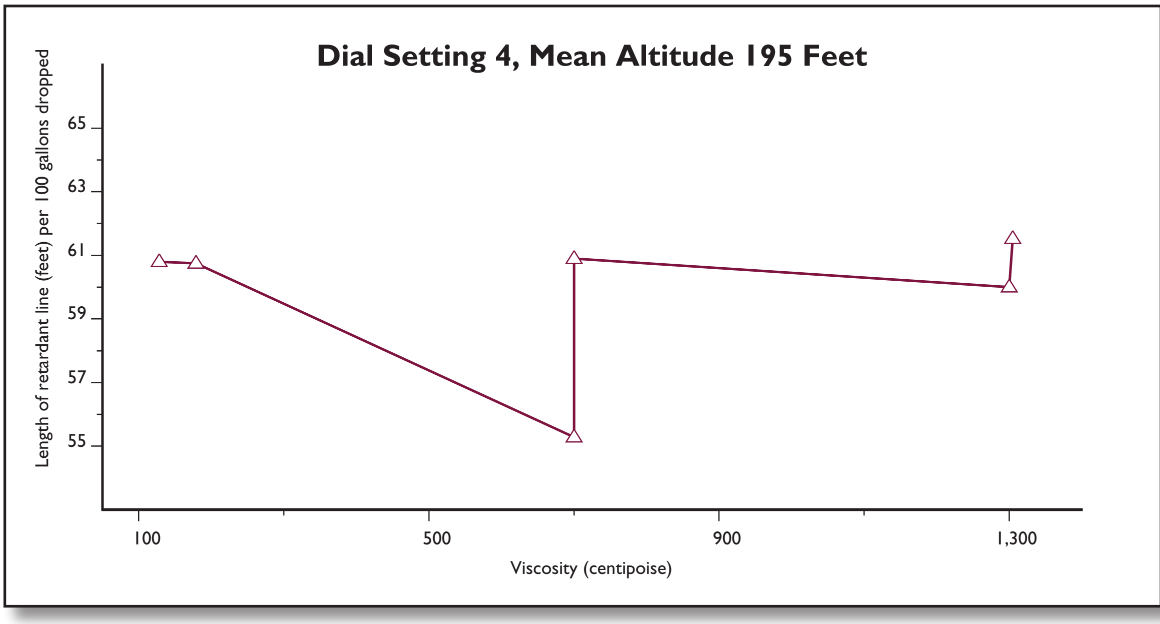

Figure 27—Six drops: dial setting 4, altitudes between 190 and 200 feet, varying viscosity levels at the 1 gallon per 100 square foot coverage level.

Figure 28 shows five drops at dial setting 2 from an altitude of about 195 feet (191 to 197 feet). The low-viscosity retardant produced longer line lengths at the 1, 2, 4, and 5 gal/100 ft^2 levels. The high-viscosity drop performed well at the 3 gal/100 ft^2 level. If we consider the theory that gum thickener creates larger droplets, we would expect more of the retardant of a high-viscosity drop pattern concentrated at a higher coverage, relatively speaking.

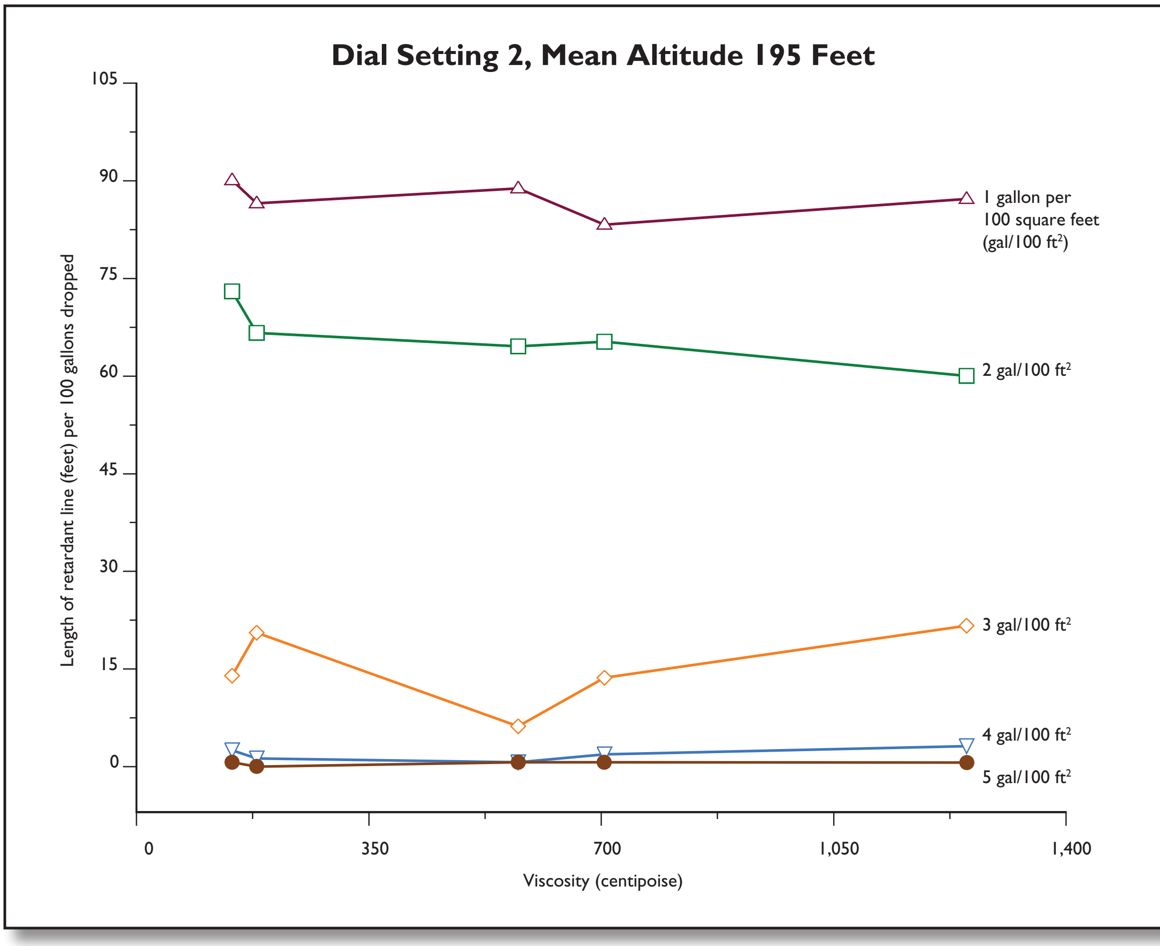

Figure 28—Five drops: dial setting 2, altitudes between 191 and 197 feet, varying viscosity levels.

Figure 29 shows the last example of drops from an altitude above 193 feet (190 to 199 feet). We include it here as a replicate. The medium-viscosity drops (700 cP) performed well at all coverage levels except for the 1 gal/100 ft^2 level.

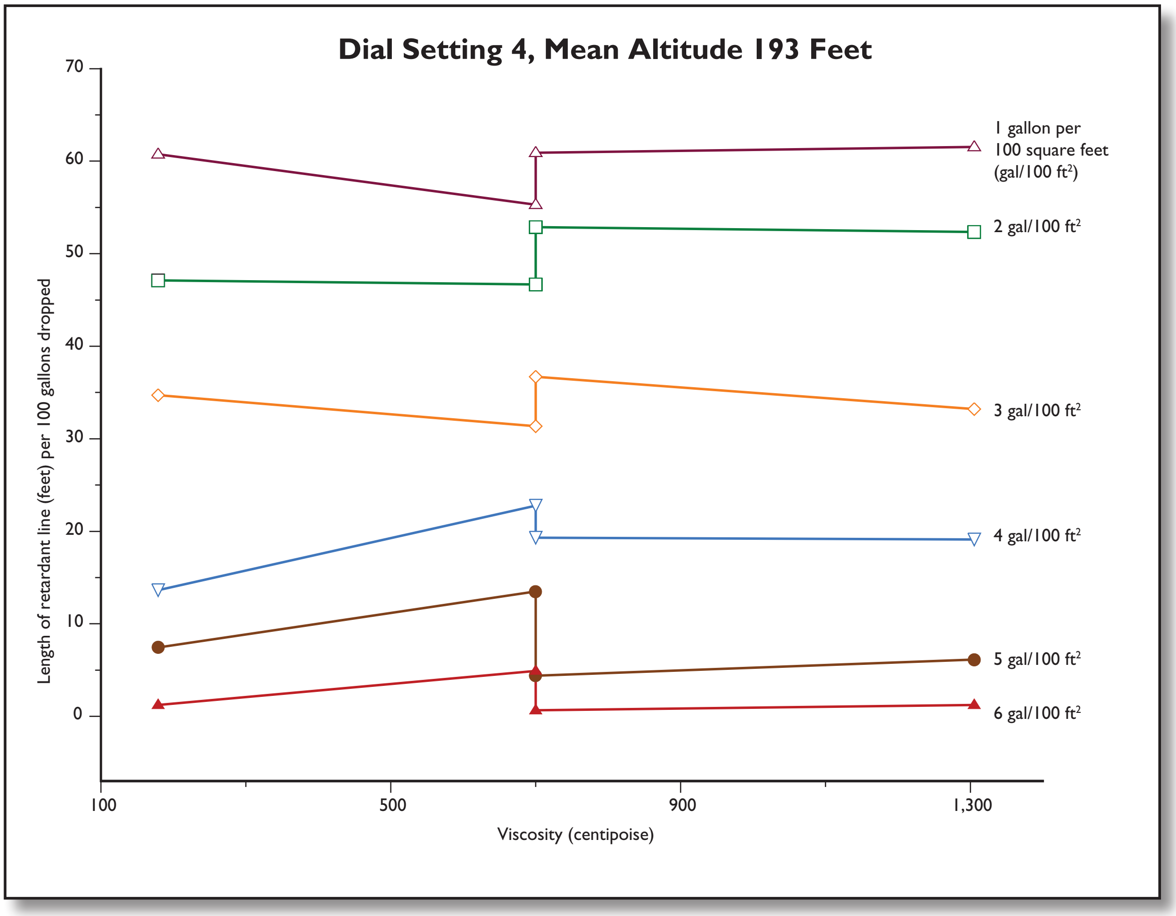

Figure 29—Four drops: dial setting 4, altitudes between 190 and 199 feet, varying viscosity levels.

Figures 30 and 31 show drops from a mean altitude of 179 feet (171 to 186 feet and 171 to 183 feet). The first drop was at dial setting 4. The second drop was at dial setting 2. Figure 30 shows that higher viscosity products produced longer line lengths at the 1, 6, 8, and 10 gal/100 ft^2 coverage levels, while the medium-viscosity retardants produced longer line lengths at the 2, 3, and 4 gal/100 ft^2 coverage levels.

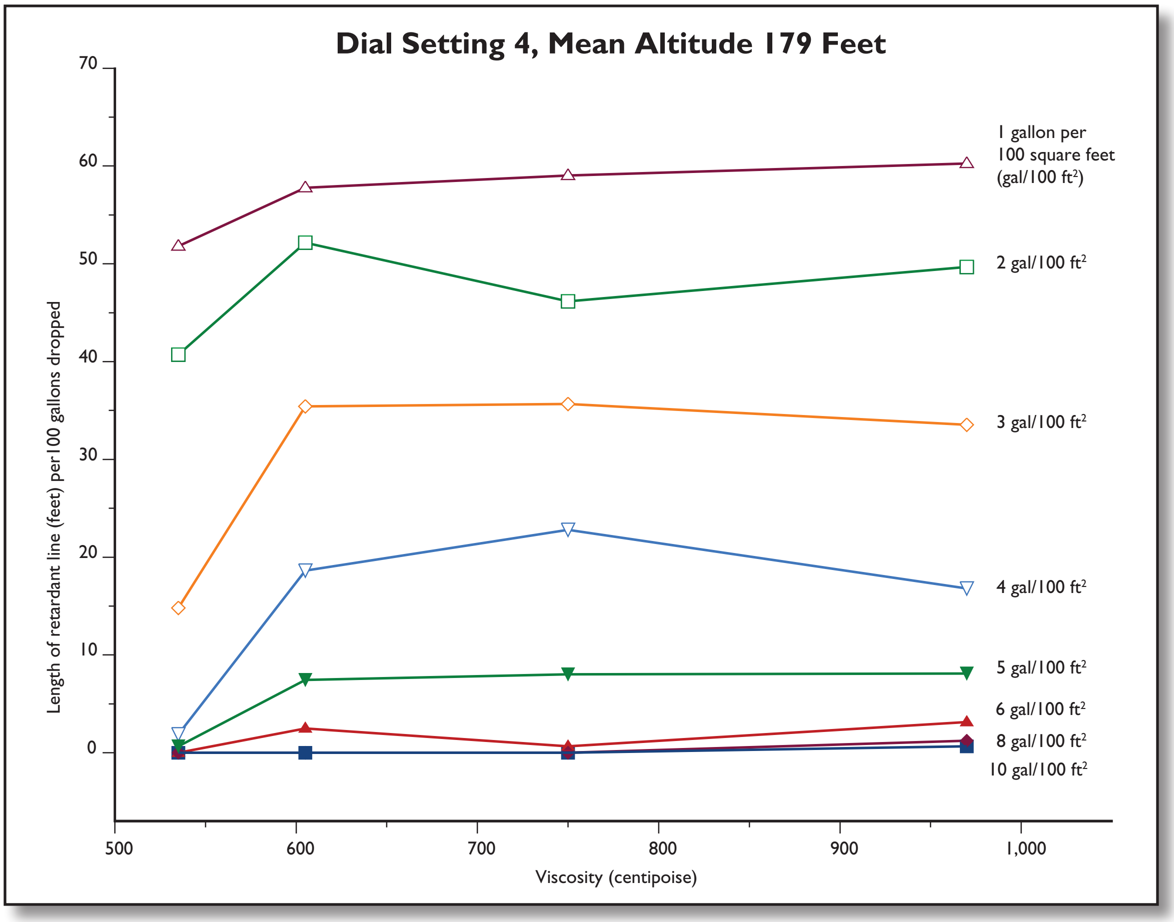

Figure 30—Four drops: dial setting 4, altitudes between 171 and 186 feet, varying viscosity levels.

Figure 31 shows roughly the same altitudes as figure 30, but at dial setting 2. The higher viscosity retardants performed better at dial settings 1, 2, and 4, the medium-viscosity retardants performed best at 3 gal/100 ft^2, and the low-viscosity retardants outperformed at 5 gal/100 ft^2.

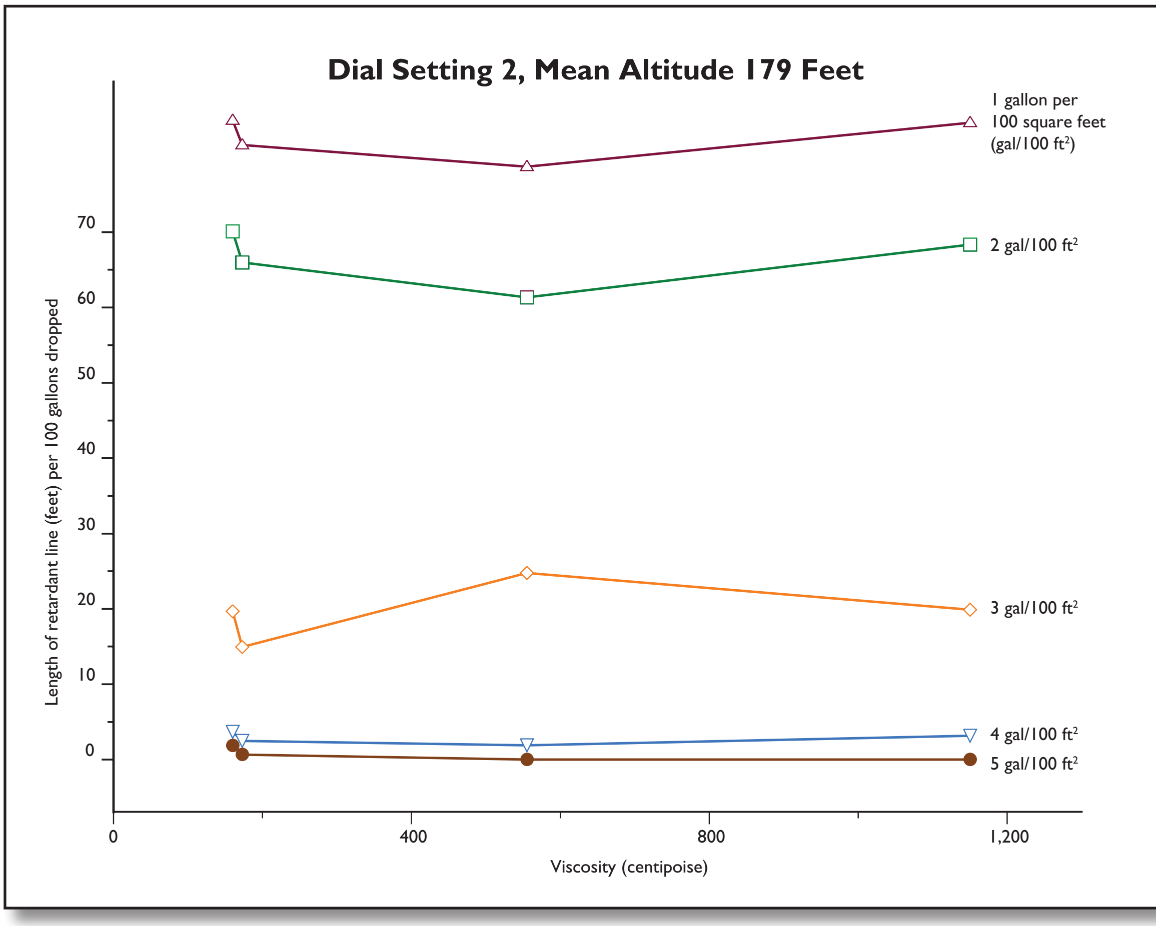

Figure 31—Four drops: dial setting 2, altitudes between 171 and 183 feet, varying viscosity levels.

The next set of graphs show drops from altitudes between 152 and 165 feet. Figure 32 shows two levels of high-viscosity retardant (1,050 cP and 1,315 cP).

Figure 32 shows the higher viscosity retardant (1,315 cP) created a longer line length at the 4 gal/100 ft^2 coverage level. The 1,050 cP retardant created longer line lengths at the 1, 2, 3, 6, 8, and 10 gal/100 ft^2 coverage levels.

