HIGH ALTITUDE RETARDANT DROP MECHANIZATION STUDY

Final Report
Volume I

Northern Forest Fire Laboratory
Missoula, Montana

Honeywell

Honeywell

HIGH ALTITUDE RETARDANT

DROP MECHANIZATION STUDY

FINAL REPORT

VOLUME I

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I. INTRODUCTION AND SUMMARY

A. INTRODUCTION

Contract 26-2888 was awarded to Honeywell Inc. on 22 May 1972 and completed on 30 March 1973. This final report summarizes results of the effort that led to recommendation of an Experimental Tank and Gating System and Test Plan for a definitive experiment to perfect and calibrate simulation models of tank performance.

The purpose of U.S. Forest Service Contract No. 26-2888 (High-Altitude Retardant Drop Mechanization Study) was to conduct analyses, design studies, and laboratory tests of critical elements leading to understanding of improved methods of aerial retardant dispensing.

The objectives were to produce conceptual retardant dispensing designs and perform tradeoff studies and laboratory tests of candidate concepts. This led to the recommendation of the experimental tank and gating system.

Results from retardant drop tests at Porterville, California, and Maranna, Arizona, became available during the contract and changed both retardant delivery concepts and contract direction. The tests showed that, in some cases, higher altitudes improved pattern performance and provided substantial performance data on a range of tanking systems.

Forest Service studies on Fire Fundamentals, Fuels, and Retardant Effects were used in contractor studies of vertical fuels coverage and on-target effectiveness to develop terminal criteria for pattern performance in both line building and direct attack. The results of these two factors placed emphasis on advanced cascade systems (as opposed to containerized concepts) in the later stages of study. Data analysis of the Maranna and

Porterville tests replaced a substantial amount of contractor tests that were limited to a look-in basis to gain understanding of specific phenomena.

The potential for changes in tactical options, aircraft availability, and ultimate potential of new fire fighting techniques was considered to assure adaptability and capability of future proposed concepts.

B. SUMMARY

Tradeoff studies on alternative conceptual approaches to High-Altitude Retardant Delivery problems led to the conclusion that advanced cascade systems offered the most practical approach to achieving improved safety and effectiveness against the broad spectrum of fires and fire control missions. These studies included the effect of various delivery options on accuracy, vertical fuels coverage, and the direct-attack capability.

Direct attack and line building are two legitimate options in fire control that impose substantially different requirements on the tanking system. Current tanking systems appear far from optimum in reconciling these requirements, and, with few exceptions, they are not designed to maximize capability in terms of either of the two missions. As a result, there is considerable latitude to improve performance of current and new tankers through understanding of the mission and tanking characteristics that affect performance.

The solution to achieving substantial improvement in aerial retardant delivery operations requires two related, yet independent, developments: (1) development of quantitative tactical models of effectiveness, the concrete specification of what a tanker should do, and (2) development of the physical and empirical bases for designing tanking systems to meet these requirements. Effort in the final portions of this contract was directed specifically toward the latter objective.

The complex hydrodynamic events that determine how a pattern develops from a given release are capable of simulation in such a way that design characteristics of the tank can be traced to observable characteristics of the pattern. Dominant characteristics, such as flow rate, volume, door-opening rates and tank geometry, match, within the accuracy of available input data, the pattern development downrange from the release. This capability enables identification of promising and relatively simple approaches to increase performance in both direct-attack and line-building modes regardless of the altitude.

Effects of other variables, such as release geometry, multiple-tank releases and tank-to-tank separation, cannot be quantified from currently available test data. A definitive experiment is thus recommended to (1) achieve sufficient refinement of input data to the simulation to determine the effect of the variables on pattern formation on the range leg and (2) determine the effect of the variables on the development of a pattern in cross range where their resolution may be amplified.

The recommended experiment has been planned for a test tank designed to answer specific experimental questions rather than to produce an optimum tank concept for a specific aircraft. This will enable completion of an extended general model that can be used in association with the results of tactical effectiveness studies to establish guidelines for the use of current tankers, assess practical modifications to improve the current tanker fleet, and provide quantitative design data for new tankers as they are introduced.

II. THE ROLE OF THE TANKER

To determine what a retardant delivery system should be and subsequently conduct an evaluation, it is necessary to determine what it should do. The design study matrix shown in Figure 1 formed the starting point for tradeoff studies. To evaluate concepts across this matrix, a first logical step was evaluation of on-target effectiveness. If we can determine the role of the tanker, and anticipate changes in the mission required by technological advances, we can then make engineering conclusions leading to the specification of tanking characteristics, control and features.

The airtanker is only one of the tools available to the fire boss in the control or suppression of fires. It is unrealistic to expect technological improvements in aircraft or delivery systems that will make the tanker by itself the sole resource for suppressing all fires, although in the initial attack of small fire starts it can potentially decide the issue without the use of ground-based personnel. Therefore, it is useful to view the tanker within a total mission context as shown in Figure 2.

Significant improvements in controlling or suppressing wild fire in the next decade will come from increased understanding of the enemy, the real-time information available to the fire boss, and improved strategy decisions resulting from this information. Within this context, the airtanker is a tool designed to optimize the advances of: Increased Knowledge of the Fire, Improved Strategy Decisions, and Advanced Training and Coordination. Fuels characteristics, suppression and retardant missions, and accuracy are discussed in the following subsections.