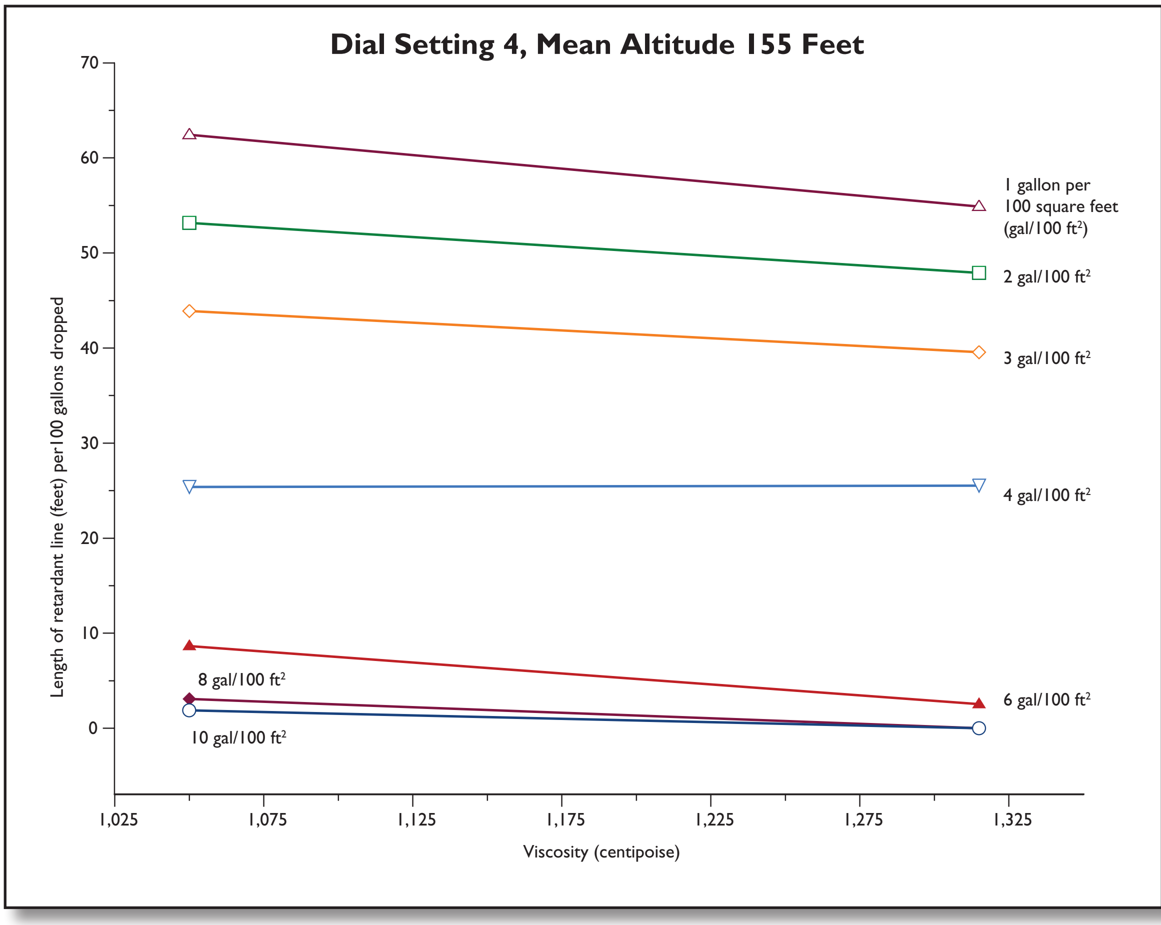

Figure 32—Two drops: dial setting 4, altitudes of 152 and 165 feet, two viscosity levels.

In this graph (figure 33), we display two viscosity levels of 620 cP and 1,450 cP at dial setting 2. The higher viscosity retardant outperformed the lower viscosity retardant at all levels except the 5 gal/100 ft^2 coverage level, where they were equal. It is interesting to note in figure 32 that the 1,050 cP level created longer line lengths at 3, 4, and 5 gal/100 ft^2 coverage levels than the 1,450 cP retardant in figure 33.

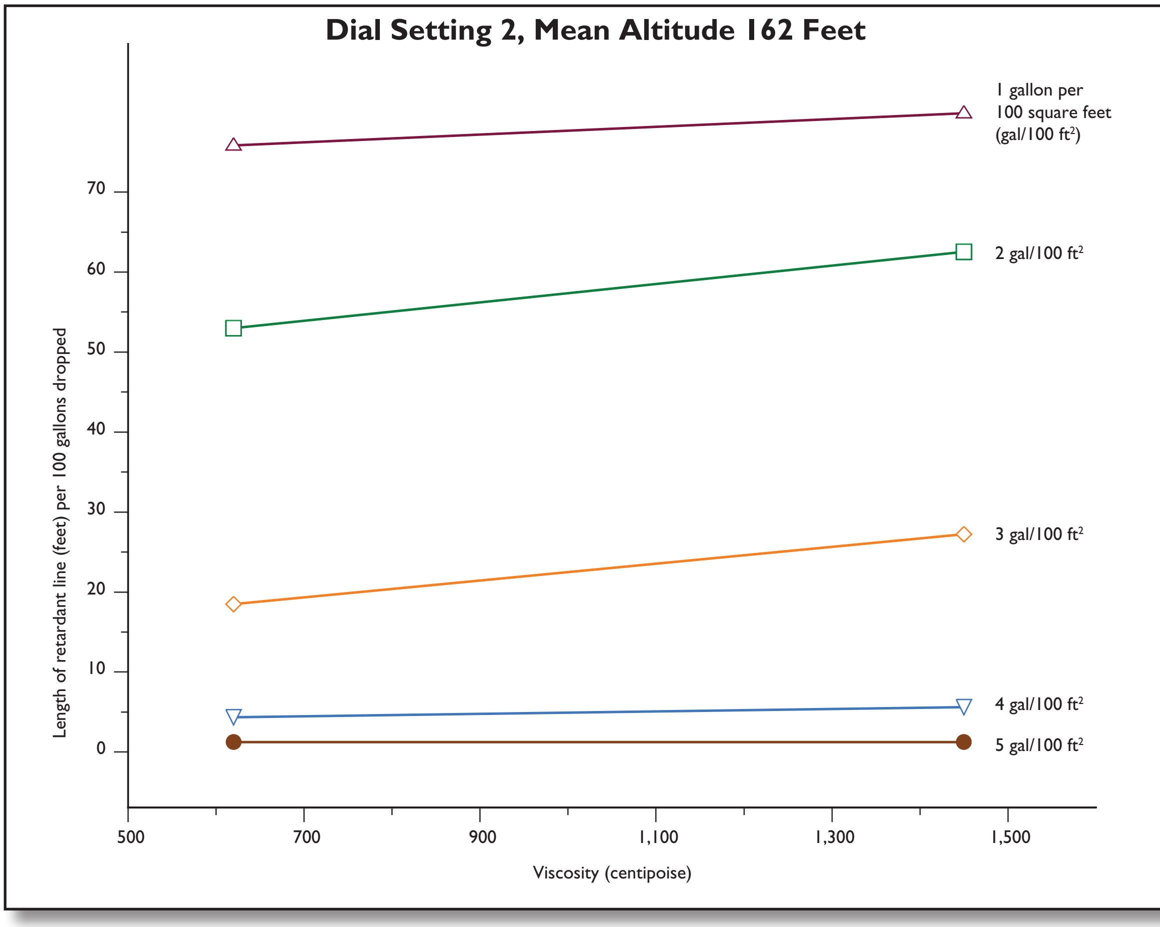

Figure 33—Two drops: dial setting 2, altitudes of 158 and 165 feet, two viscosity levels.

The graph in figure 34 shows two drops at altitudes of 121 and 122 feet. The lower viscosity drop created longer line lengths at the 3, 4, 6, and 8 gal/100 ft^2 coverage levels.

Note: this drop altitude is not recommended for the S2T.

As we examined figures 26 through 34 and considered how viscosity levels impact retardant line-length production, we noted that the medium- and high-viscosity retardants performed at about the same level. Of the 34 individual coverage levels displayed in the line plots, the high-viscosity retardants created longer line lengths 17 times, the medium-viscosity retardants created longer line lengths 15 times, and the low-viscosity retardants created longer line lengths twice. If we ignore coverage level 1 gal/100 ft^2, then medium-viscosity retardants performed better 14 times and high-viscosity retardants performed better 13 times. Given the inherent variability in drop test data, we can make the case that differences in line length between the viscosity levels were too small to be considered significant.

So far we have looked at two comparisons: drop altitude versus line-length production and viscosity level versus line-length production. We saw an advantage for withstanding changes in altitude when using gum-thickened retardants over both water and unthickened retardants. We noticed that changes in altitude have a dramatic effect on line-length production, width, and consistency. The addition of gum thickener assisted in mitigating the negative effects of dropping from a higher altitude, but there seemed to be diminishing returns as viscosity increased. Viscosity levels of 1,000 cP and higher do not seem to add to the line-length production of gum-thickened retardant at dial settings 2 and 4.

Adding gum thickener to retardant did reduce drift as the retardant moved from the tank of the aircraft to the fuel on the ground.

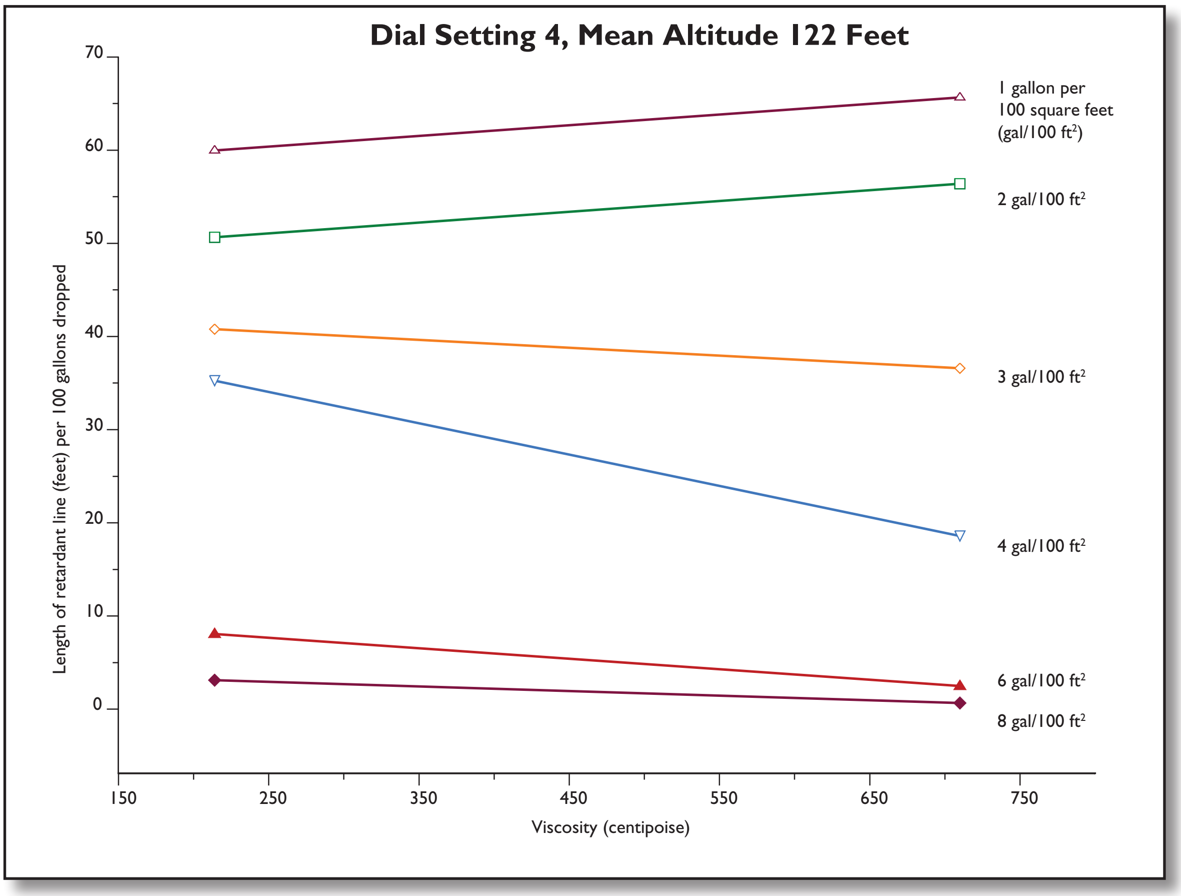

Figure 34—Two drops: dial setting 4, altitudes of 121 and 122 feet, two viscosity levels.

Our next set of plots compare viscosity levels to drift, measured in feet. Figure 35 shows the drop altitude in feet on the x-axis and the distance the pattern drifted in feet on the y-axis. Each point is represented by a viscosity value of the retardant in centipoise. So, for the point circled in red (1,315 cP) the drop altitude was 157 feet, the drift was 22 feet, and the viscosity level was 1,315 cP.

We would expect higher viscosity retardants to drift the least and be grouped toward the bottom and lower viscosity retardants to drift the most and be grouped toward the top. This, however, was not the case. We saw an 8 cP retardant with the same drift as a 1,295 cP retardant dropped from the same altitude. We saw a 179 cP retardant drifting less than a 700 cP and 1,305 cP retardant at the same altitude.

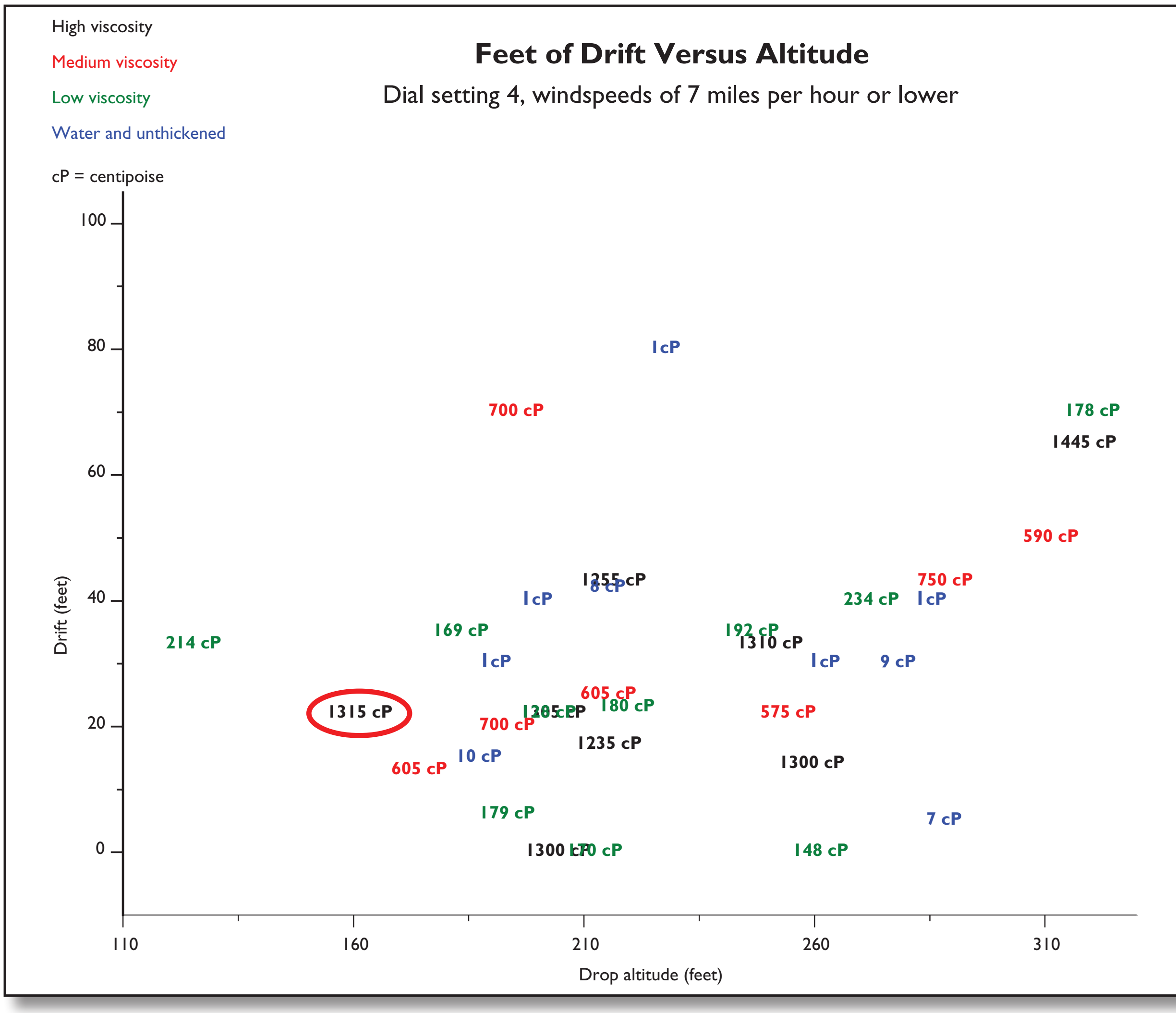

Figure 35—Feet of drift versus drop altitude at different viscosity levels using dial setting 4.

Figure 36 shows the same graph using drops at dial setting 2. The lowest altitude shown is 172 feet. For an S2T system, all forward momentum ceases at altitudes above 150 feet. These data were all from drops falling vertically, like heavy rain. We observed that viscosity levels did not seem to trend toward more or less drift.

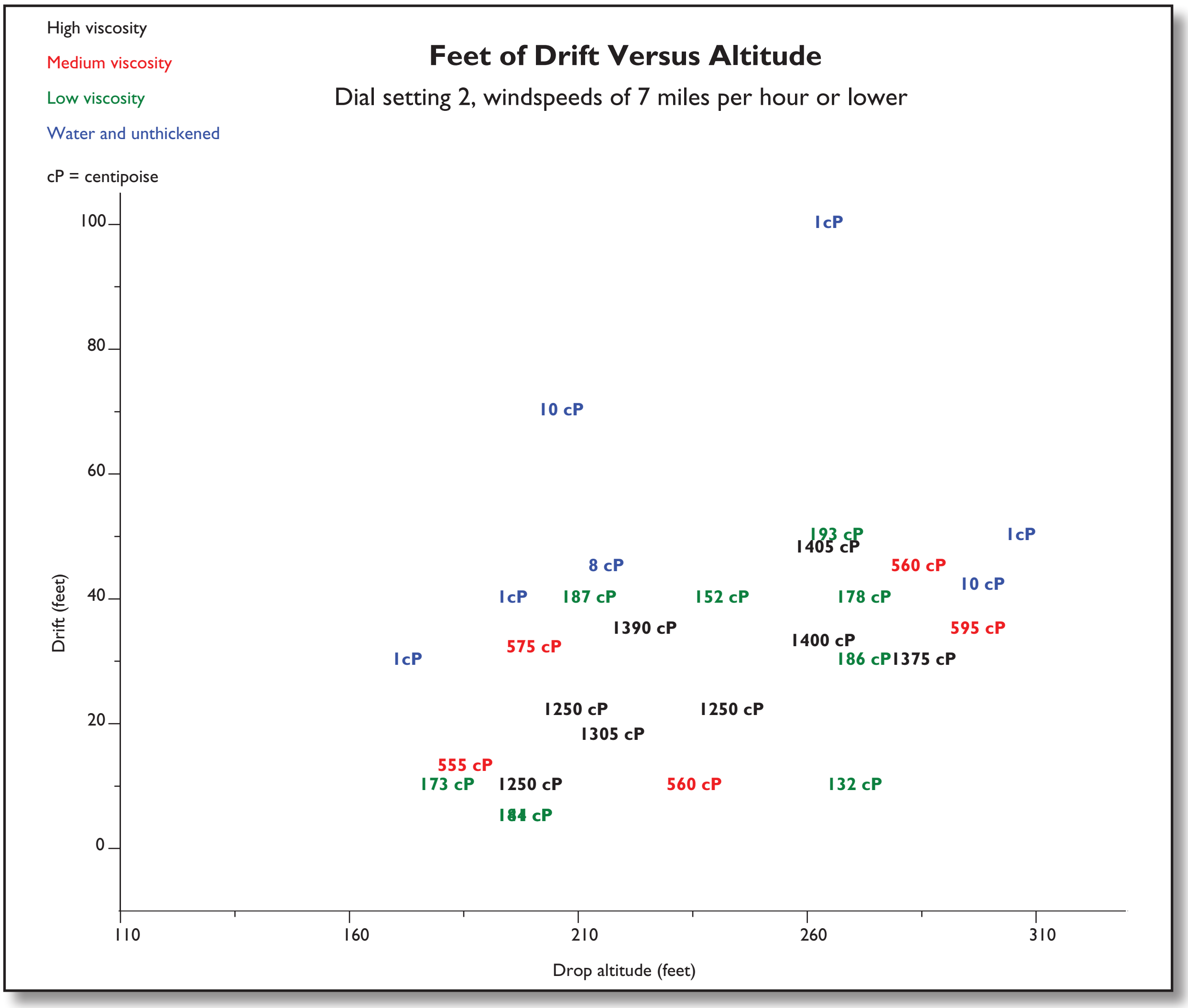

Figure 36—Feet of drift versus drop altitude at different viscosity levels using dial setting 2.

Conclusions

One of our goals in the 2005 drop test was to compare the performance of firefighting chemicals exhibiting different Brookfield viscosities and types of thickener in controlled test conditions and in low wind. We based this test plan on the drop tests of the 1970s when important rheological studies were conducted to compare water, clay-thickened retardants, and gum-thickened retardants (Anderson and Wong: 1978; Anderson et al. 1974a, 1974b, 1976, 1977; George 1975, George et al. 1976; Swanson and Helvig 1973, 1974; Swanson et al. 1975). The early studies led to development of user guidelines for airtankers (Swanson et al. 1975) and policies for viscosity levels (USDA FS 2007).

The 2005 drop test confirmed the idea that the addition of a little gum thickener goes a long way toward improving drop characteristics (Vandersall 1991). The data also suggests that, at dial settings 2 and 4, increasing the viscosity of a fire suppressant increased its performance at line-length production, up to a point. After this point, increasing the viscosity of the retardant did not seem to produce as great a return. This indicates that the effective viscosity of aerial-delivered retardants may have an optimal level where the gum thickener adds desirable characteristics to the retardant pattern while not contributing negative characteristics.

We should keep in mind this drop test doesn't give us any information about the coating, clinging, and penetrating characteristics of the fire suppressant. The drop test also does not provide insight into performance at winds above 13 mi/h or at flow rates above 600 gal/s. We are simply looking at line-length production, pattern continuity, and drift under controlled conditions. Increasing the viscosity level above 800 cP may be detrimental if this level impedes the canopy penetration capabilities of the retardants. We recommend a canopy penetration study to further understand how viscosity levels impact aerial application of retardant.

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Appendix A

2005 Drop Test Data

Drop number	Firefighting chemical	Dial setting	Flow rate (gallons per second)	Volume (gallons)	Percent recovered	Density (grams per cubic centimeter)	Viscosity (centipoise)	Refracto-meter index	Height (feet)	Speed (knots)	Wind-speed (miles per hour)	Wind direction (degrees)	Temperature (degrees Fahrenheit)	Relative humidity (percent)
101	Water	4	540	1,200	37	1.000	1	No reading	170	125	10	60	89	15
102	Water	2	301	1,209	58	1.000	1	No reading	109	128	7	45	89	13
103	Water	4	523	1,224	66	1.000	1	No reading	245	129	3	30	89	13
104	HV-G[1]	4	531	1,213	88	1.062	1,050	11	152	130	3	300	89	10
105	HV-G	2	326	1,212	83	1.075	1,450	13	158	133	6	20	89	10
106	MV-G[2]	4	527	1,211	89	1.067	710	11.5	121	125	4	20	66	35
107	HV-G	2	311	1,214	88	1.067	1,275	11.2	115	125	5	50	70	34
108							No useable data							
109	MV-G	2	311	1,203	81	1.055	800	9.7	216	128	8	20	78	25
110	MV-G	4	560	1,220	81	1.051	750	9.5	180	128	6	35	81	23
111	MV-G	2	308	1,225	73	1.052	760	9.5	145	134	8	90	87	14
112	LV-G[3]	4	549	1,214	95	1.032	214	6	122	124	6	30	56	67
113	LV-G	2	300	1,220	90	1.035	160	6	187	125	6	45	61	60
114	LV-G	2	303	1,207	94	1.033	152	6	238	135	6	30	66	53
115	LV-G	4	561	1,216	92	1.032	148	6	258	132	0.5	120	73	39
116	HV-X[4]	2	310	1,216	89	1.074	1,250	13.8	239	132	2	230	73	40
117	HV-X	4	542	1,224	88	1.075	1,300	13.5	255	138	1	290	75	38
118	HV-X	4	561	1,225	89	1.075	1,300	14	200	129	2	320	78	28
119	HV-X	2	310	1,213	88	1.078	1,250	14	195	130	2	270	79	27
120	MV-X[5]	4	590	1,221	85	1.052	700	10	190	138	4	120	80	26
121	MV-X	2	318	1,217	89	1.051	620	9.5	165	119	9	45	59	44
122	MV-X	4	562	1,215	83	1.046	600	9.2	279	122	9	45	63	40
123	MV-X	2	301	1,221	82	1.044	560	9.2	281	128	7	30	66	34
124	LV-X[6]	4	543	1,212	83	1.020	234	6.2	269	126	6	45	71	30
125	LV-X	2	306	1,219	75	1.022	193	6	263	126	7	45	77	25
126	LV-X	4	530	1,217	84	1.023	180	5.5	216	133	4	90	79	23
127	LV-X	2	296	1,219	69	1.023	187	5.2	209	134	7	70	82	16
128	Water	2	323	1,216	67	1.000	1	No reading	195	133	6	120	83	15
129	Water	2	284	1,218	43	1.000	1	No reading	260	120	9	45	58	44
130	Unthickened	2	296	1,214	63	1.077	8	12	291	121	9	45	63	38
131	Unthickened	4	551	1,214	68	1.081	7	13.5	306	130	9	45	66	35

[1] High-viscosity guar [2] Medium-viscosity guar [3] Low-viscosity guar [4] High-viscosity xanthan [5] Medium-viscosity xanthan [6] Low-viscosity xanthan

2005 Drop Test Data

Drop number	Firefighting chemical	Dial setting	Flow rate (gallons per second)	Volume (gallons)	Percent recovered	Density (grams per cubic centimeter)	Viscosity (centipoise)	Refracto-meter index	Height (feet)	Speed (knots)	Wind-speed (miles per hour)	Wind direction (degrees)	Temperature (degrees Fahrenheit)	Relative humidity (percent)
132	Unthickened	4	533	1,214	79	1.072	8	12.2	214	132	5	70	68	33
133	Unthickened	2	293	1,213	64	1.069	8	10.5	215	132	7	45	77	27
134	Water	4	540	1,225	73	1.000	1	No reading	199	132	6	45	79	26
135	HV-G	4	533	1,208	82	1.059	970	10.5	179	134	8	60	83	21
136	HV-G	2	319	1,207	82	1.060	1,150	11	172	133	8	60	83	20
137	HV-G	4	503	1,205	89	1.066	1,255	11.5	212	120	5	60	58	47
138	HV-G	2	294	1,208	92	1.065	1,405	11.2	260	122	5	50	60	45
139	MV-G	2	285	1,211	89	1.057	950	10	268	134	9	45	65	39
140	MV-G	4	551	1,214	91	1.051	750	9.2	285	131	6	60	68	37
141	MV-G	4	558	1,207	90	1.051	700	9	192	128	5	60	73	32
142	MV-G	2	310	1,207	84	1.051	705	9,2	191	125	6	80	77	32
143	LV-G	2	304	1,182	88	1.033	144	6	195	131	2	30	78	31
144	LV-G	4	554	1,209	86	1.030	128	5.7	199	132	5	120	81	26
145	LV-G	2	315	1,204	86	1.030	132	5.7	267	141	2	200	82	25
146	LV-G	4	560	1,215	87	1.029	123	5.5	253	136	2	180	82	25
147	HV-X	4	557	1,212	91	1.080	1,310	14	246	135	4	60	53	45
148	HV-X	2	296	1,217	91	1.079	1,400	14.5	259	130	3	60	58	46
149	HV-X	2	308	1,221	93	1.075	1,305	13.5	213	126	2	90	64	39
150	HV-X	4	545	1,219	90	1.079	1,305	13.5	199	133	3	90	71	31
151	MV-X	4	564	1,208	89	1.047	605	9.2	171	132	2	180	77	21
152	MV-X	2	318	1,211	85	1.046	555	9	182	127	1	30	80	16
153	MV-X	2	320	1,213	79	1.047	560	9	232	136	4	180	84	11
154	MV-X	4	563	1,216	72	1.047	535	9	186	131	13	270	84	10
155	LV-X	4	541	1,213	87	1.025	192	5.5	243	132	3	60	52	32
156	LV-X	2	298	1,212	90	1.026	186	5.5	269	127	1	60	58	28
157	LV-X	2	299	1,205	94	1.028	181	5.5	195	129	1	220	64	21
158	LV-X	4	555	1,211	93	1.027	170	5.5	209	132	1	300	69	17
159	Water	2	311	1,207	42	1.000	1	No reading	264	137	6	250	75	13
160	No useable data													
161	Unthickened	4	564	1,218	67	1.077	9	13	277	141	5	240	81	9
162	Unthickened	2	315	1,200	58	1.078	10	15	204	133	7	90	87	7
163	Unthickened	4	553	1,195	74	1.082	10	15	185	135	3	350	89	9
164	Unthickened	2	322	1,219	49	1.076	12	13.5	201	134	8	40	90	8

2005 Drop Test Data

Drop number	Firefighting chemical	Dial setting	Flow rate (gallons per second)	Volume (gallons)	Percent recovered	Density (grams per cubic centimeter)	Viscosity (centipoise)	Refracto-meter index	Height (feet)	Speed (knots)	Wind-speed (miles per hour)	Wind direction (degrees)	Temperature (degrees Fahrenheit)	Relative humidity (percent)
165	Water	2	303	1,224	65	1.000	1	No reading	172	135	6	45	90	8
166	Water	4	557	1,220	57	1.000	1	No reading	227	138	5	60	92	8
167	HV-G	4	560	1,175	87	1.068	1,315	12	157	138	6	40	75	23
168	HV-G	2	318	1,214	83	1.066	1,390	11.5	220	126	6	20	78	21
169	HV-G	2	312	1,211	83	1.068	1,375	12	281	133	5	30	80	19
170	HV-G	4	568	1,213	80	1.065	1,280	11.5	258	125	9	130	84	16
171	HV-X	4	534	1,220	71	1.075	1,400	17.5	273	125	13	135	85	16
172	HV-X	2	300	1,204	82	1.082	1,255	14.5	265	127	10	30	61	39
173	HV-X	2	299	1,206	88	1.083	1,250	13.5	205	126	6	20	63	37
174	HV-X	4	534	1,199	91	1.080	1,235	14.5	211	137	6	45	69	32
175	MV-X	4	575	1,220	86	1.040	605	9.5	212	128	6	45	72	29
176	MV-X	2	301	1,208	79	1.045	575	9.2	197	136	6	40	77	25
177	MV-X	2	321	1,264	78	1.046	595	9.5	294	127	6	40	79	23
178	MV-X	4	590	1,216	79	1.048	575	9	251	130	1	90	83	18
179	LV-X	4	556	1,210	84	1.021	179	5.2	190	136	3	220	82	20
180	LV-X	2	308	1,205	76	1.023	173	5.2	178	136	3	120	84	15
181	LV-X	2	294	1,207	80	1.027	178	5.2	269	124	5	60	54	45
182	LV-X	4	547	1,204	67	1.023	178	5.5	317	123	5	45	57	42
183	Water	4	558	1,213	77	1.000	1	No reading	289	129	4	40	62	39
184	Water	2	308	1,190	69	1.000	1	No reading	306	133	3	80	66	34
185	Unthickened	2	301	1,177	68	1.082	10	14	296	131	2	60	74	27
186	Unthickened	4	565	1,193	51	1.081	8	13	286	133	3	30	77	24
187	Unthickened	4	556	1,185	65	1.078	7	14	287	139	6	280	79	17
188	Unthickened	2	298	1,189	66	1.078	7	13	175	125	4	180	80	17
189	HV-G	4	561	1,201	75	1.066	1,445	12	314	130	7	60	80	14
190	Water	4	567	1,203	71	1.000	1	No reading	190	129	6	30	82	13
191	MV-X	4	551	1,204	74	1.047	590	9.5	308	129	4	60	84	13
192	LV-X	4	549	1,195	78	1.019	169	5	180	131	4	70	86	12

2005 Drop Test Data—Table Extension

Drop number	Line length (feet)											Area (square feet)										
	0.5	1	2	3	4	5	6	7	8	9	10	0.5	1	2	3	4	5	6	7	8	9	10
101	825	638	315	75	0	0	0	0	0	0	0	80,100	40,050	12,038	788	0	0	0	0	0	0	0
102	1,095	923	195	38	0	0	0	0	0	0	0	86,119	37,575	2,306	338	0	0	0	0	0	0	0
103	863	578	278	75	0	0	0	0	0	0	0	90,506	36,675	8,100	1,575	0	0	0	0	0	0	0
104	855	758	645	533	308	143	105	45	38	23	23	61,594	40,050	24,975	12,994	5,738	2,306	1,181	338	281	169	169
105	1,163	968	758	330	68	15	0	0	0	0	0	80,944	46,069	22,781	5,513	675	113	0	0	0	0	0
106	885	795	683	443	225	45	30	8	8	0	0	79,256	47,644	26,325	7,931	2,306	338	225	56	56	0	0
107	1,133	923	720	255	45	0	0	0	0	0	0	86,231	51,075	23,738	3,994	338	0	0	0	0	0	0
108	No useable data																					
109	1,155	1,035	743	128	30	8	0	0	0	0	0	81,506	48,319	18,506	2,081	225	56	0	0	0	0	0
110	825	720	563	435	278	98	8	0	0	0	0	59,794	41,119	24,413	11,756	4,781	844	56	0	0	0	0
111	1,170	975	443	75	23	8	8	8	0	0	0	95,006	41,738	9,675	731	169	56	56	56	0	0	0
112	848	728	615	495	428	263	98	75	38	15	8	62,719	41,006	26,269	15,694	9,169	3,319	900	563	281	113	56
113	1,208	1,035	855	240	45	23	0	0	0	0	0	94,275	53,044	23,513	3,431	338	169	0	0	0	0	0
114	1,253	1,013	803	135	0	0	0	0	0	0	0	102,938	54,900	22,275	1,350	0	0	0	0	0	0	0
115	893	720	593	435	195	75	30	0	0	0	0	76,894	47,644	28,013	11,419	3,094	563	225	0	0	0	0
116	1,283	1,110	848	83	0	0	0	0	0	0	0	96,919	54,450	21,881	619	0	0	0	0	0	0	0
117	870	713	540	308	75	0	0	0	0	0	0	76,219	50,569	27,394	7,931	956	0	0	0	0	0	0
118	870	735	645	555	203	45	8	0	0	0	0	69,244	46,631	29,588	11,869	1,969	338	56	0	0	0	0
119	1,193	1,058	728	263	38	8	0	0	0	0	0	88,144	52,538	22,331	2,981	281	56	0	0	0	0	0
120	795	675	570	383	278	165	60	15	0	0	0	65,588	41,063	24,131	11,756	5,231	1,856	506	113	0	0	0
121	1,043	923	645	225	53	15	0	0	0	0	0	91,238	49,275	23,006	3,319	450	113	0	0	0	0	0
122	690	555	450	300	113	38	8	0	0	0	0	75,263	41,850	22,388	8,775	2,475	394	56	0	0	0	0
123	1,200	968	578	68	8	0	0	0	0	0	0	103,331	49,106	13,050	506	56	0	0	0	0	0	0
124	750	630	458	383	75	23	0	0	0	0	0	72,281	42,300	23,288	10,913	1,575	281	0	0	0	0	0
125	1,125	893	428	15	0	0	0	0	0	0	0	97,594	45,956	9,788	225	0	0	0	0	0	0	0
126	885	728	600	338	135	45	8	0	0	0	0	75,600	43,481	23,625	8,213	1,913	394	56	0	0	0	0
127	1,200	945	323	23	0	0	0	0	0	0	0	98,663	39,038	5,794	169	0	0	0	0	0	0	0
128	1,133	855	323	15	0	0	0	0	0	0	0	89,888	38,306	6,469	113	0	0	0	0	0	0	0
129	1,073	525	0	0	0	0	0	0	0	0	0	83,025	13,106	0	0	0	0	0	0	0	0	0
130	1,185	713	0	0	0	0	0	0	0	0	0	115,706	24,019	0	0	0	0	0	0	0	0	0
131	780	525	210	0	0	0	0	0	0	0	0	93,094	40,613	7,819	0	0	0	0	0	0	0	0
132	788	653	443	173	23	0	0	0	0	0	0	84,150	44,381	17,494	4,050	225	0	0	0	0	0	0
135	878	728	600	405	203	98	38	23	15	8	8	65,250	41,513	23,288	10,181	3,150	1,238	338	169	113	56	56
136	1,163	1,020	825	240	38	0	0	0	0	0	0	81,000	47,475	22,106	2,588	281	0	0	0	0	0	0