RETARDANT	FIXED-WING AIRCRAFT		HELICOPTER
	BOMB BAY	AFT LOADING	TEST BED AND SPECIAL APPLICATIONS
ADVANCED CASCADE (WITH VARYING RHEOLOGICAL PROPERTIES)	CONSIDER: ● GRAVITY RELEASE ● GRAVITY AND PRESSURE	CONSIDER: ● PRESSURE EJECT ● PRESSURE AND GRAVITY ● GRAVITY RELEASE	CONSIDER QUICK TURNAROUND ● SLING-LOADED ● RIGIDLY ATTACHED
CONTAINS (FOR EXAMPLE, PREFILLED CAPSULES OR BAGGIES, SELF-FILLING CONTAINERS, FROZEN, HYBRID OR COMBINATIONS OF THE ABOVE, AND OTHER AS PROPOSED BY CONTRACTOR)	CONSIDER: ● GRAVITY RELEASE ● GRAVITY AND PRESSURE ● OTHER	CONSIDER: ● PRESSURE EJECT ● CONVEYOR ● PARACHUTE EXTRACTION ● GRAVITY ● COMBINATIONS OF ABOVE ● OTHER	CONSIDER QUICK TURNAROUND SYSTEMS SUCH AS: ● SLING-LOADED ● RIGIDLY ATTACHED ● OTHER

Figure 1. Design Study Matrix

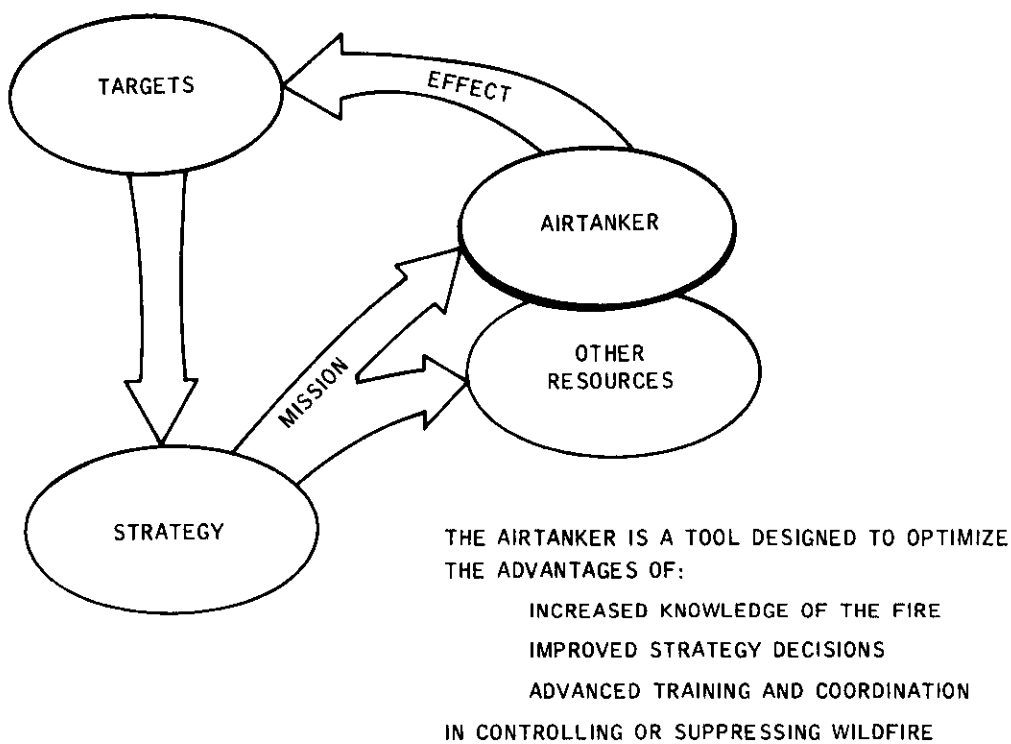


Figure 2. Role of the Airtanker

A. FUELS CHARACTERISTICS

Considerable research information is now available about the fuels, the chemistry of burning, and the mechanisms of fire spread and suppression. Effort is now under way to develop the technology for providing real-time information on the fire's condition and the contribution of fire weather to the dynamics of propagation. Fundamentally, the more we know about the enemy the better we can deal with him, if our response mechanisms, in this case the airtanker, are provided with options that take advantage of this knowledge.

To represent the range of fires and fuel types that may be encountered, four baseline fuels were defined by the U.S. Forest Service. These fuels, shown in Figure 3, represent selected points on a spectrum of potential fires, with a wide range of characteristics that can be related to the demands on the air delivery system in both direct-attack (suppression) or line-building (retardant) missions.

B. SUPPRESSION AND RETARDANT MISSIONS

Retardant delivery missions may be characterized by their intent in terms of the tactics employed over a wide range of potential fire situations. It is convenient to distinguish between two basic intents, i.e., direct attack, in which the retardant is delivered against the fire to reduce its intensity or to extinguish it, and indirect attack, in which the retardant is delivered in advance of the fire front to slow or in some cases extinguish the fire by the action of long-term retardants on the fuels. This is shown schematically in Figure 4. An advanced retardant system must maximize the ability to deal with both situations, although each situation poses substantially different implications for the airtanker as shown in Figure 5. Essentially, direct attack implies high concentrations of water and thickeners delivered with sufficient energy to penetrate the fire plumes. These concentrations require high accuracy,