2005 Drop Test Data—Table Extension

Drop number	Line length (feet)										Area (square feet)										
	0.5	1	2	3	4	5	6	7	8	9	10	0.5	1	2	3	4	5	6	7	8	9	10
137	863	720	585	473	165	83	30	15	0	0	0	76,669	45,000	24,694	10,969	2,081	619	225	113	0	0	0
138	1,163	1,065	848	120	23	0	0	0	0	0	0	96,975	58,163	21,713	1,069	169	0	0	0	0	0	0
139	1,260	1,043	675	53	15	8	0	0	0	0	0	109,294	56,363	14,006	506	113	56	0	0	0	0	0
140	863	705	548	443	195	45	15	0	0	0	0	79,088	46,406	25,706	10,575	2,025	338	113	0	0	0	0
141	870	735	638	443	233	53	8	0	0	0	0	75,544	44,044	24,244	10,969	3,656	563	56	0	0	0	0
142	1,155	1,005	788	165	23	8	0	0	0	0	0	92,813	50,063	19,519	2,081	169	56	0	0	0	0	0
143	1,200	1,065	863	165	30	8	0	0	0	0	0	91,350	54,450	21,544	1,350	225	56	0	0	0	0	0
144	825	735	548	398	158	75	8	8	0	0	0	76,163	46,238	24,413	9,450	1,575	563	56	56	0	0	0
145	1,238	930	675	45	0	0	0	0	0	0	0	99,056	50,569	17,550	338	0	0	0	0	0	0	0
146	900	758	570	420	98	30	0	0	0	0	0	77,569	49,219	25,763	8,775	1,069	225	0	0	0	0	0
147	833	705	555	368	143	53	8	0	0	0	0	78,806	47,588	26,944	9,956	2,700	731	113	0	0	0	0
148	1,193	1,065	923	165	8	0	0	0	0	0	0	99,563	53,888	23,175	1,800	56	0	0	0	0	0	0
149	1,185	1,035	953	248	38	0	0	0	0	0	0	92,700	56,869	28,238	2,363	281	0	0	0	0	0	0
150	833	750	638	405	233	75	15	0	0	0	0	73,350	46,238	27,113	11,081	3,769	563	113	0	0	0	0
151	833	698	630	428	225	90	30	8	0	0	0	67,444	42,919	26,156	11,700	4,838	1519	281	56	0	0	0
152	1,170	953	743	300	23	0	0	0	0	0	0	83,644	47,250	22,838	2,756	169	0	0	0	0	0	0
153	1,170	930	690	203	15	0	0	0	0	0	0	84,431	43,200	16,031	2,138	113	0	0	0	0	0	0
154	735	630	495	180	23	8	0	0	0	0	0	73,125	45,281	19,181	3,038	225	56	0	0	0	0	0
155	833	705	540	323	165	30	0	0	0	0	0	85,444	45,056	22,669	7,481	2,419	225	0	0	0	0	0
156	1,230	1,065	660	143	8	0	0	0	0	0	0	108,000	54,394	17,213	1,350	56	0	0	0	0	0	0
157	1,215	1,043	803	248	15	0	0	0	0	0	0	98,044	53,100	21,375	3,094	113	0	0	0	0	0	0
158	840	720	503	398	270	68	8	8	8	0	0	77,625	47,081	23,906	12,150	3,825	506	56	56	56	0	0
159	1,013	188	0	0	0	0	0	0	0	0	0	83,138	7,706	0	0	0	0	0	0	0	0	0
160	No useable data																					
161	735	585	270	83	8	0	0	0	0	0	0	84,600	37,013	8,831	1,013	56	0	0	0	0	0	0
162	1,028	600	143	23	0	0	0	0	0	0	0	82,800	27,281	5,344	394	0	0	0	0	0	0	0
163	825	638	398	248	98	15	8	0	0	0	0	73,350	34,313	14,906	5,681	900	113	56	0	0	0	0
164	893	495	60	0	0	0	0	0	0	0	0	81,056	20,250	900	0	0	0	0	0	0	0	0
165	1,110	953	248	15	8	0	0	0	0	0	0	96,019	37,913	3,769	169	56	0	0	0	0	0	0
166	758	585	278	0	0	0	0	0	0	0	0	81,281	32,963	7,481	0	0	0	0	0	0	0	0
167	788	645	563	465	300	83	30	8	0	0	0	59,006	39,544	25,819	14,006	4,781	900	225	56	0	0	0
168	1,155	945	698	128	15	15	8	0	0	0	0	88,256	49,725	20,363	1,519	225	169	56	0	0	0	0

2005 Drop Test Data—Table Extension

Drop number	Line length (feet)											Area (square feet)										
	0.5	1	2	3	4	5	6	7	8	9	10	0.5	1	2	3	4	5	6	7	8	9	10
169	1,088	960	780	90	15	8	0	0	0	0	0	87,694	51,356	20,588	844	113	56	0	0	0	0	0
170	825	668	623	300	68	15	0	0	0	0	0	75,825	42,919	23,456	5,513	619	113	0	0	0	0	0
171	788	660	413	188	30	8	8	0	0	0	0	81,000	414,56	14,119	3,038	225	56	56	0	0	0	0
172	1,230	1,013	495	0	0	0	0	0	0	0	0	108,675	50,794	7,875	0	0	0	0	0	0	0	0
173	1,238	1,043	750	158	15	0	0	0	0	0	0	90,731	52,144	21,375	1,519	113	0	0	0	0	0	0
174	878	713	630	488	240	75	23	8	0	0	0	73,463	44,606	26,269	11,475	3,825	563	169	56	0	0	0
175	773	653	578	420	240	98	38	15	0	0	0	66,825	44,550	25,200	11,644	4,163	844	281	113	0	0	0
176	1,253	1,073	780	75	8	8	0	0	0	0	0	95,513	49,444	14,569	619	56	56	0	0	0	0	0
177	1,125	953	683	90	0	0	0	0	0	0	0	95,456	50,344	16,931	731	0	0	0	0	0	0	0
178	735	660	563	435	173	23	0	0	0	0	0	68,006	43,538	24,356	9,900	2,250	169	0	0	0	0	0
179	870	735	570	420	165	90	15	8	0	0	0	73,913	41,850	22,781	9,450	2,925	788	169	56	0	0	0
180	1,155	983	795	180	30	8	0	0	0	0	0	77,963	46,575	19,744	2,194	225	56	0	0	0	0	0
181	1,095	968	623	23	0	0	0	0	0	0	0	97,031	55,181	14,681	338	0	0	0	0	0	0	0
182	765	615	435	128	8	0	0	0	0	0	0	68,175	43,256	19,406	2,756	113	0	0	0	0	0	0
183	810	608	398	105	0	0	0	0	0	0	0	93,881	43,481	15,863	1,294	0	0	0	0	0	0	0
184	1,080	803	38	0	0	0	0	0	0	0	0	105,581	37,631	450	0	0	0	0	0	0	0	0
185	1,155	863	68	0	0	0	0	0	0	0	0	101,363	34,650	506	0	0	0	0	0	0	0	0
186	878	675	300	38	8	0	0	0	0	0	0	66,656	33,075	6,863	281	56	0	0	0	0	0	0
187	735	593	203	0	0	0	0	0	0	0	0	86,456	37,631	5,625	0	0	0	0	0	0	0	0
188	1,200	930	128	0	0	0	0	0	0	0	0	96,806	37,406	1,069	0	0	0	0	0	0	0	0
189	720	615	465	248	68	23	15	0	0	0	0	69,806	42,019	21,488	6,131	675	169	113	0	0	0	0
190	720	578	480	203	23	0	0	0	0	0	0	72,394	40,556	20,475	2,925	169	0	0	0	0	0	0
191	773	638	480	233	23	8	8	0	0	0	0	75,150	43,088	18,394	3,544	169	56	56	0	0	0	0
192	795	705	555	338	128	23	0	0	0	0	0	69,019	41,006	20,813	7,594	1,856	225	0	0	0	0	0

Appendix B

The drop test grid contains an array of sampling cups placed at specific crossrange and downrange spacing. The spacing can vary depending on the test objectives. The raw data is the measured mass of liquid collected from each cup, which is converted to gallons per 100 square feet (gal/100 ft^2). The data can be presented with greater resolution by predicting unknown values between observed values.

We use a weighted average of the observed gal/100 ft^2 values to predict unknown values. We use kriging to determine the weights for the weighted average. These kriging weights are based on distance, direction, and variability of the known values.

The first step in determining the kriging weights is creating a model (called the variogram) that describes the variation of the observed gal/100 ft^2 values. The variogram is the average squared difference between pairs of gal/100 ft^2 values.

Table B–1 shows the variogram values for drop 104. The first line of the table shows that there are 4,120 pairs of cups at a distance of 23.97096 feet. The average squared difference between these cups is 0.145876.

The distances in table B–1 are calculated using the length of the pattern for drop 104 and the grid spacing.

Table B–1—Variogram values for drop 104

Distance	Gamma (variogram)	Number of pairs
23.97096	0.145876	4,120
58.1154	0.294227	18,028
86.77792	0.334119	11,831
111.9615	0.481884	30,293
145.6326	0.553698	29,346
170.1047	0.613125	34,471
201.5029	0.679907	42,091
227.975	0.694383	41,259
257.2455	0.781188	50,939
283.3795	0.771159	42,779
310.9756	0.875735	61,842
342.395	0.889409	60,465
369.5541	0.928662	61,478
400.3173	0.975992	67,232
427.0981	0.987465	60,637
456.3625	1.044142	72,292
484.288	1.049219	63,810
512.6638	0.948816	75,918
542.5489	0.911984	68,710
569.6804	0.808484	73,019

Figure B-1 shows the plot of sample data from drop 104 with a trend line drawn over. The variogram value (gamma) is shown on the y-axis and the distance is shown on the x-axis. This trend line models variation as a function of distance and direction.

Three features of the trend line are used to calculate weights in our weighted average. They are:

- **Range—**As the distance between pairs increases, the average squared difference between pairs increases. Eventually, an increase in distance no longer produces an increase in average squared difference, and the variogram reaches a plateau. The range is the distance at which the plateau is reached.
- **Sill—**The value of the average squared difference at the range.
- **Nugget—**The vertical jump between zero and the first variogram value.

Knowing the range, sill, and nugget, we can calculate the weights using some sample data.

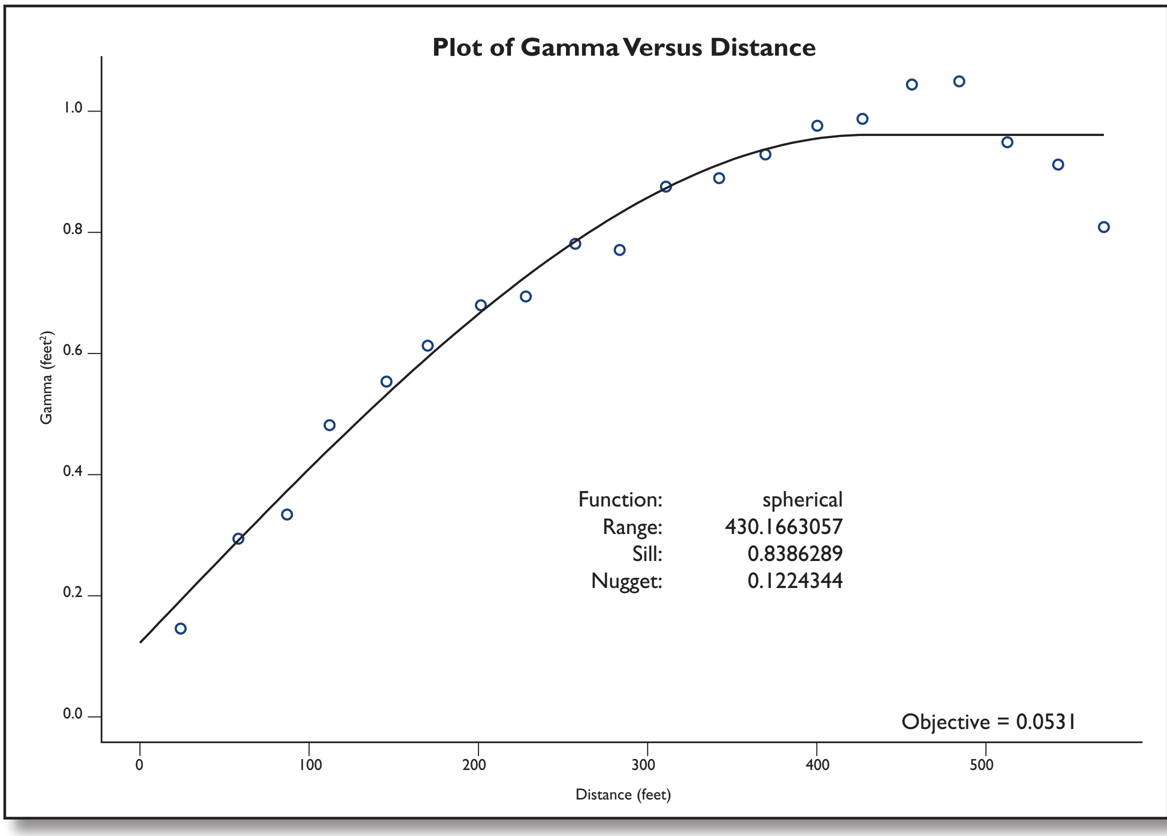


Figure B–1—A plot of sample data from drop 104.

Figure B–2 shows an example of gal/100 ft^2 values from drop 104 in their positions on the grid with the unknown values we want to predict.

For the purpose of this explanation, we will focus only on 12 observed gal/100 ft^2 values to predict one unknown value. Figure B–3 shows the area we will focus on inside the box.

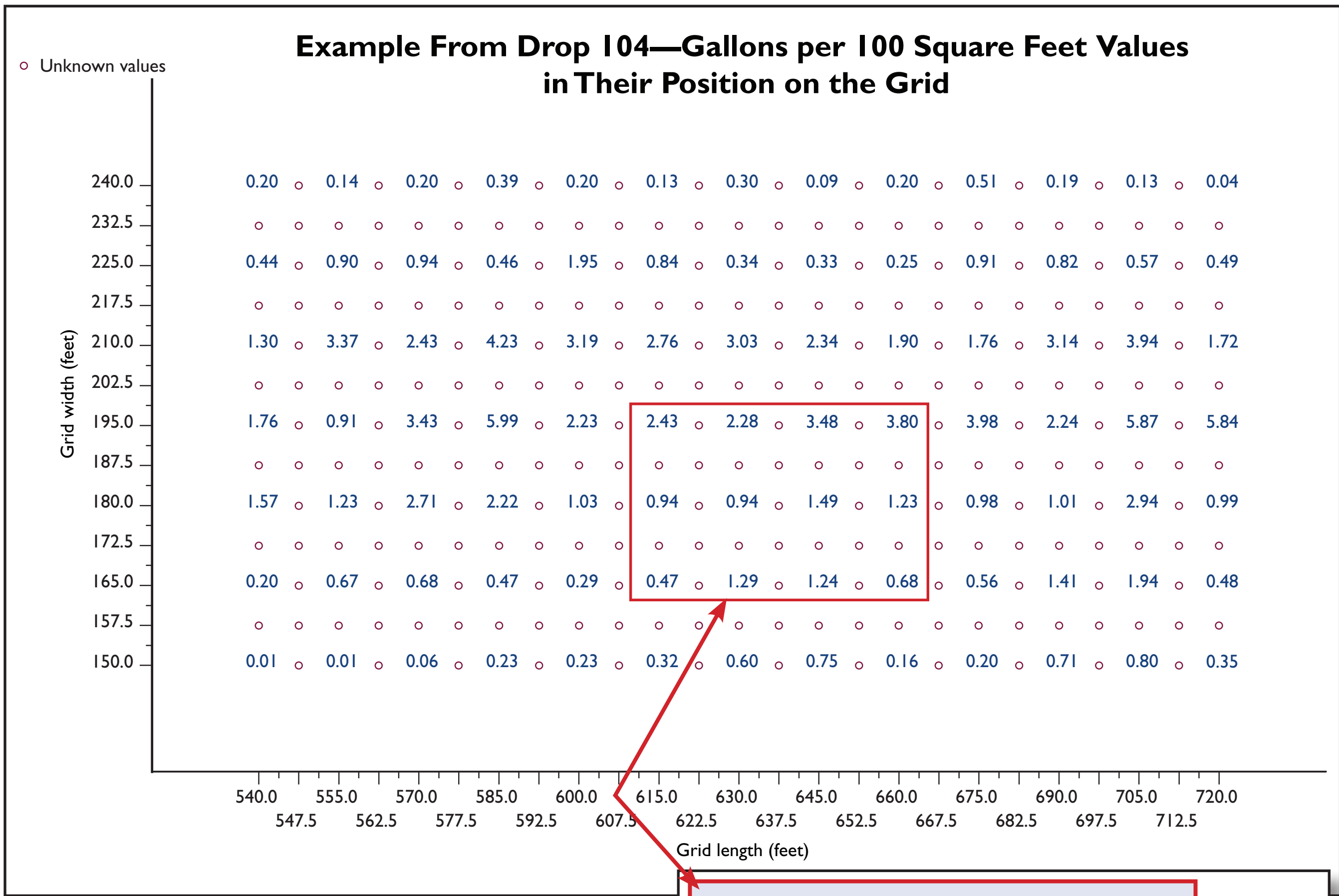


Figure B–2—Grid position of gallons per 100 feet squared values from drop 104 with unknown values to be predicted.

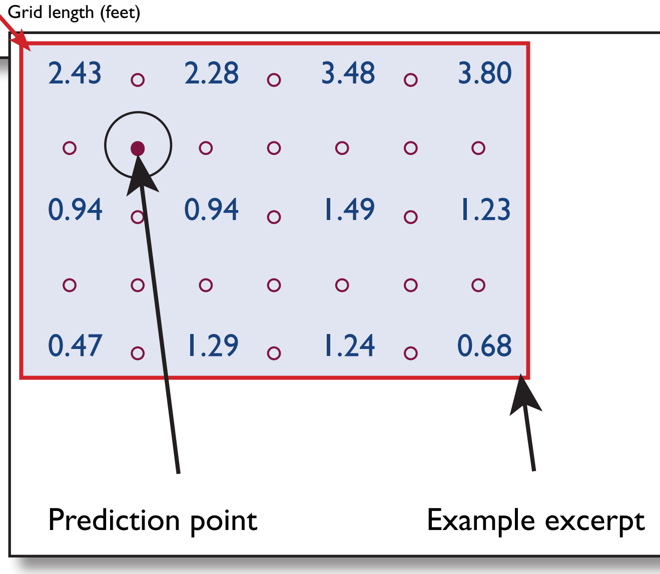


Figure B–3—Detail of the highlighted box from figure B–2.

Figure B–4 shows the enlarged area with the prediction point in red (see figure B–3).

Table B–2 shows the position of the known values, the corresponding gal/100 ft^2 values, and the distance to the unknown values.