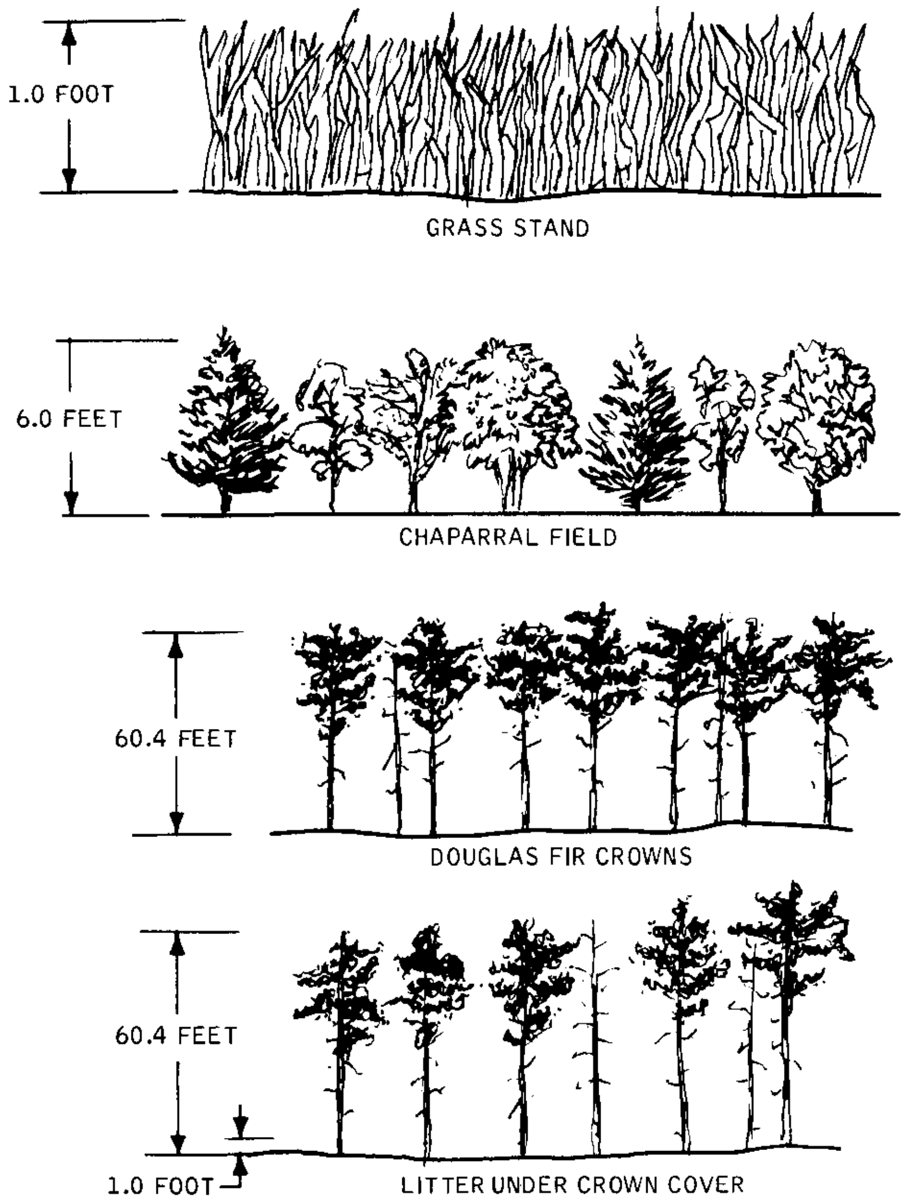


Figure 3. Representative Fuel Types

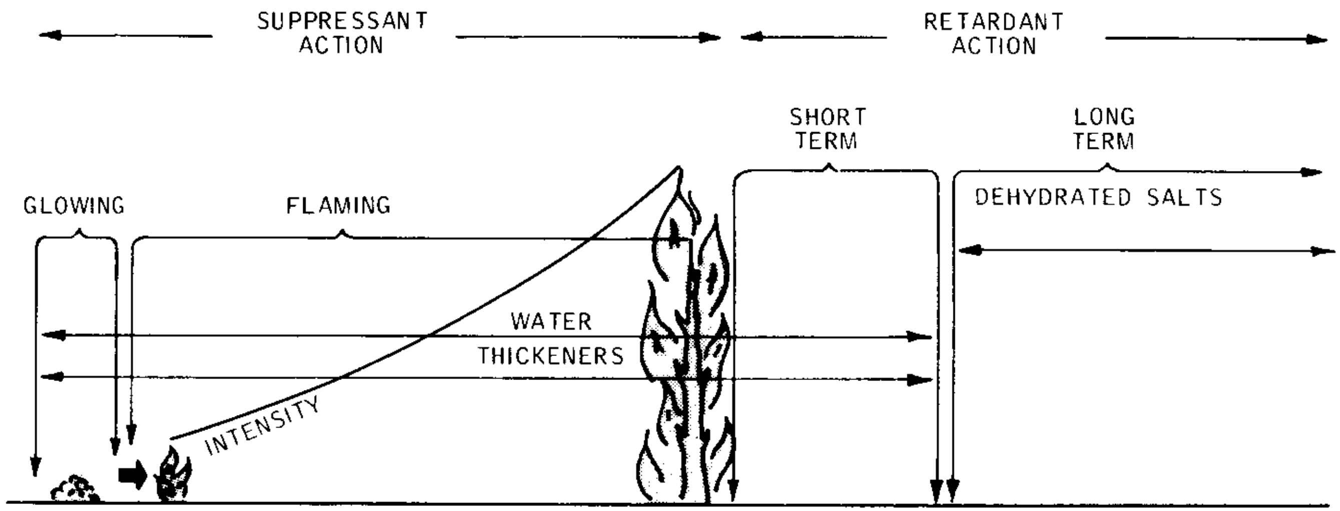


Figure 4. Fire Spectrum

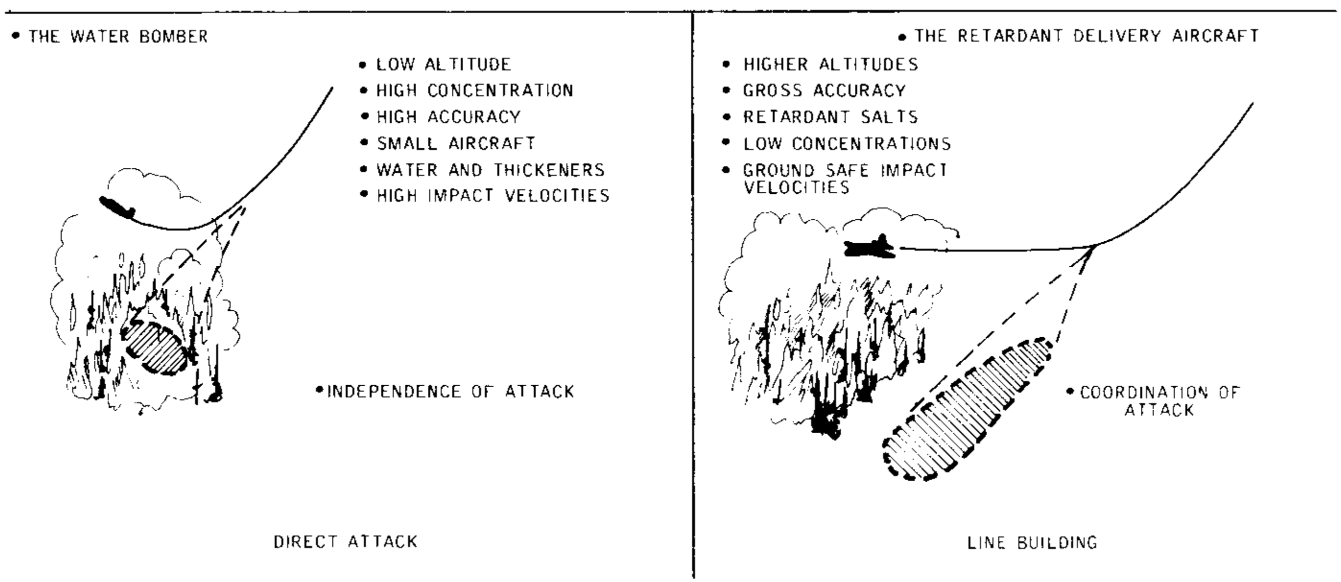


Figure 5. What a Design Should Do Confronts Two Current Tendencies

benefit from low altitudes, and suggest small aircraft with considerable maneuverability. Treatment of the fuels in advance of the fire generally benefits from higher altitude to generate wide and long patterns of relatively low density. These patterns require gross accuracy (the ability to overlap patterns or apply coverage to geographically selected locations), rely primarily on long-term retardant salts and, since they are not delivered on the fire, place a premium on ground personnel safety. In addition direct attack, if successful, has obvious immediate benefits. The significance of line building, however, is in its use in close coordination with other elements of the suppression mission, and it is seldom a sufficient end in itself. The time saved by a single pattern with a typical width of 100 feet is highly dependent on the fire spread rate and the amount of reduction afforded by fuel treatment. In extreme fires (500 feet per minute) the saving is insignificant -- about 0.2 minute per pattern yielding a treatment halving the spread rate. Nor is the amount of stand saved as a result of this savings significant in itself. On the other hand, reduction of intensity is roughly related to the square of the ratios of the treated to untreated spread rates, and herein resides substantial leverage on the fire. It is tantamount to the "knockdown" spoken of in conventional fire fighting and is relatable to the ability of the fire to cross a weak natural barrier, or to the ease with which ground or subsequent air attack can achieve suppression. This does not deny the fact that in some cases fuel treatment alone can extinguish the fire, but it yields the conclusion that: primary effect of long-term retardants is "knockdown," i.e., the reduction of fire intensity.

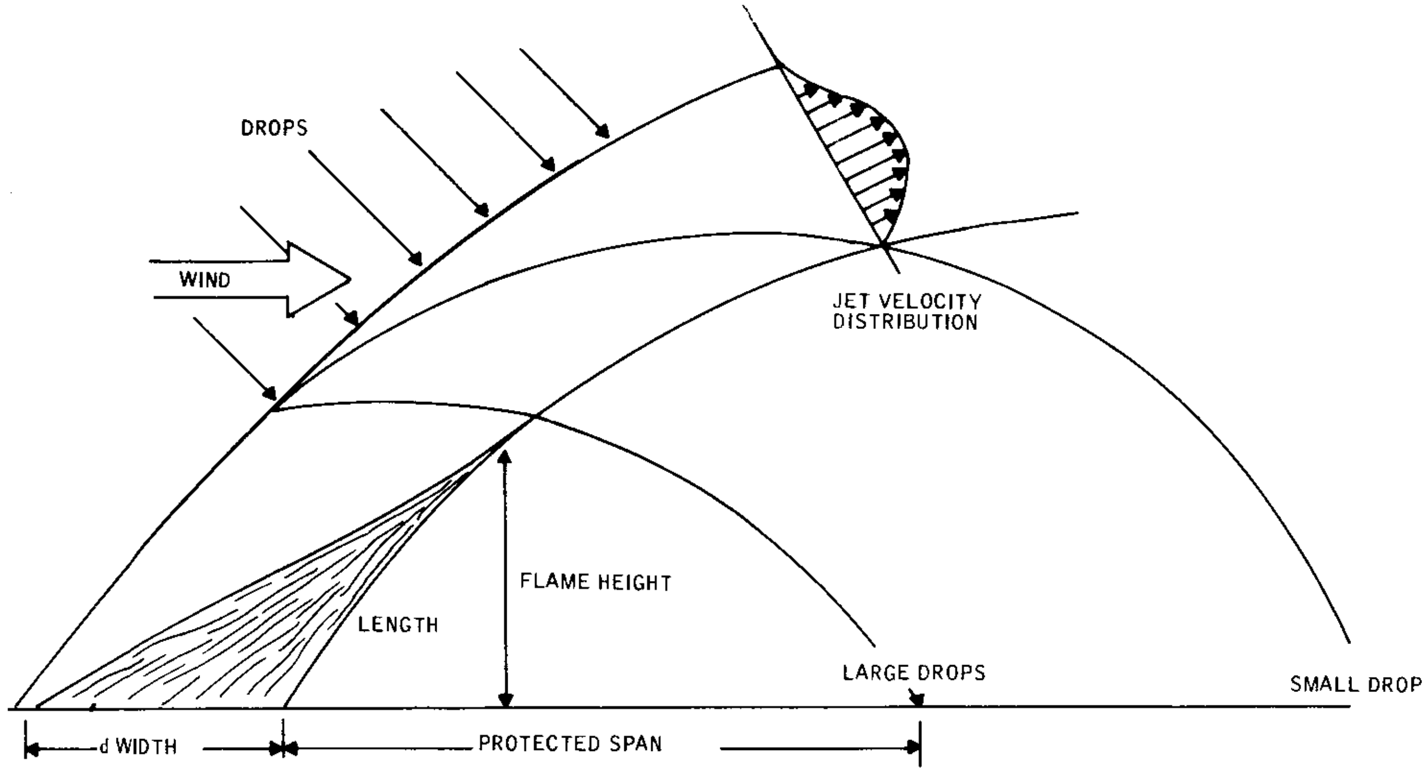
The indirect attack mode is the easiest to characterize analytically because it is based on a singular rather than complex set of phenomena. Specifically, it requires distribution of an initially wet but subsequently dehydrated salt concentration on the fuel surface area. The effect of salt concentration on the fuel is measurable in terms of the resulting fire spread rate. The effect of moisture introduced as a means of salt delivery on spread rate can also be assessed, although in the typical low-humidity, high-temperature situation conducive to fires, this effect is temporal and ceases to contribute significantly if the line is much in advance of the fire front.