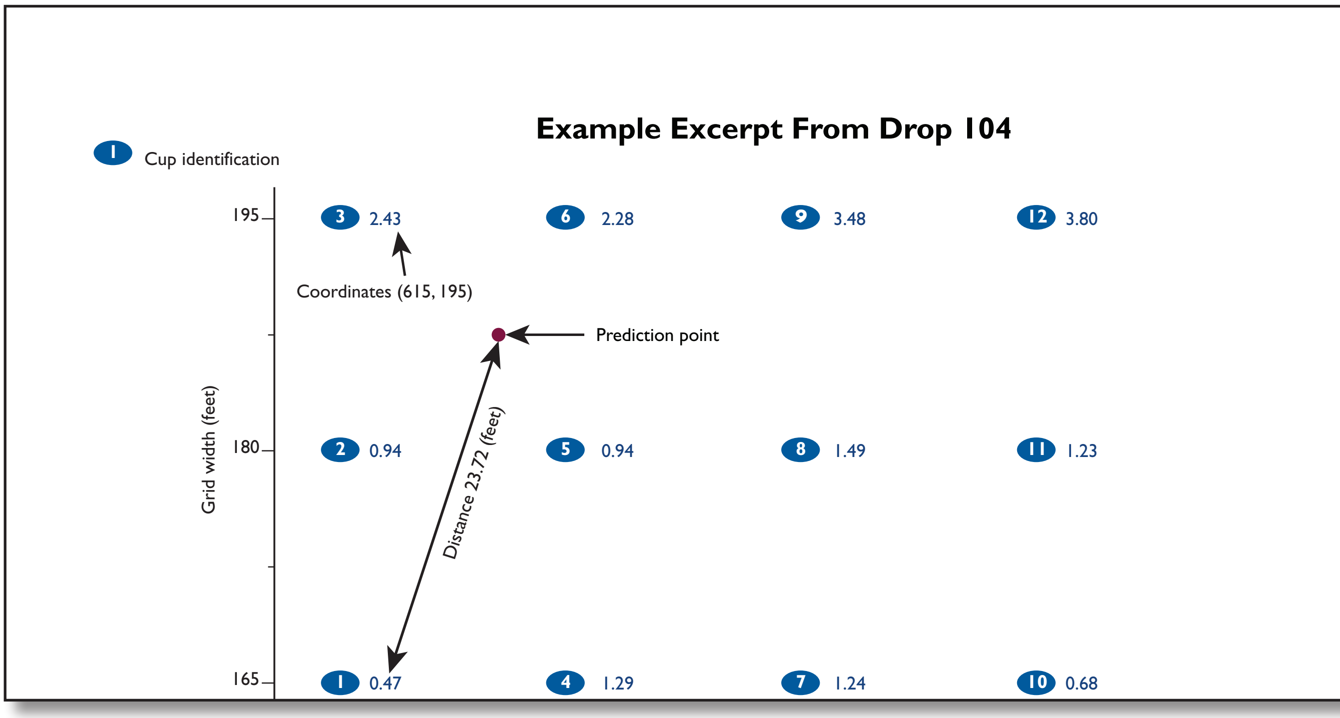


Figure B–4—Further detail of the highlighted box from figure B–2 with the prediction point in red.

Table B–2—Position of known value, corresponding gallons per 100 square feet and distance to unknown values

Cup identification	X	Y	Z	Distance from unknown (feet)
1	615	165	0.468742	23.72
2	615	180	0.937485	10.61
3	615	195	2.432393	10.61
4	630	165	1.292209	23.72
5	630	180	0.937485	10.61
6	630	195	2.280368	10.61
7	645	165	1.241534	31.82
8	645	180	1.494908	23.72
9	645	195	3.483896	23.72
10	660	165	0.68411	43.73
11	660	180	1.228865	38.24
12	660	195	3.800614	38.24

The next step is to determine all the distances between the known and unknown values. Table B–3 shows these distances.

We estimate the covariance with the following formula:

$$\mathrm{Cov}(h) = \begin{cases} sill & if\ |h| = 0 \\ (sill - nugget)e^{\left(\frac{-3|h|}{range}\right)} & if\ |h| > 0 \end{cases}$$

Cov *(h)* means the covariance at distance *h*

The plot in figure B–1 shows that the range = 430.1663057, the nugget = 0.1224344, and the sill = 0.8386289.

We calculate all the covariances at these distances from table B–3.

Table B–4 shows the calculations from the first column of table B–3.

Table B–3—Matrix of distances *(h)* (feet)

Cup identification	0 (unknown)	1	2	3	4	5	6	7	8	9	10	11	12
0 (unknown)	0.00	23.72	10.61	10.61	23.72	10.61	10.61	31.82	23.72	23.72	43.47	38.24	38.24
1	23.72	0.00	15.00	30.00	15.00	21.21	33.54	3.00	33.54	46.23	45.00	46.23	54.08
2	10.61	15.00	0.00	15.00	21.21	15.00	21.21	33.54	30.00	33.54	47.43	45.00	47.43
3	10.61	30.00	15.00	0.00	33.54	21.21	15.00	42.43	33.54	30.00	54.08	47.43	45.00
4	23.72	15.00	21.21	33.54	0.00	15.00	30.00	15.00	21.21	33.54	30.00	33.54	42.43
5	10.61	21.21	15.00	21.21	15.00	0.00	15.00	21.21	15.00	21.21	33.54	30.00	33.54
6	10.61	33.54	21.21	15.00	30.00	15.00	0.00	33.54	21.21	15.00	42.43	33.54	30.00
7	31.82	30.00	33.54	42.43	15.00	21.21	33.54	0.00	15.00	30.00	15.00	21.21	33.54
8	23.72	33.54	30.00	33.54	21.21	15.00	21.21	15.00	0.00	15.00	33.54	21.21	15.00
9	23.72	42.43	33.54	30.00	33.54	21.21	15.00	30.00	15.00	0.00	33.54	21.21	15.00
10	43.47	45.00	47.43	54.08	30.00	33.54	42.43	15.00	33.54	33.54	0.00	15.00	30.00
11	38.24	47.43	45.00	47.43	33.54	30.00	33.54	21.21	21.21	21.21	15.00	0.00	15.00
12	38.24	54.08	47.43	45.00	42.43	33.54	30.00	33.54	15.00	15.00	30.00	15.00	0.00

Table B–4—Calculating covariances

Cov *(h)*	**Covariances for distance** *(h)*
C(00.00)	sill = 0.8386289
C(23.72)	$0.7161945e^{\frac{-3}{430.1663057}(23.72)}$ = 0.60699146[1]
C(10.61)	$0.7161945e^{-0.006974\,(10.61)}$ = 0.665113126[2]
C(10.61)	0.66511312
C(23.72)	0.606991467
C(10.61)	0.66511312
C(10.61)	0.66511312
C(31.82)	0.573660412
C(23.72)	0.606991467
C(23.72)	0.606991467
C(43.47)	0.528895018
C(38.24)	0.548542205
C(38.24)	0.548542205

[1] Fully worked example [2] Partially worked example

The equation to determine kriging weights is matrix **C** multiplied by the kriging weights vector equals *d*:

$$\mathbf{C} \times \text{kriging weights} = d$$

We know **C** and *d* and we need to find the kriging weights vector.

We use the values in matrix **B** (table B–5) to get matrix **C** and vector *d*.

The first column of table B–5, or first row, are the covariances between known values and the unknown point we are trying to predict. We call it vector *d* (table B–6).

Table B–5—Matrix of covariances B

Cup identification	0 (unknown)	1	2	3	4	5	6	7	8	9	10	11	12
0 (unknown)	0.8386	0.6070	0.6651	0.6651	0.6070	0.6651	0.6651	0.5737	0.6070	0.6070	0.5289	0.5485	0.5485
1	0.6070	0.8386	0.6451	0.5810	0.6451	0.6177	0.5668	0.7014	0.5668	0.5188	0.5233	0.5188	0.4912
2	0.6651	0.6451	0.8386	0.6451	0.6177	0.6451	0.6177	0.5668	0.5810	0.5668	0.5145	0.5233	0.5145
3	0.6651	0.5810	0.6451	0.8386	0.5668	0.6177	0.6451	0.5327	0.5668	0.5810	0.4912	0.5145	0.5233
4	0.6070	0.6451	0.6177	0.5668	0.8386	0.6451	0.5810	0.6451	0.6177	0.5668	0.5810	0.5668	0.5327
5	0.6651	0.6177	0.6451	0.6177	0.6451	0.8386	0.6451	0.6177	0.6451	0.6177	0.5668	0.5810	0.5668
6	0.6651	0.5668	0.6177	0.6451	0.5810	0.6451	0.8386	0.5668	0.6177	0.6451	0.5327	0.5668	0.5810
7	0.5737	0.5810	0.5668	0.5327	0.6451	0.6177	0.5668	0.8386	0.6451	0.5810	0.6451	0.6177	0.5668
8	0.6070	0.5668	0.5810	0.5668	0.6177	0.6451	0.6177	0.6451	0.8386	0.6451	0.5668	0.6177	0.6451
9	0.6070	0.5327	0.5668	0.5810	0.5668	0.6177	0.6451	0.5810	0.6451	0.8386	0.5668	0.6177	0.6451
10	0.5289	0.5233	0.5145	0.4912	0.5810	0.5668	0.5327	0.6451	0.5668	0.5668	0.8386	0.6451	0.5810
11	0.5485	0.5145	0.5233	0.5145	0.5668	0.5810	0.5668	0.6177	0.6177	0.6177	0.6451	0.8386	0.6451
12	0.5485	0.4912	0.5145	0.5233	0.5327	0.5668	0.5810	0.5668	0.6451	0.6451	0.5810	0.6451	0.8386

Table B–6—Vector *d*

Cup identification	0 (unknown)
0 (unknown)	0.8386
1	0.6070
2	0.6651
3	0.6651
4	0.6070
5	0.6651
6	0.6651
7	0.5737
8	0.6070
9	0.6070
10	0.5289
11	0.5485
12	0.5485

The remaining matrix is the covariances among just the known values and we call it matrix **C** (table B–7).

The easiest way to solve this equation is by using linear algebra.

We can multiply both sides by **C** inverse ($\mathbf{C}^{-1}$), shown in table B–8, to isolate the kriging weights matrix to one side:

$$= \mathbf{C}^{-1} \times \mathbf{C} \times \text{weights} = d \times \mathbf{C}^{-1}$$
$$= \mathbf{I} \times \text{weights} = d \times \mathbf{C}^{-1}$$
$$= \text{weights} = d \times \mathbf{C}^{-1}$$

Table B–7—Matrix C

Cup identi-fication	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0.8386	0.6451	0.5810	0.6451	0.6177	0.5668	0.7014	0.5668	0.5188	0.5233	0.5188	0.4912	1
2	0.6451	0.8386	0.6451	0.6177	0.6451	0.6177	0.5668	0.5810	0.5668	0.5145	0.5233	0.5145	1
3	0.5810	0.6451	0.8386	0.5668	0.6177	0.6451	0.5327	0.5668	0.5810	0.4912	0.5145	0.5233	1
4	0.6451	0.6177	0.5668	0.8386	0.6451	0.5810	0.6451	0.6177	0.5668	0.5810	0.5668	0.5327	1
5	0.6177	0.6451	0.6177	0.6451	0.8386	0.6451	0.6177	0.6451	0.6177	0.5668	0.5810	0.5668	1
6	0.5668	0.6177	0.6451	0.5810	0.6451	0.8386	0.5668	0.6177	0.6451	0.5327	0.5668	0.5810	1
7	0.5810	0.5668	0.5327	0.6451	0.6177	0.5668	0.8386	0.6451	0.5810	0.6451	0.6177	0.5668	1
8	0.5668	0.5810	0.5668	0.6177	0.6451	0.6177	0.6451	0.8386	0.6451	0.5668	0.6177	0.6451	1
9	0.5327	0.5668	0.5810	0.5668	0.6177	0.6451	0.5810	0.6451	0.8386	0.5668	0.6177	0.6451	1
10	0.5233	0.5145	0.4912	0.5810	0.5668	0.5327	0.6451	0.5668	0.5668	0.8386	0.6451	0.5810	1
11	0.5145	0.5233	0.5145	0.5668	0.5810	0.5668	0.6177	0.6177	0.6177	0.6451	0.8386	0.6451	1
12	0.4912	0.5145	0.5233	0.5327	0.5668	0.5810	0.5668	0.6451	0.6451	0.5810	0.6451	0.8386	1
13	1	1	1	1	1	1	1	1	1	1	1	1	0

Table B–8—Matrix $\mathbf{C}^{-1}$

Cup identi-fication	1	2	3	4	5	6	7	8	9	10	11	12	13
1	4.083	-1.216	-0.461	-0.722	-0.294	-0.137	-2.655	0.458	0.325	0.523	0.161	-0.064	0.139
2	-1.304	4.506	-1.239	-0.657	-0.842	-0.478	0.660	-0.267	-0.176	-0.232	-0.031	0.061	0.091
3	-0.441	-1.255	3.914	-0.132	-0.461	-1.228	0.286	-0.075	-0.394	-0.045	-0.015	-0.154	0.165
4	-1.280	-0.507	-0.066	4.425	-0.806	-0.045	-0.297	-0.695	-0.087	-0.658	-0.160	0.175	0.061
5	-0.452	-0.802	-0.441	-0.819	4.971	-0.781	-0.066	-0.862	-0.425	-0.258	-0.170	0.105	-0.023
6	-0.076	-0.500	-1.234	-0.074	-0.790	4.557	0.053	-0.375	-1.097	-0.039	-0.126	-0.299	0.054
7	-0.359	-0.082	0.039	-1.066	-0.334	0.016	4.924	-1.246	-0.044	-1.465	-0.552	0.170	0.053
8	-0.099	-0.091	-0.014	-0.534	-0.804	-0.363	-1.142	5.029	-0.748	0.411	-0.366	-1.279	0.010
9	0.048	-0.087	-0.364	0.006	-0.393	-1.093	-0.047	-0.735	4.548	-0.200	-0.570	-1.115	0.051
10	-0.186	-0.010	0.032	-0.461	-0.186	-0.023	-1.298	0.402	-0.221	3.875	-1.359	-0.565	0.162
11	0.007	0.019	0.001	-0.111	-0.153	-0.123	-0.543	-0.361	-0.571	-1.351	4.415	-1.229	0.080
12	0.058	0.023	-0.167	0.145	0.093	-0.302	0.126	-1.274	-1.110	-0.560	-1.227	4.195	0.158
13	0.169	0.085	0.160	0.074	-0.020	0.051	-0.045	0.032	0.063	0.190	0.087	0.153	-0.599

Multiplying $d \times \mathbf{C}^{-1}$ gives us the following vector (table B–9). In table B–10, we multiply each value by the weight and take the average.

Table B–9—Kriging weights

Cup identification	Kriging weights
1	0.058
2	0.199
3	0.225
4	0.038
5	0.175
6	0.198
7	0.004
8	0.038
9	0.054
10	0.004
11	0.003
12	0.003

Table B–10—Calculating predicted gallons per 100 square feet for the unknown

Cup identification	X	Y	Z	Distance from unknown (feet)	Kriging weights	Product
1	615	165	0.468742	23.72	0.058	0.027164915
2	615	180	0.937485	10.61	0.199	0.186443159
3	615	195	2.432393	10.61	0.225	0.546960529
4	630	165	1.292209	23.72	0.038	0.049666153
5	630	180	0.937485	10.61	0.175	0.163602356
6	630	195	2.280368	10.61	0.198	0.452333773
7	645	165	1.241534	31.82	0.004	0.005331766
8	645	180	1.494908	23.72	0.038	0.056440308
9	645	195	3.483896	23.72	0.054	0.188875433
10	660	165	0.68411	53.05	0.004	0.003056074
11	660	180	1.228865	38.24	0.003	0.003582303
12	660	195	3.800614	38.24	0.003	0.012744684
					Total	**1.696201453**

So our predicted gal/100 ft^2 value is 1.696 (figure B–5).

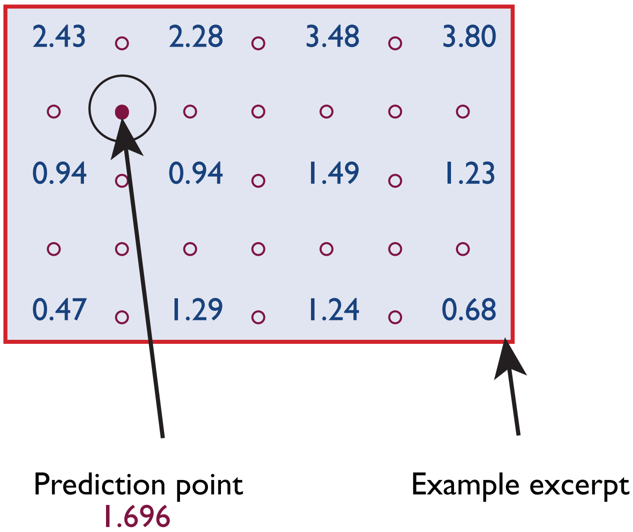


Figure B–5—The predicted gallons per 100 feet squared value is 1.696.

Recap:

- Model the variation across the raw data.
- Use the features of the model to calculate kriging weights.
- Calculate the weighted average of the raw data.

Appendix C

Percent Recovered Tables

Percent Recovered for Drops at Dial Setting 2

Fire suppressant	Mean (percent)	Standard deviation (percent)
Water	57	12
Unthickened	61	7
Low viscosity	84	9
Medium viscosity	82	5
High viscosity	87	4

Percent Recovered for Drops at Dial Setting 2 Broken Out by Type of Gum

Fire suppressant	Mean (percent)	Standard deviation (percent)
LV-G[1]	90	3
LV-X[2]	81	10
MV-X[3]	82	4
MV-G[4]	82	7
HV-G[5]	85	4
HV-X[6]	89	4

Percent recovered for Drops at Dial Setting 4

Fire suppressant	Mean (percent)	Standard deviation (percent)
Water	64	15
Unthickened	67	10
Low viscosity	85	8
Medium viscosity	84	6
High viscosity	85	7

Percent Recovered for Drops at Dial Setting 4 Broken Out by Type of Gum

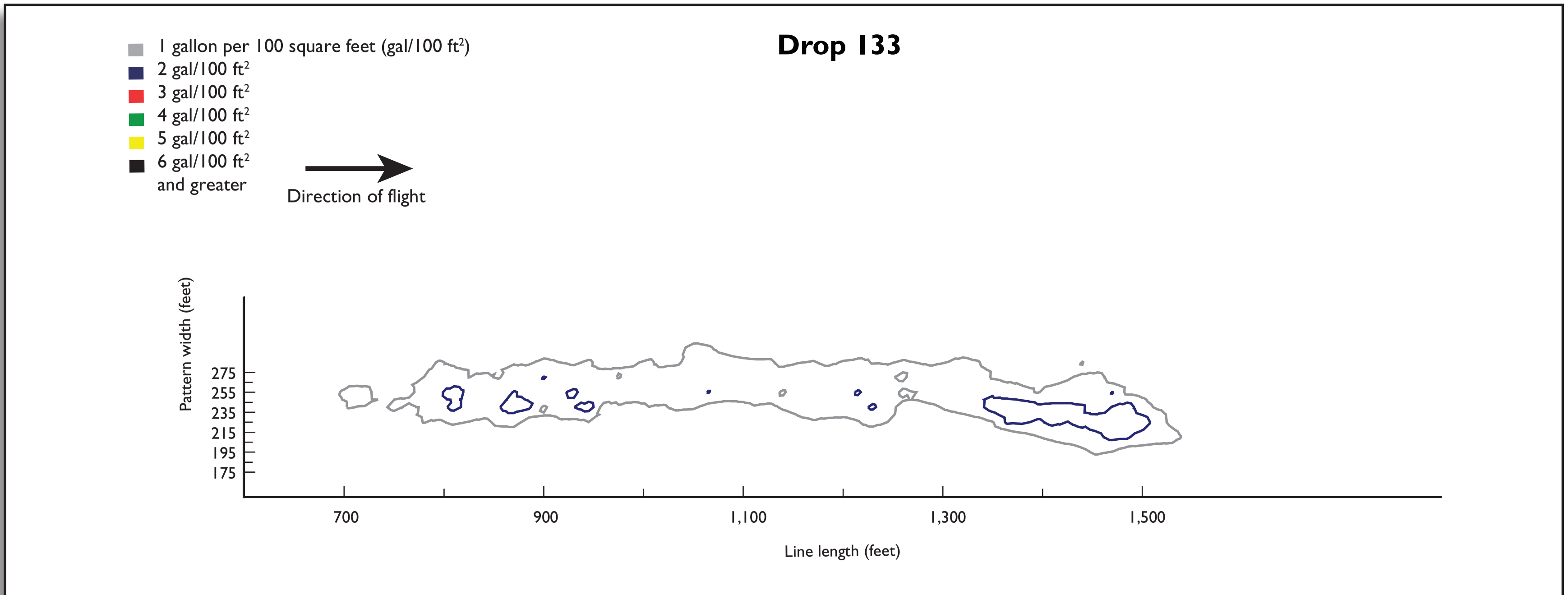
Fire suppressant	Mean (percent)	Standard deviation (percent)
LV-G[1]	90	4
LV-X[2]	82	2
MV-X[3]	88	5
MV-G[4]	81	6
HV-G[5]	84	5
HV-X[6]	87	8