Although the primary effects of a retardant salt are to reduce the fire spread rate through the treated fuel, in some cases it is theoretically possible and potentially practical to zero the fire rate (essentially suppressing the fire) by means of the dry salt concentration alone. In any case, the amount of retardant to achieve prescribed levels of effectiveness is determined primarily by the concentration onthe fuels.

Direct attack on the fire is considerably more complex phenomenologically, and the force that must be applied to effect a significant change in the fire condition is a function of the fire intensity. Since the controlling force must be applied at or near the base of the flame, i.e., within the reaction zone, any force delivered from the top of the flame must penetrate the plume, and only that which survives this penetration can produce a significant effect on combustion. There is a distinct limit therefore to the flame pressure (or the thermal updraft) that a given object (or drop) can penetrate, particularly in a free-fall mode.

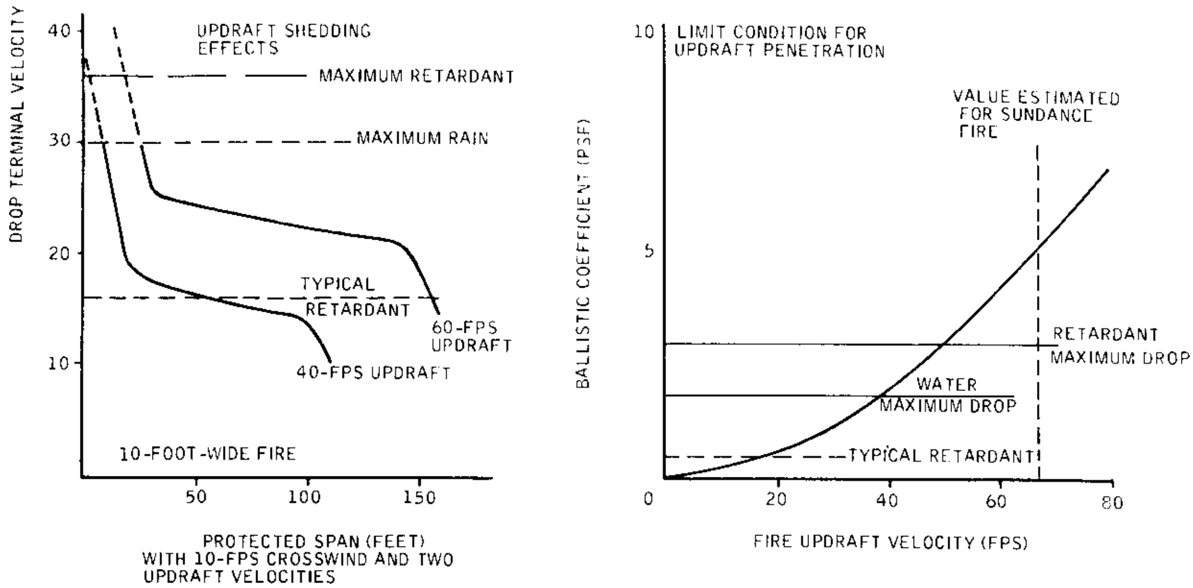
Figure 6 shows schematically the protective effect of the fire updraft. A fire of a given width, d, generates an updraft with a velocity generally considered relatable to the mass reaction rate. Velocities up to 65 feet per second based on fire-related phenomena have been estimated (45-mph estimate for vertical velocities in the Sundance Fire).(1) In windy conditions, the resultant jet deflects droplets of rain or retardant resulting in a potentially large protected area; i.e., with a 30-foot flame width, a 40-fps updraft, and a 10-mph wind, the protected span for raindrops can extend 100 feet from the fire front.(2)

Figure 7 shows the effect of these conditions on typical retardants delivered as droplets from high altitudes. Figure 7a shows the limit condition vertical updraft penetration based on the ballistic coefficient of drops taken from Aerospace Corp. data estimating water and retardant drop distributions. Figure 7b relates droplet terminal velocities to the protected span for a 10-foot wide reaction zone. From these values it can be seen that for high-intensity fires



NOTE: 30-FOOT FRONT AT 40-FPS UPDRAFT UNDER 10-MPH WIND CAN BE AS MUCH AS 100 FEET

Figure 6. Protective Phenomenon Resisting Direct Attack



(a) (b)

Figure 7. Mechanical Difficulties of Direct Attack

the only practical approach in air attack is treatment of the fuels in advance of the fire.

As the fire increases in intensity, the concentration required to penetrate the plume and establish a sufficient cooling thrust will soon exceed the concentration required to modify the spread rate in long-term retardant application. This condition suggests a limit condition above which delivery should be in advance of the reaction front. With the consequent reduction in spread rate and hence intensity, it may then be practical to consider direct attack against the weakened flame. In other words, the sequence of delivery strategies supplants the cooling flux rate in traditional knockdown time studies.

Since the analysis of tactics of suppression and the study of suppressants per se is beyond the scope of the current contract, it is necessary to establish some limiting ground rules on the direct-attack situation to assure that response capability is maximized in situations where direct attack is the most appropriate tactic. It was initially agreed that the direct-attack option is most critical in an initial response condition when the fire is small, on the order of 1 to 10 square feet, and may be alternately glowing or actively burning, or of relatively low intensity covering 200 to 1,000 square feet. In both cases, suppressant concentrations compatible with the upper levels of desired retardant concentrations should be effective. The small fire will be treated as a control on accurate and repeatable delivery, i.e., a point target against which some volume increment must be aimed to provide an effective pattern encompassing the fire. A control factor in the larger fire is effectively the ballistic coefficient of the droplets or containers that is relatable to the ability to penetrate a fire plume.

Subsequent analysis has shown that, based on studies of vertical fuel modeling and Canadian data on water as a suppressant,[(3)] more detailed guidelines can be generated. Although such an exercise is speculative, it is based on the best information to date. Further studies to quantify relationships suggested in the following discussion are recommended to refine these tactical considerations.

Little data have been generated on the quantities of material required to suppress a fire from the air, nor is there any agreement on the characteristic of the fire that determines this value. Canadian studies[(3)] have evaluated the amount of water to suppress test fires of low intensity (measured on the Byram Intensity Scale), while the effects of viscous water and retardant salts have been evaluated in conventional fire fighting. Sprinkler studies in which the fire-fighting fluid is delivered from above the fire generally concede that the primary effects are cooling of the adjacent fuels and the air above the flame rather than the fire itself, i.e., the liquid is substantially shed by the flame plume; its primary function is to prevent spread, allowing the flame to burn out by means of fuel starvation. In any case, we do not have a cooling flux in aerial delivery so much as a cooling impulse.

To place the direct-attack and line-building roles in perspective, a qualitative analysis of the two tactical options was undertaken. Figure 8 shows a summary plot of the Canadian data[3] on water required to suppress two fires of low intensity. In at least one fuel (Balsam Fir Slash), the curves were found to extrapolate with reasonable accuracy to fires of higher intensity.

Further examination of the data would appear to order the effects of direct suppression versus the short-term retardant effects of the water on the test fuel beds. This is liberally interpreted in Figure 9 as a method of estimating the effect of retardants versus water capabilities in the suppression mission. Note that in the experiment water was delivered not simply to the reaction zone but to the entire fuel bed. When the fire was not actually extinguished by the application it could still be suppressed while traversing the treated fuel. It was further reported that on reignition the spread rate and intensity were reduced considerably. The curves for extinguishment and delayed extinguishment diverge quite rapidly indicating the difference in force required to operate on the fire or on the fuel to achieve the same end.

A report on the effect of viscous water in fire fighting characterizes three stages of fire suppression: knockdown, flame extinguishment, and total extinguishment as a function of application times.[4] If we assume that the volume of application is the critical value, the ratios of the times to achieve control with viscous materials and water established in the above report can be used to estimate volume reductions in the aircraft delivery mode that may be associated with retardants. This is not necessarily a valid assumption in that the times are large compared* to those achieved in air drops, but it should yield a limit condition.

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*The application of a flux differs significantly from an impulse or single treatment in several respects. A molecular thickness of water is sufficient to prevent fuel burning if it is continuously replaced at a sufficient rate. Additionally, the application of a spray to a flame gains penetration as initial particles erode or reduce the heat shield.

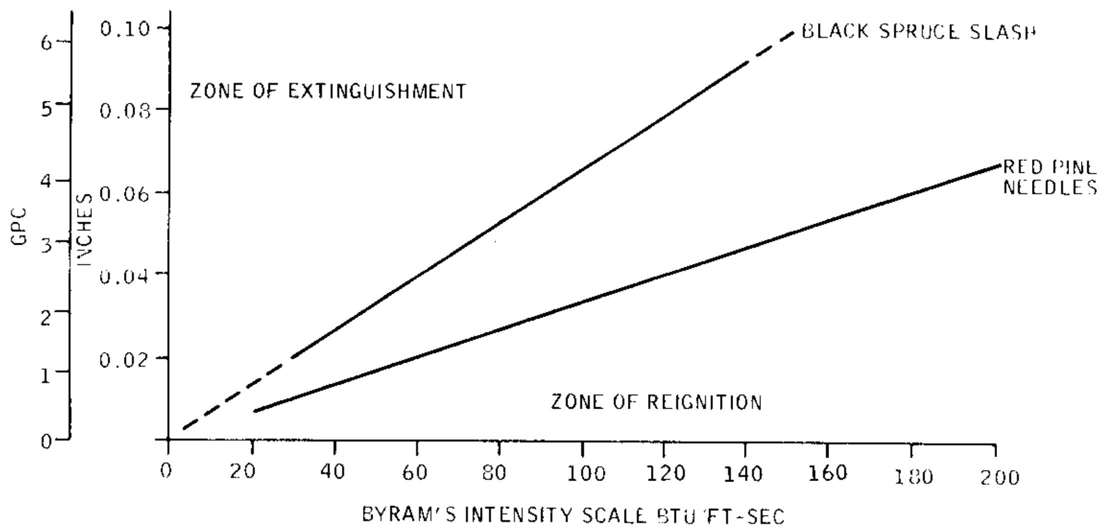


Figure 8. Water Application Depths Required for Extinguishment of Low-Intensity Fires in Forest Fuels