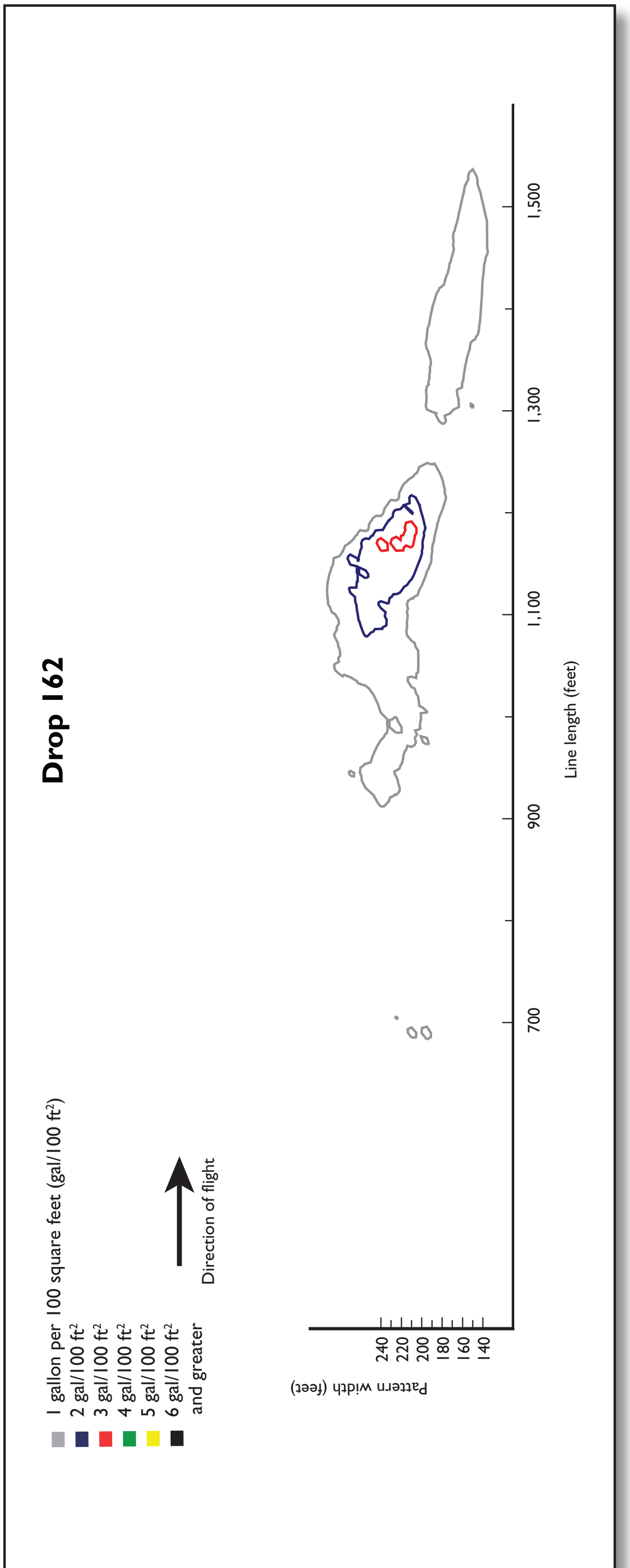
[1] Low-viscosity guar [2] Low-viscosity xanthan [3] Medium-viscosity xanthan [4] Medium-viscosity guar [5] High-viscosity guar [6] High-viscosity xanthan

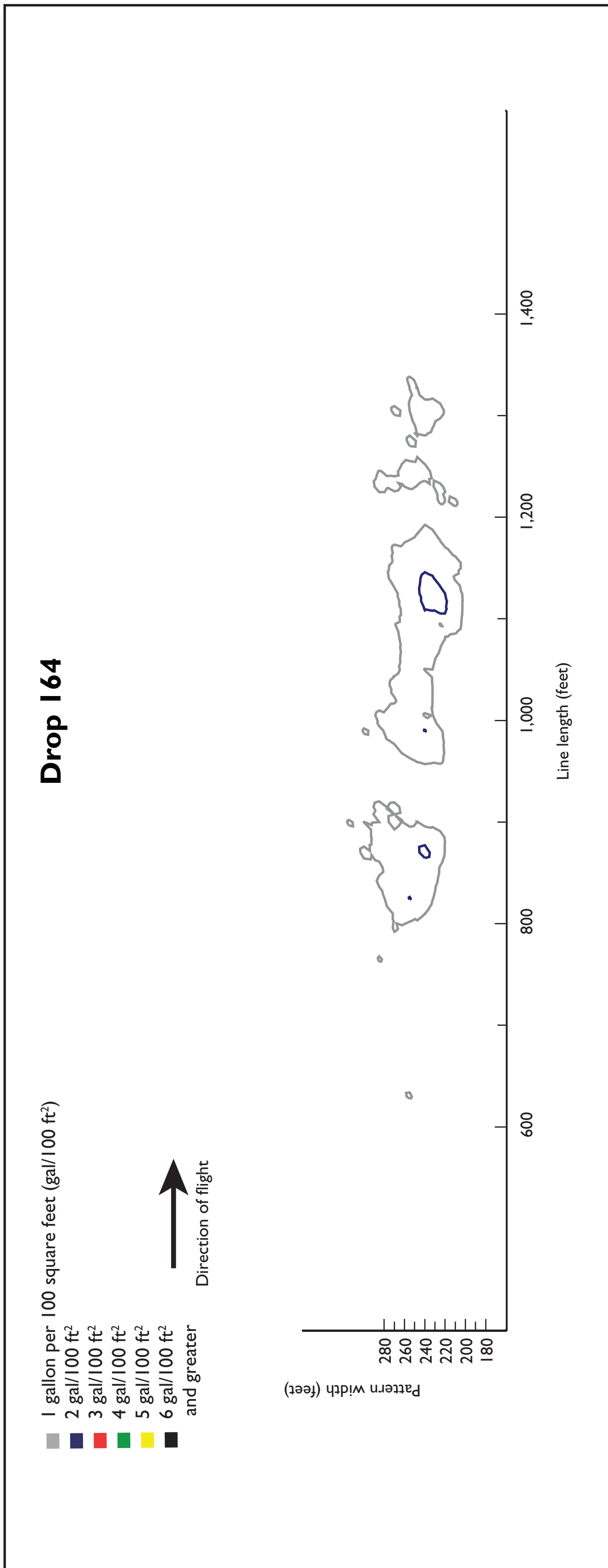
Replicates Tables

Unthickened Retardant, Dial Setting 2

Drop number	Volume (gallons)	Percent recovered	Viscosity (centipoise)	Altitude (feet)	Speed (knots)	Windspeed (miles per hour)	Wind direction (degrees)	Normalized line length (feet)				Normalized area (square feet)			
								0.5	1	2	3	0.5	1	2	3
133	1,213	64	8	215	132	7	45	88	69	23	0	7,740	3,255	413	0
162	1,200	58	10	204	133	7	90	86	50	12	2	6,900	2,273	445	33
164	1,219	49	12	201	134	8	40	73	41	5	0	6,649	1,661	74	0
Mean								82	53	13	1	7,096	2,396	311	11
Standard deviation								8	14	9	1	571	804	206	19
Coefficient of variation (percent)								10	27	68	173	8	34	66	173

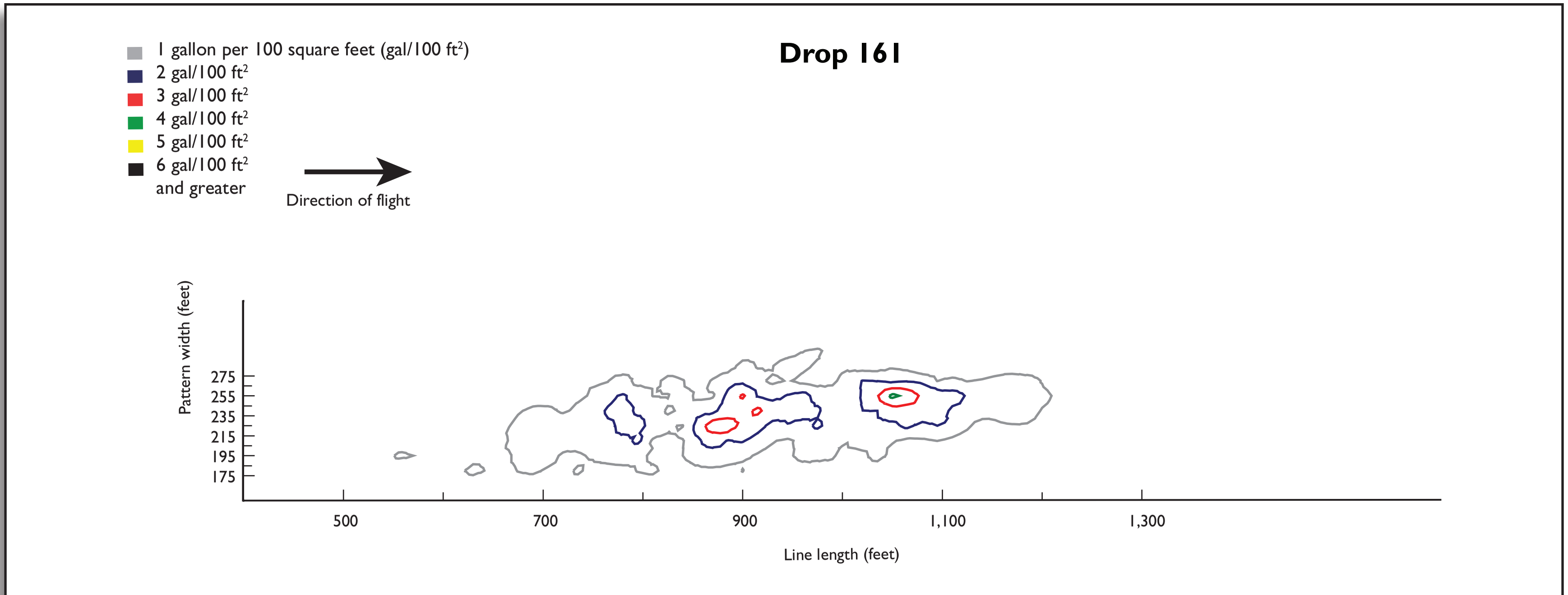


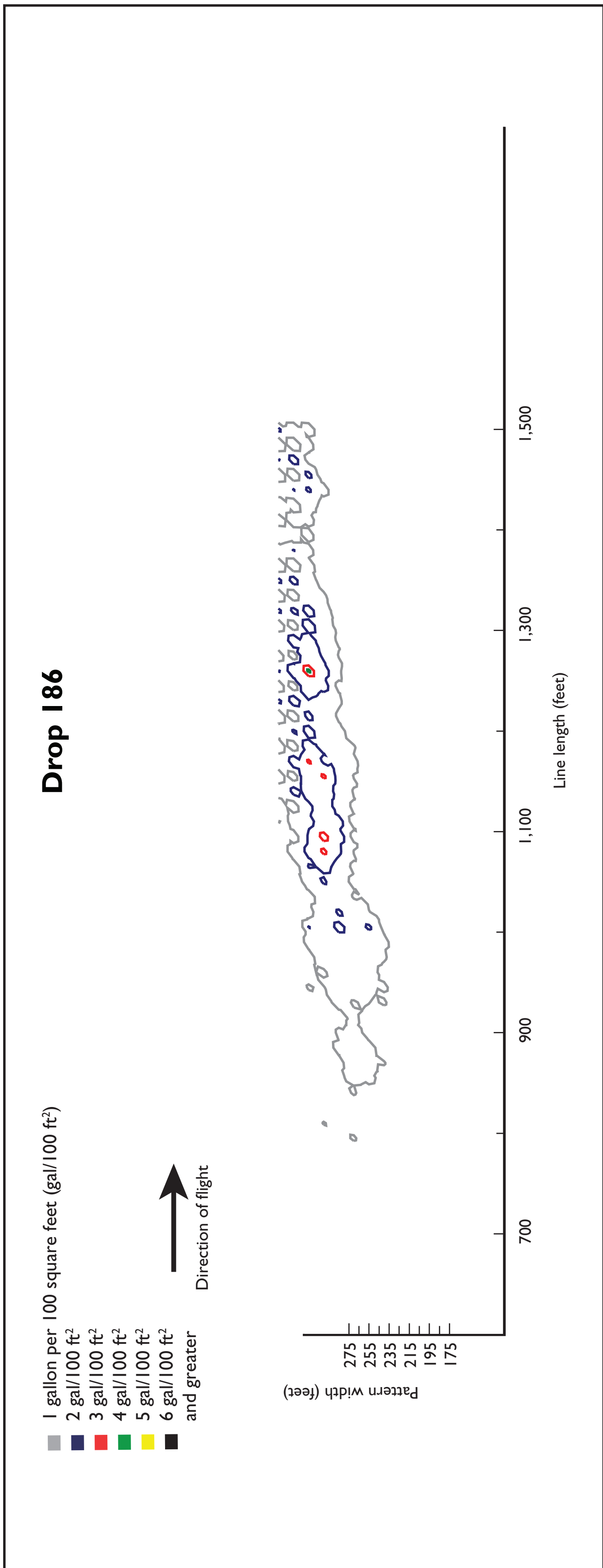

Drop 162
1 gallon per 100 square feet (gal/100 ft²)
2 gal/100 ft²
3 gal/100 ft²
4 gal/100 ft²
5 gal/100 ft²
6 gal/100 ft²
and greater
Direction of flight
Pattern width (feet)
240
220
200
180
160
140
700
900
1,100
1,300
1,500
Line length (feet)

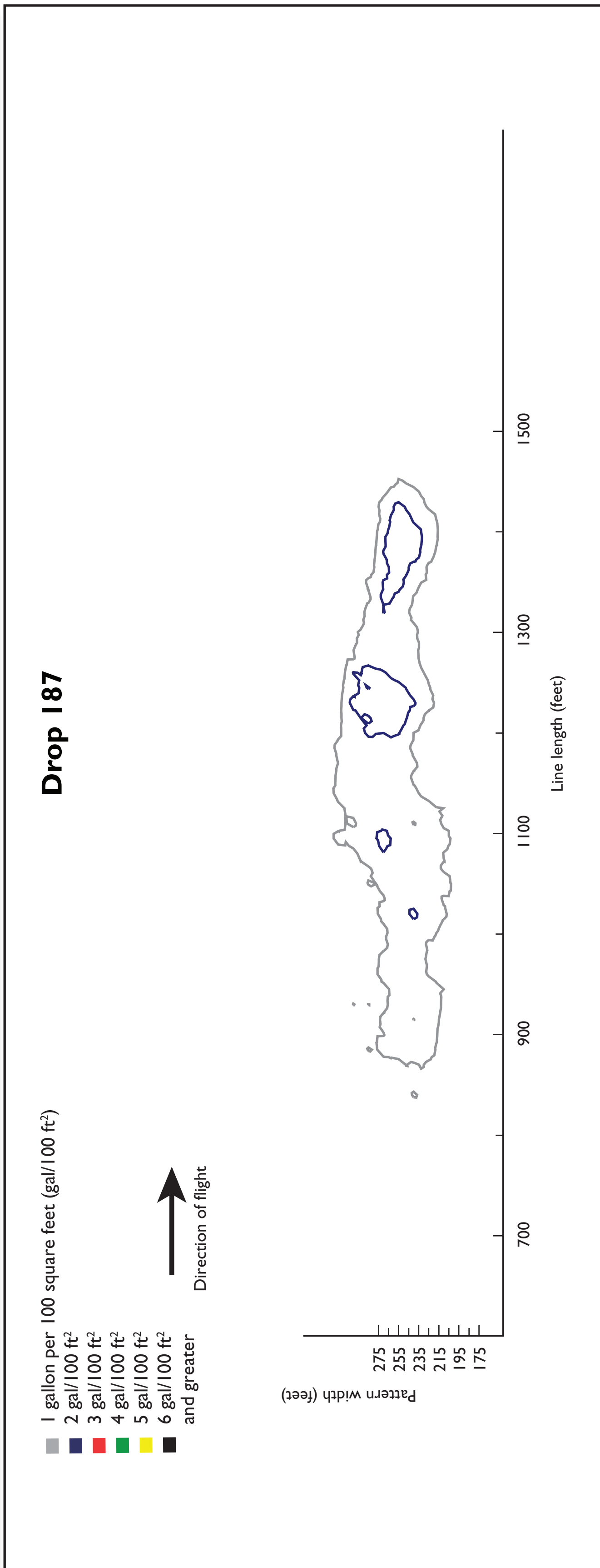

Drop 164
1 gallon per 100 square feet (gal/100 ft²)
2 gal/100 ft²
3 gal/100 ft²
4 gal/100 ft²
5 gal/100 ft²
6 gal/100 ft²
and greater
Direction of flight
Pattern width (feet)
280
260
240
220
200
180
600
800
1,000
1,200
1,400
Line length (feet)

Unthickened Retardant, Dial Setting 4

Drop number	Volume (gallons)	Percent recovered	Viscosity (centipoise)	Altitude (feet)	Speed (knots)	Windspeed (miles per hour)	Wind direction (degrees)	Normalized line length (feet)					Normalized area (square feet)				
								0.5	1	2	3	4	0.5	1	2	3	4
161	1,218	67	9	277	141	5	240	60	48	22	7	1	6,946	3,039	725	83	5
186	1,193	51	8	286	133	3	30	74	57	25	3	1	5,587	2,772	575	24	5
187	1,185	65	7	287	139	6	280	62	50	17	0	0	7,296	3,176	475	0	0
Mean																	
								65	52	21	3	0	6,610	2,996	592	36	3
Standard deviation																	
								7	5	4	3	0	903	205	126	43	3
Coefficient of variation (percent)																	
								11	9	19	102	87	14	7	21	120	87