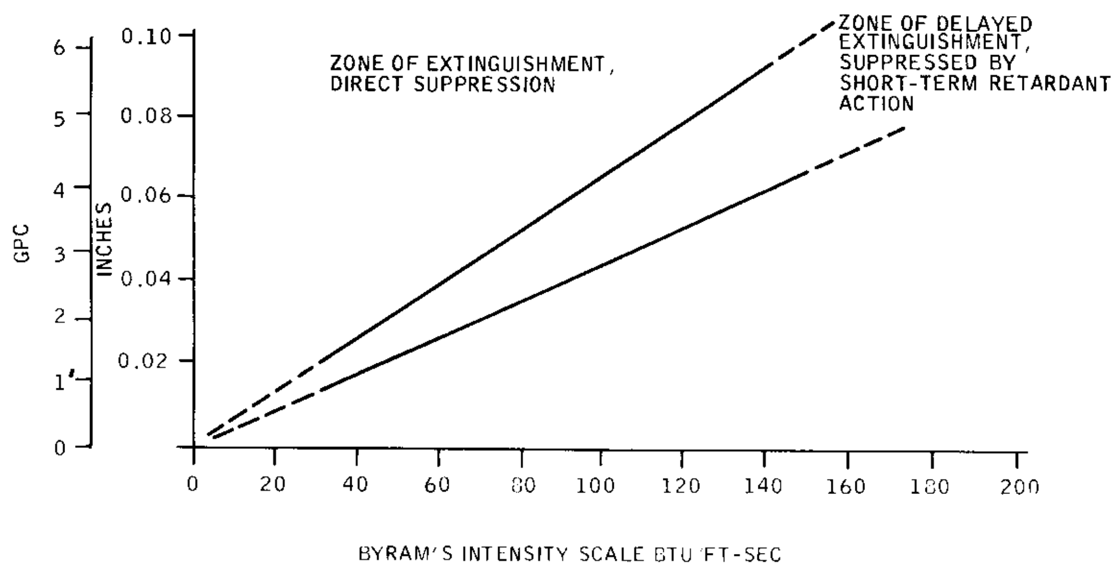


Figure 9. Three Degrees of Suppressant Effects

The Grove data show that the effects of viscous water are relatively constant above 20 centipoise. The improvements in application time over water for each stage were reported as follows:

	Percent Time Less Than Water
Knockdown	40
Flame Extinguishment	52
Total Extinguishment	28

The report also shows that the retardant salts do not significantly change extinguishment times for the various preburn times. It is likely, however, that the salts would have shown an effect if they had been used in the Canadian tests.

Using the above assumption, the limit conditions on the relative changes in Canadian results caused by the use of a retardant as opposed to water can be estimated as shown in Figure 10.

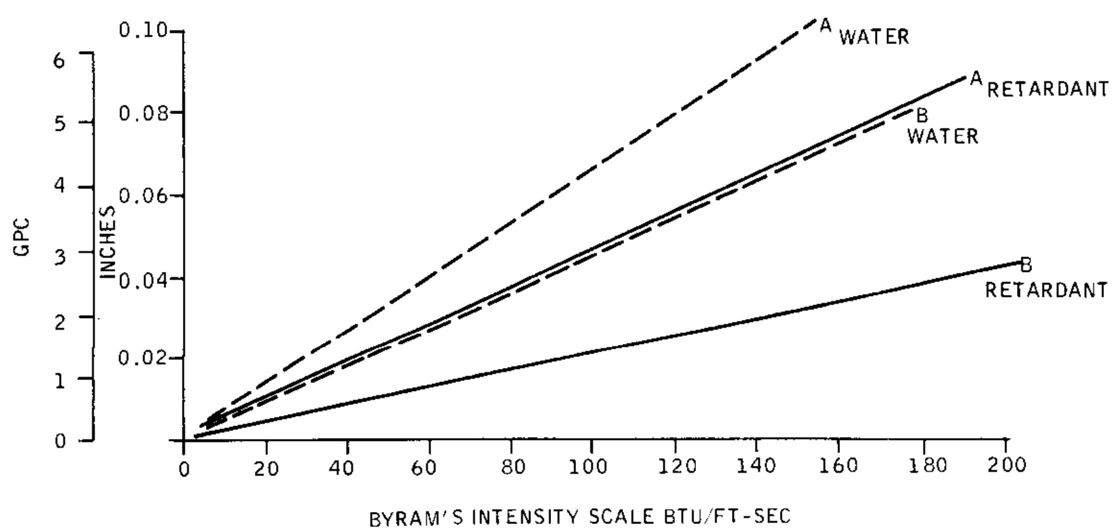


Figure 10. Quantities to Achieve Suppression Adjusted for Retardant Effects

Letting Canadian data for pine needles and Black Spruce slash represent the range of fires of interest, and adjusting the volumetric relationships in terms of retardants, the region of suppression plotted on a logarithmic scale of Byram's intensity is shown in Figure 11. The data show that only a small range of the fire fuel spectrum is subject to direct suppression with quantities achievable in a single aerial attack.

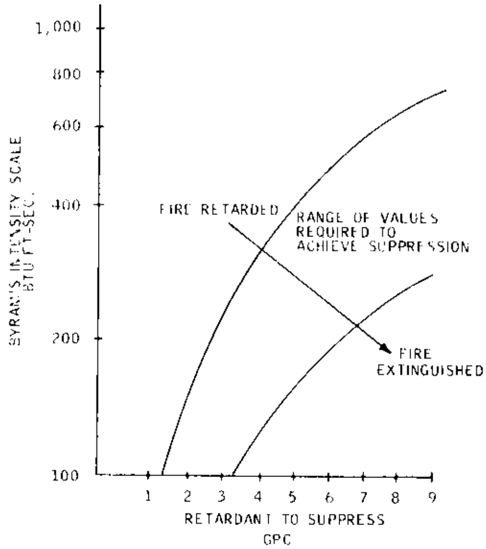


Figure 11. Quantities of Retardant Required to Suppress Low-Intensity Fires

Honeywell studies[5] modeling the application of retardant to vertical fuel structures show that the amount of retardant that will drip and run to coat the vertical fuels and the film thickness that will remain on the fuel surfaces (without running off) reach a definite tradeoff limit. These limits, determined substantially by the rheology of the retardant, are similar to those experienced in rainfall. The model was based on Forest Hydrological studies, making use of the Grah-Wilson concept of equivalent film thickness. Effects of the coatings were based on a retardant effectiveness parameter developed by the Forest Service.[6]

The graph in Figure 12 shows the reduction in intensity or knockdown achievable by retardant application to the fuels in front of the fire. This reduction is important in minimizing the ability of the fire to jump a physical barrier or in preparing the fire for subsequent direct attack by ground or air operations.