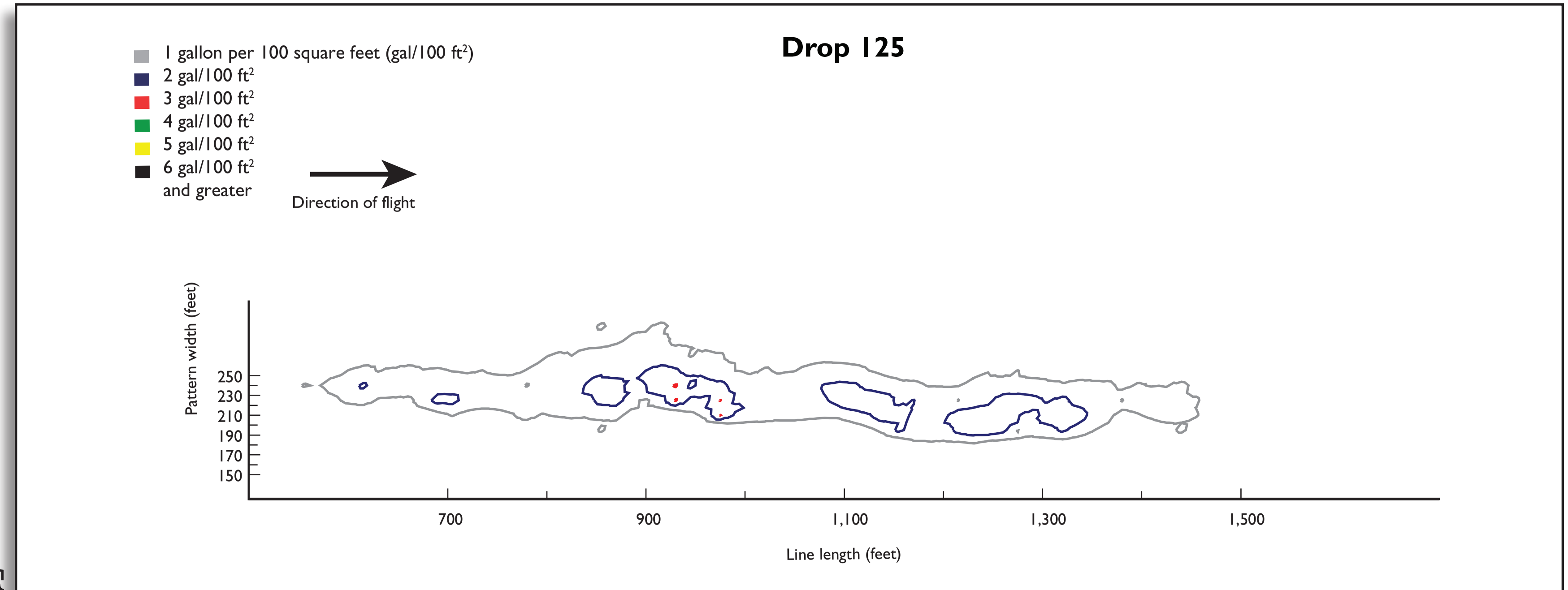


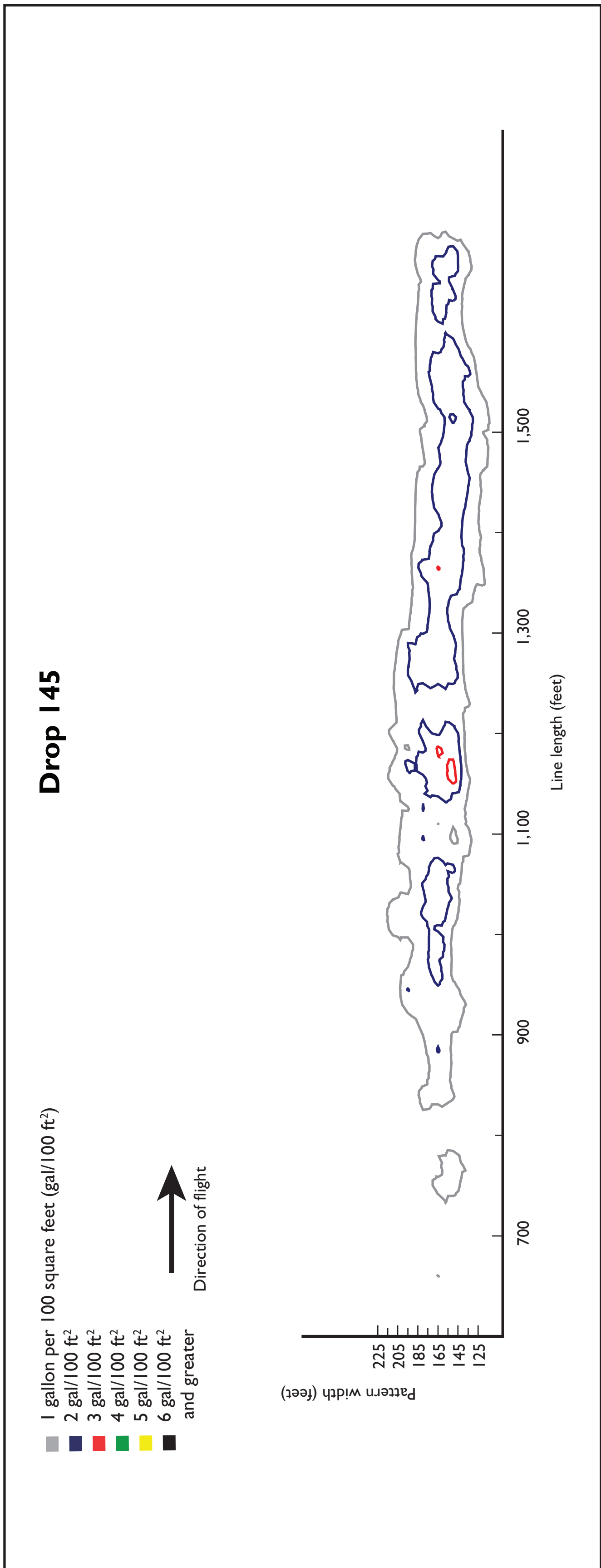

Drop 186
1 gallon per 100 square feet (gal/100 ft²)
2 gal/100 ft²
3 gal/100 ft²
4 gal/100 ft²
5 gal/100 ft²
6 gal/100 ft²
and greater
Direction of flight
Pattern width (feet)
275
255
235
215
195
175
Line length (feet)
700
900
1,100
1,300
1,500

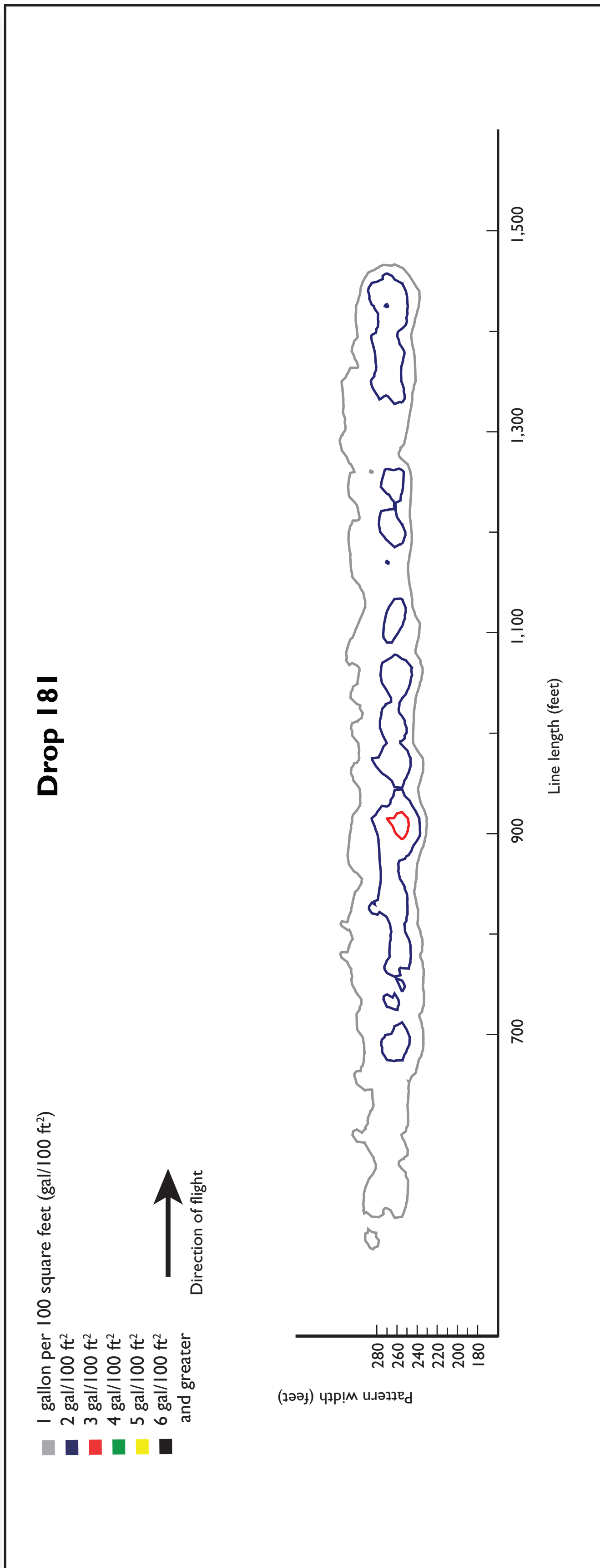

Drop 187
1 gallon per 100 square feet (gal/100 ft²)
2 gal/100 ft²
3 gal/100 ft²
4 gal/100 ft²
5 gal/100 ft²
6 gal/100 ft²
and greater
Direction of flight
Pattern width (feet)
275
255
235
215
195
175
Line length (feet)
700
900
1100
1300
1500

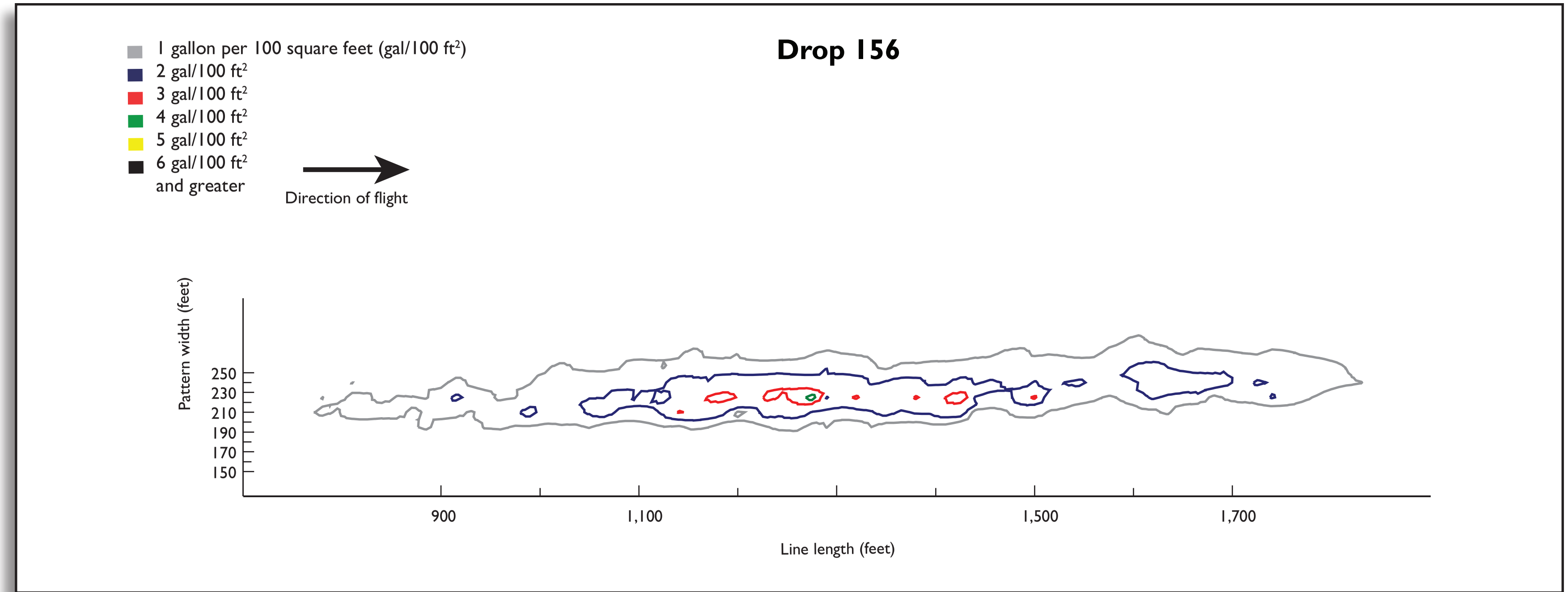
Low-Viscosity Retardant, Dial Setting 2

Drop number	Volume (gallons)	Percent recovered	Viscosity (centipoise)	Altitude (feet)	Speed (knots)	Wind-speed (miles per hour)	Wind direction (degrees)	Normalized line length (feet)					Normalized area (square feet)				
								0.5	1	2	3	4	0.5	1	2	3	4
125	1,219	75	193	263	126	7	45	92	73	35	1	0	8,006	3,770	803	18	0
145	1,204	86	132	267	141	2	200	103	77	56	4	0	8,227	4,200	1,458	28	0
181	1,207	80	178	269	124	5	60	91	80	52	2	0	8,039	4,572	1,216	28	0
156	1,212	90	186	269	127	1	60	101	88	54	12	1	8,911	4,488	1,420	111	5
								Mean									
								97	80	49	5	0	8,296	4,258	1,224	46	1
								Standard deviation									
								6	6	10	5	1	422	362	300	43	3
								Coefficient of variation (percent)									
								6	8	20	104	200	5	9	25	94	200



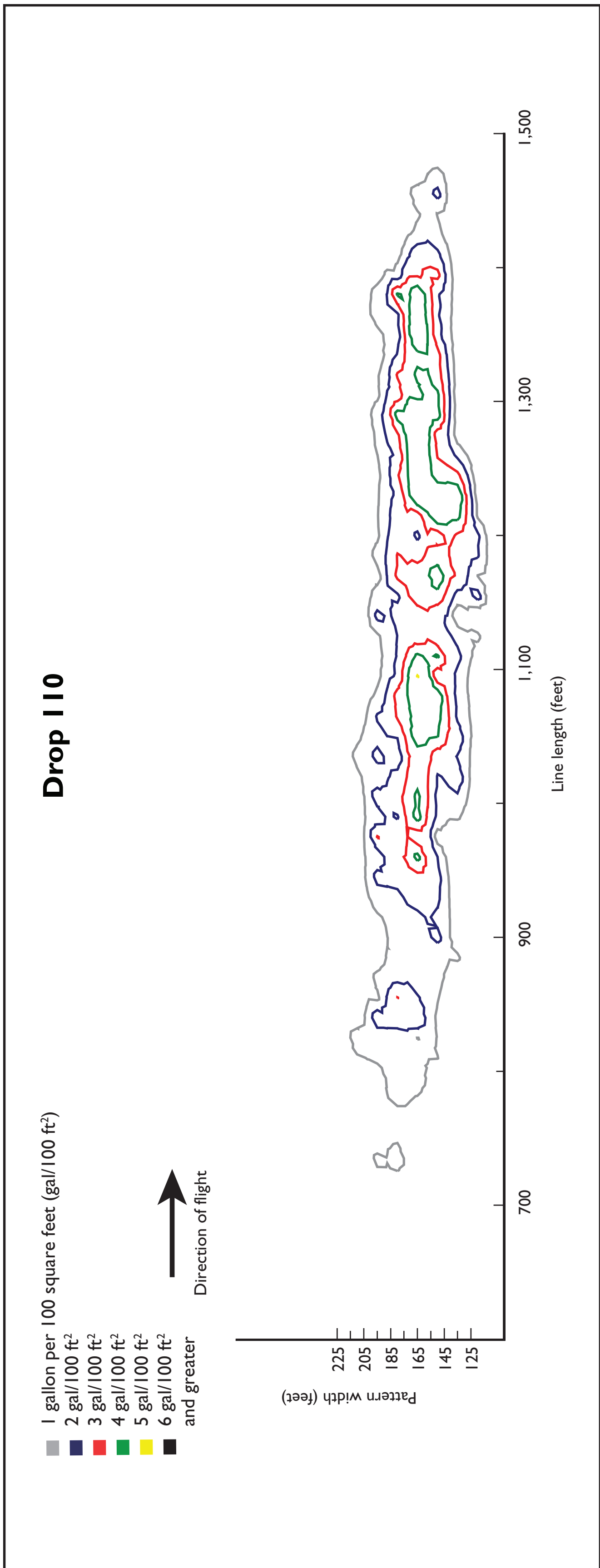

Drop 145
1 gallon per 100 square feet (gal/100 ft2)
2 gal/100 ft2
3 gal/100 ft2
4 gal/100 ft2
5 gal/100 ft2
6 gal/100 ft2
and greater
Direction of flight
Pattern width (feet)
225
205
185
165
145
125
700
900
1,100
1,300
1,500
Line length (feet)

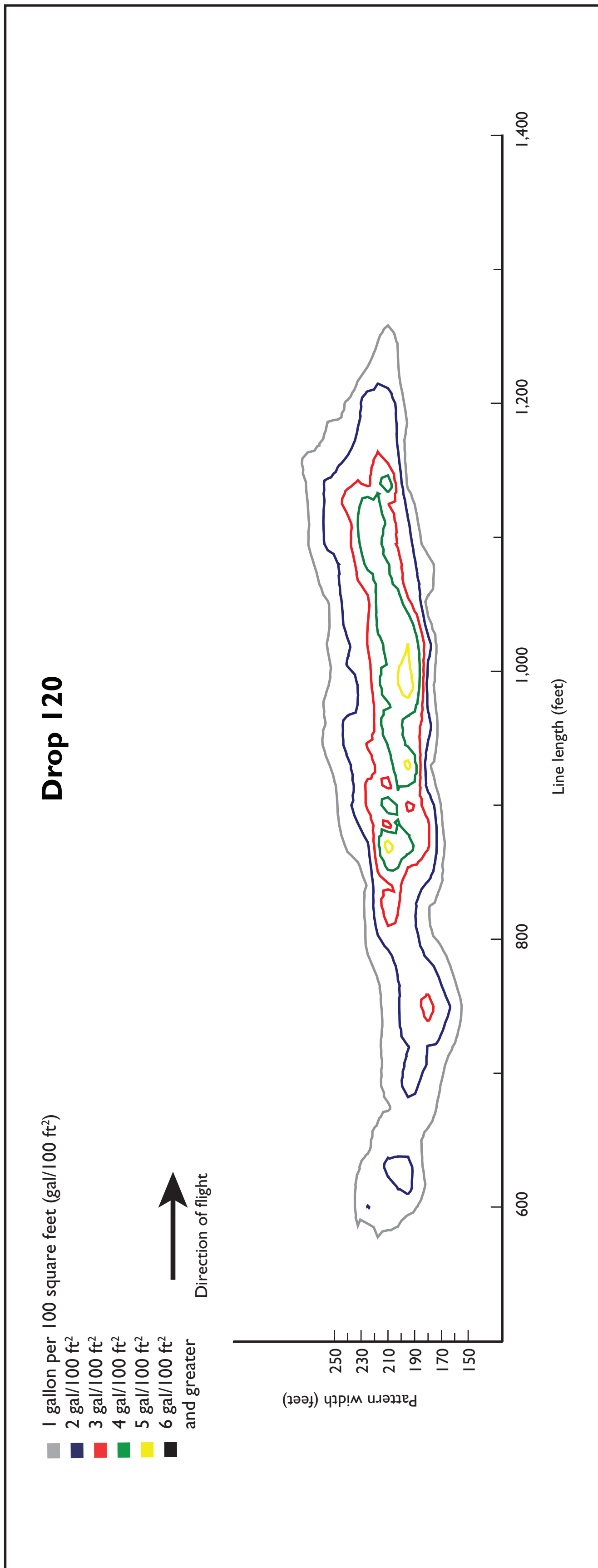

Drop 181
1 gallon per 100 square feet (gal/100 ft2)
2 gal/100 ft2
3 gal/100 ft2
4 gal/100 ft2
5 gal/100 ft2
6 gal/100 ft2
and greater
Direction of flight
Pattern width (feet)
280
260
240
220
200
180
700
900
1,100
1,300
1,500
Line length (feet)

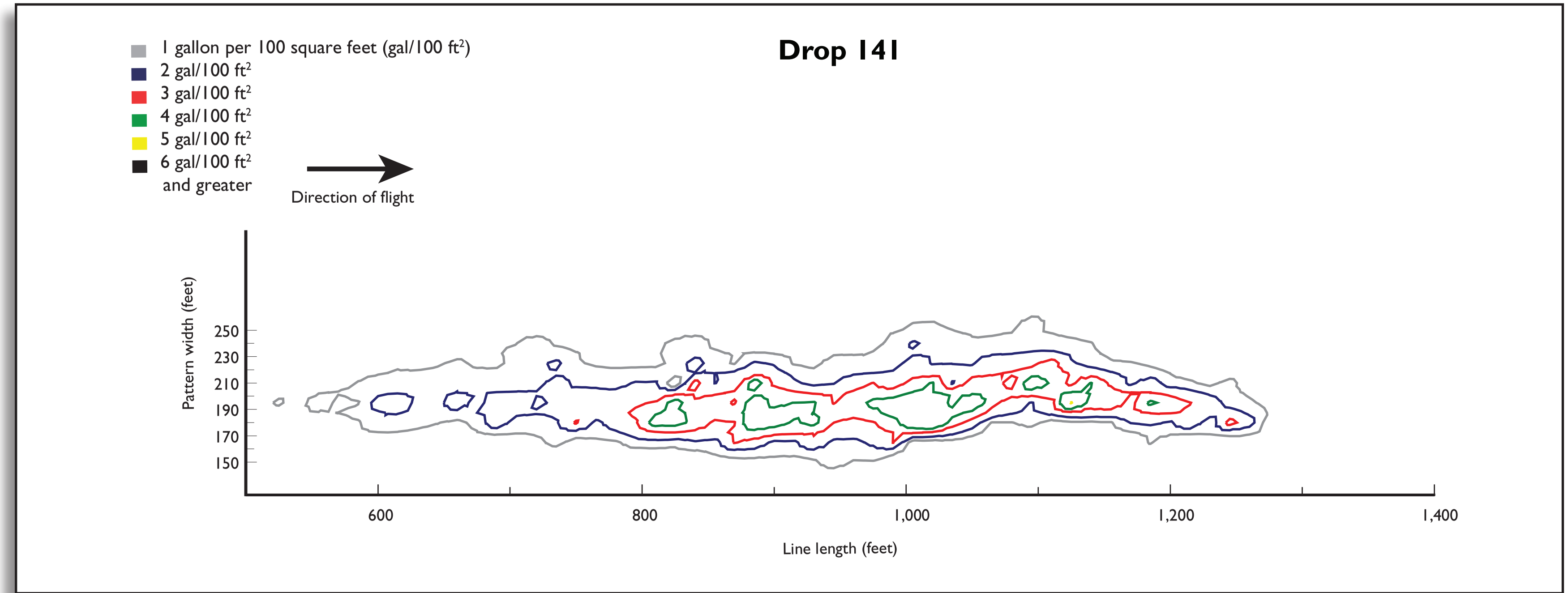


Medium-Viscosity Retardant, Dial Setting 4

Drop number	Volume (gallons)	Percent recovered	Viscosity (centipoise)	Altitude (feet)	Speed (knots)	Wind-speed (miles per hour)	Wind direction (degrees)	Normalized line length (feet)								Normalized area (square feet)							
								0.5	1	2	3	4	5	6	7	0.5	1	2	3	4	5	6	7
110	1,220	81	750	180	128	6	35	68	59	46	36	23	8	1	0	4,901	3,370	2,001	964	392	69	5	0
120	1,221	85	700	190	138	4	120	65	55	47	31	23	14	5	1	5,372	3,363	1,976	963	428	152	41	9
141	1,207	90	700	192	128	5	60	72	61	53	37	19	4	1	0	6,259	3,649	2,009	909	303	47	5	0
								Mean															
								68	58	49	35	22	9	2	0	5,511	3,461	1,995	945	374	89	17	3
								Standard deviation															
								4	3	4	3	2	5	2	1	689	163	17	31	65	56	21	5
								Coefficient of variation (percent)															
								5	5	8	8	9	53	118	173	13	5	1	3	17	62	126	173

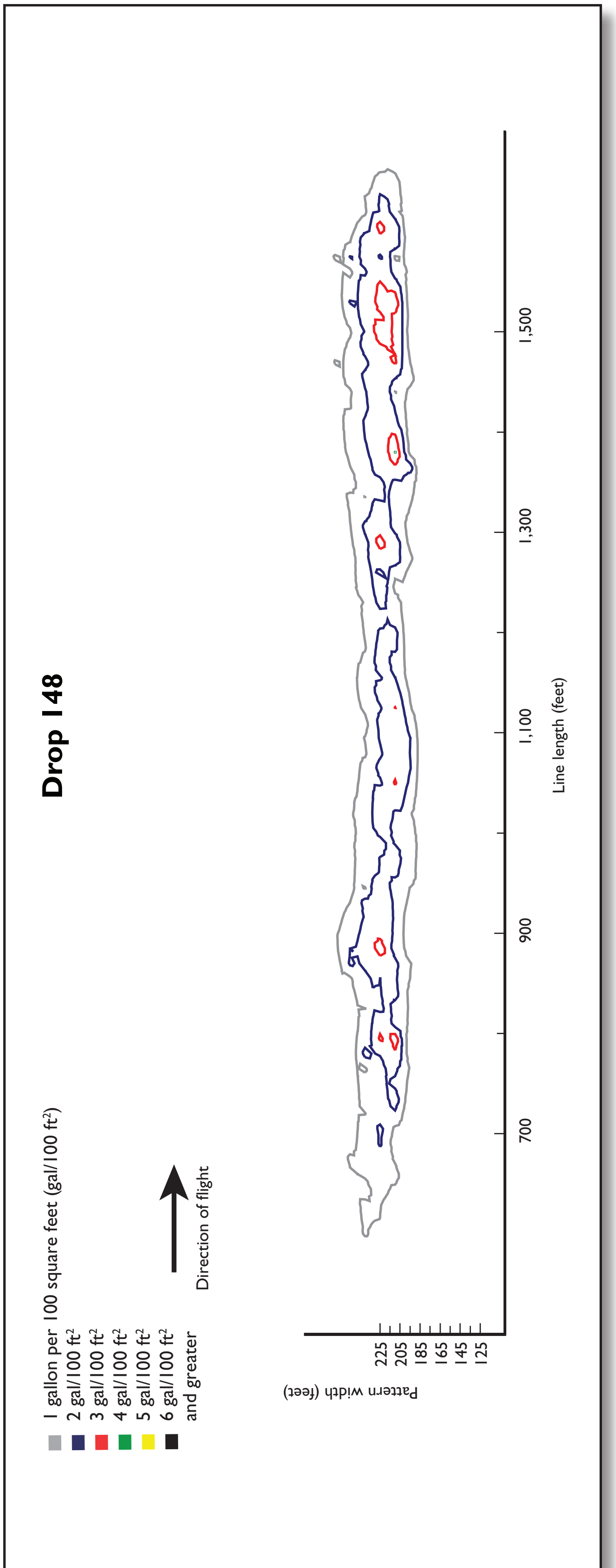

Drop 110
1 gallon per 100 square feet (gal/100 ft²)
2 gal/100 ft²
3 gal/100 ft²
4 gal/100 ft²
5 gal/100 ft²
6 gal/100 ft²
and greater
Direction of flight
Pattern width (feet)
225
205
185
165
145
125
Line length (feet)
700
900
1,100
1,300
1,500

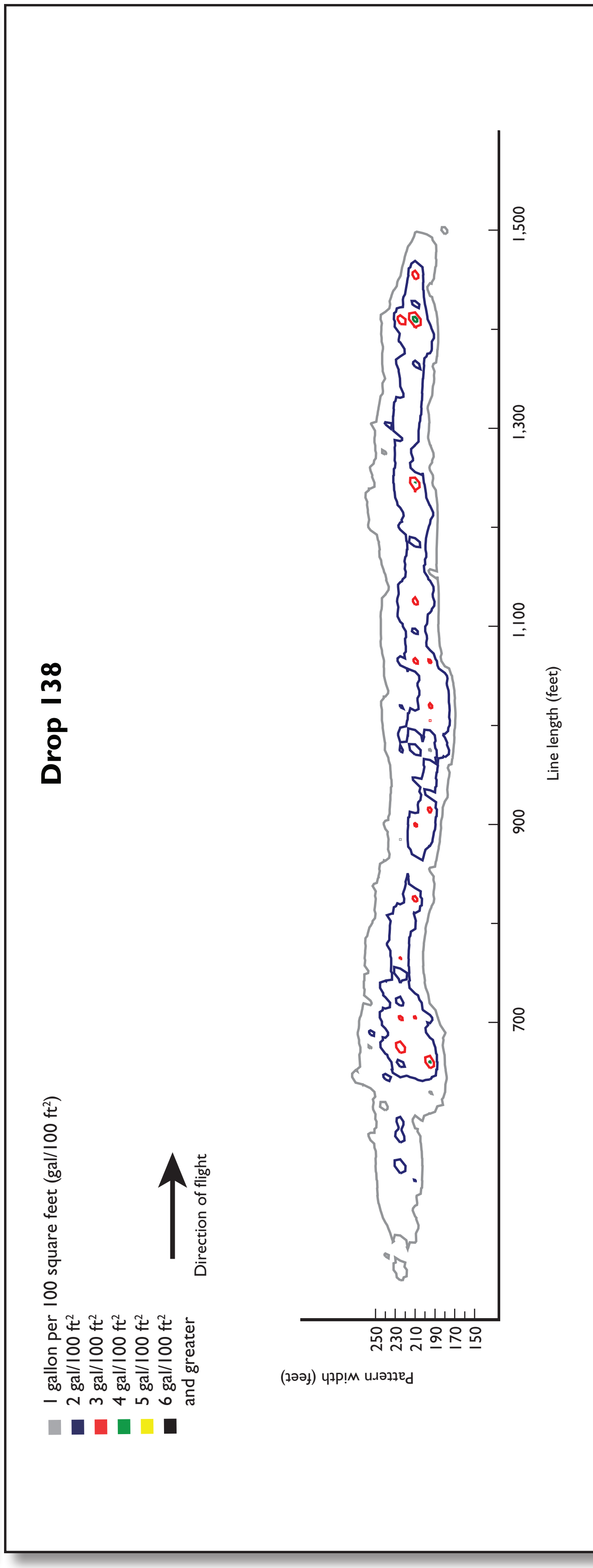

Drop 120
1 gallon per 100 square feet (gal/100 ft²)
2 gal/100 ft²
3 gal/100 ft²
4 gal/100 ft²
5 gal/100 ft²
6 gal/100 ft²
and greater
Direction of flight
Pattern width (feet)
250
230
210
190
170
150
Line length (feet)
600
800
1,000
1,200
1,400

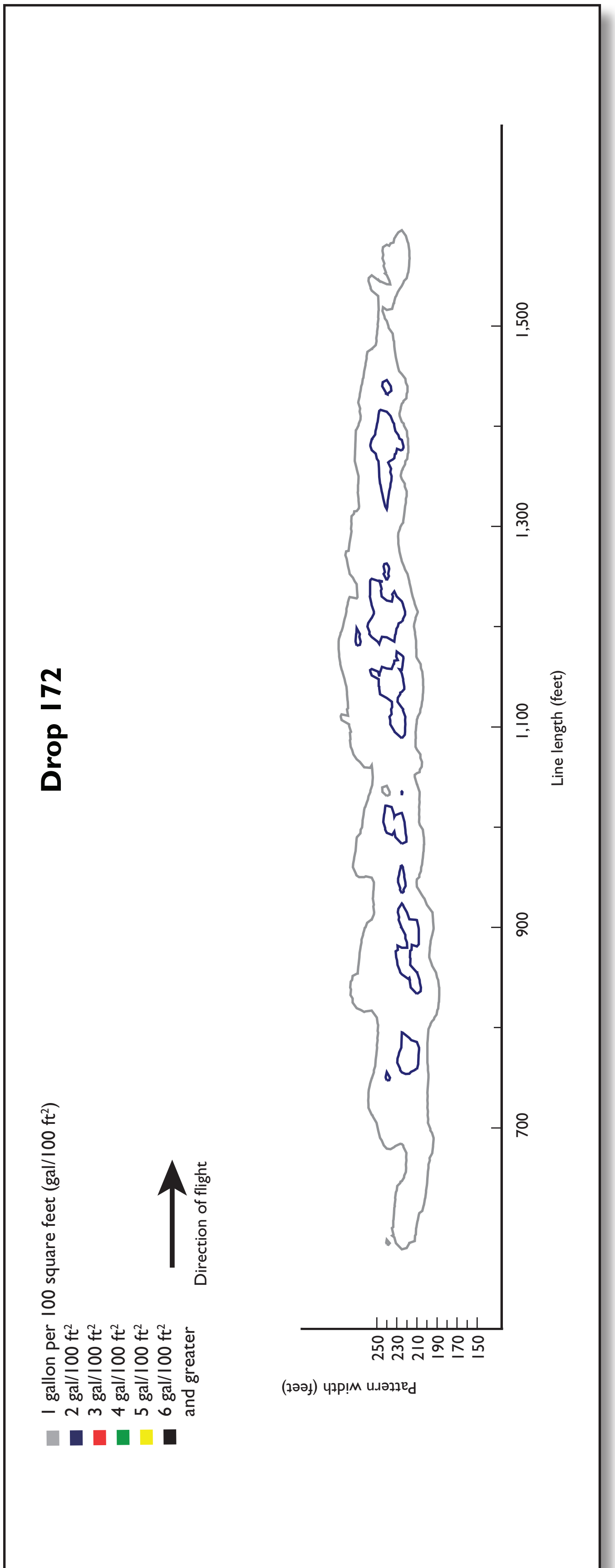


High-Viscosity Retardant, Dial Setting 2

Drop number	Volume (gallons)	Percent recovered	Viscosity (centipoise)	Altitude (feet)	Speed (knots)	Wind-speed (miles per hour)	Wind direction (degrees)	Normalized line length (feet)					Normalized area (square feet)				
								0.5	1	2	3	4	0.5	1	2	3	4
148	1,217	91	1400	259	130	3	60	98	88	76	14	1	8,181	4,428	1,904	148	5
138	1,208	92	1405	260	122	5	50	96	88	70	10	2	8,028	4,815	1,797	88	14
172	1,204	82	1255	265	127	10	30	102	84	41	0	0	9,026	4,219	654	0	0
								Mean									
								99	87	62	8	1	8,412	4,487	1,452	79	6
								Standard deviation									
								3	2	19	7	1	538	302	693	74	7
								Coefficient of variation (percent)									
								3	3	30	90	113	6	7	48	95	115


Drop 148
1 gallon per 100 square feet (gal/100 ft²)
2 gal/100 ft²
3 gal/100 ft²
4 gal/100 ft²
5 gal/100 ft²
6 gal/100 ft²
and greater
Direction of flight
Pattern width (feet)
225
205
185
165
145
125
Line length (feet)
700
900
1,100
1,300
1,500


Drop 138
1 gallon per 100 square feet (gal/100 ft²)
2 gal/100 ft²
3 gal/100 ft²
4 gal/100 ft²
5 gal/100 ft²
6 gal/100 ft²
and greater
Direction of flight
Pattern width (feet)
250
230
210
190
170
150
Line length (feet)
700
900
1,100
1,300
1,500


Drop 172
1 gallon per 100 square feet (gal/100 ft²)
2 gal/100 ft²
3 gal/100 ft²
4 gal/100 ft²
5 gal/100 ft²
6 gal/100 ft² and greater
Direction of flight
Pattern width (feet)
250
230
210
190
170
150
Line length (feet)
700
900
1,100
1,300
1,500

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- Larry Vandersall, independent consultant, Lawdon Fires Service, Inc.

About the Author

Ann Suter's Forest Service career began in 1997 performing static and drop tests of fixed- and rotary-wing aircraft to determine flow rates, tank pressures, retardant coverage levels, and line lengths and to report findings to the Interagency Airtanker Board.

Suter has collected and analyzed drop data on a wide variety of firefighting aircraft, including the C-130 MAFFS II pressurized system, the S2F Turbo Tracker, the Torrentula Valve Bambi Bucket, the Evergreen 747, the Cargo Conversions DC-10, the Bombardier 415, the Erikson Aero Tanker MD-87, the Neptune BAe-146, Aeroflite RJ85, and Coulson L-382G. She uses models to analyze large data sets collected from tank and gate systems to show relationships between factors influencing aerial delivery system performance. She also provides statistical support for Wildland Fire Chemical Systems projects.

Suter has a master's degree in international development from the American University in Washington, D.C. and a bachelors degree in mathematics from the University of Montana. She worked to control soil erosion in Jamaica for 2 years as a Peace Corps volunteer before joining the Forest Service.

Library Card

Suter, Ann. 2013. Gum-thickener study—drop test for firefighting operations, Marana, AZ. 1351–2802–NTDP. Missoula, MT: U.S. Department of Agriculture, Forest Service, National Technology and Development Program. 58 p.

This report is a summary of findings from a study we conducted during a 2005 drop test at Marana, AZ. The report explains methods we used to collect data from ground distribution patterns of retardants formulated with different amounts and types of gum thickeners. Wildland Fire Chemical Systems staff and CAL Fire (formerly known as California Department of Forestry) worked together to compare the performance of fire retardants and water with different viscosities and types of thickener. Knowing how much thickener to add and when to add it can be beneficial in fire suppression operations.

Keywords: altitude, aircraft, Brookfield viscometers, dial settings, drop tests, fire fighting, firefighting, fire suppressants, flow rates, graphs, grid data, guar gum, line lengths, retardants, statistics, wildland fires, wind direction, windspeeds, variogram, xanthan gum

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