For an effective direct-attack system, the desirable characteristics of the terminal condition of the retardant can be specified in terms of several interrelated variables.

Relatively high treatment levels reduce pattern area potentials and consequently place a premium on accuracy because errors cannot be accommodated strictly by larger, less dense patterns. This accuracy is aided by providing high momentum for the retardant cloud, making the trajectory long, and simultaneously minimizing the effects of wind on pattern placement error. The high momentum also exerts a fundamental influence on the terminal effectiveness by improving the ability of the retardant to penetrate the fire-wind and flame plume.

The significance of momentum in direct attack arises because the fire generates its own windscreen that deflects small drops, essentially generating a protected area. This is significant in direct attack because effectiveness is based not only on the quantity delivered, but on the ballistic energy available to penetrate the fire curtain.

In contrast to direct-attack requirements, the line-building problem is dominated by the need to spread retardant effects over a wide area and to achieve a relatively thin film over the fuels. Momentum is a lesser consideration and may indeed work against the film thickness retained by the fuels by shaking them, viz, lesser amounts of water are retained in a wind-driven rain than in a gentle rain. Evidence also suggests that a pattern that achieves its steady-state momentum early in its flight history remains relatively more stable throughout its flight from high altitude than a system designed to maintain its momentum for deep penetration.

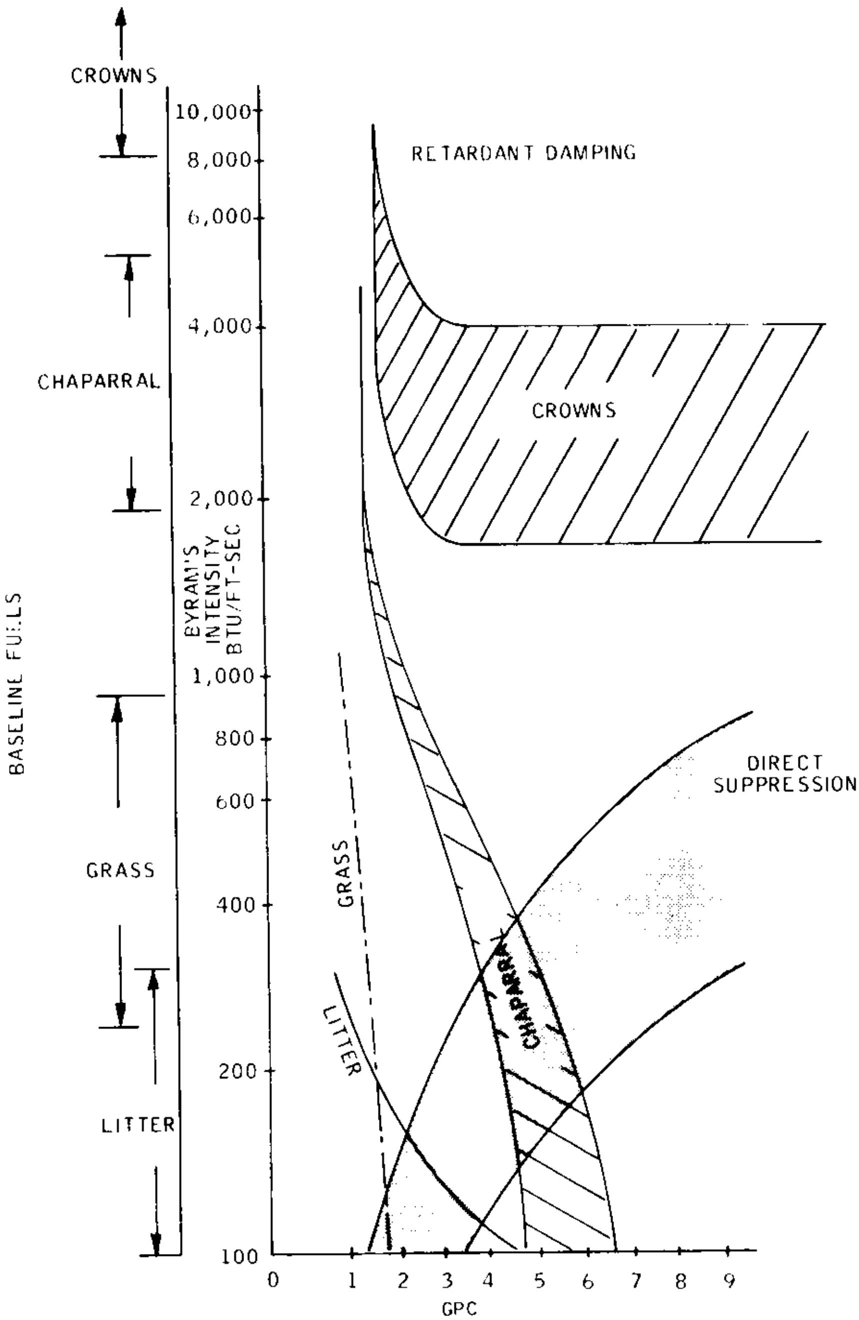


Figure 12. Effect of Retardant on Four Fires

Figure 13 relates Byram intensities to various levels of coverage on the fuels of interest. It also relates the effects of the mineral damping coefficient (long-term retardant) to various treatment levels for the vertical fuels of interest. These levels are essentially independent of fire intensity. Actual values are based somewhat speculatively on the effect of retardant on the normalized fire spread rate predicted in the vertical fuels coverage model for a retardant believed typical (four times the Grah-Wilson film thickness of water). Under the techniques used for estimating effects, a reduction in the damping coefficient causes a proportionate reduction both in spread rate and intensity. This results in dramatic changes in Byram's intensity.

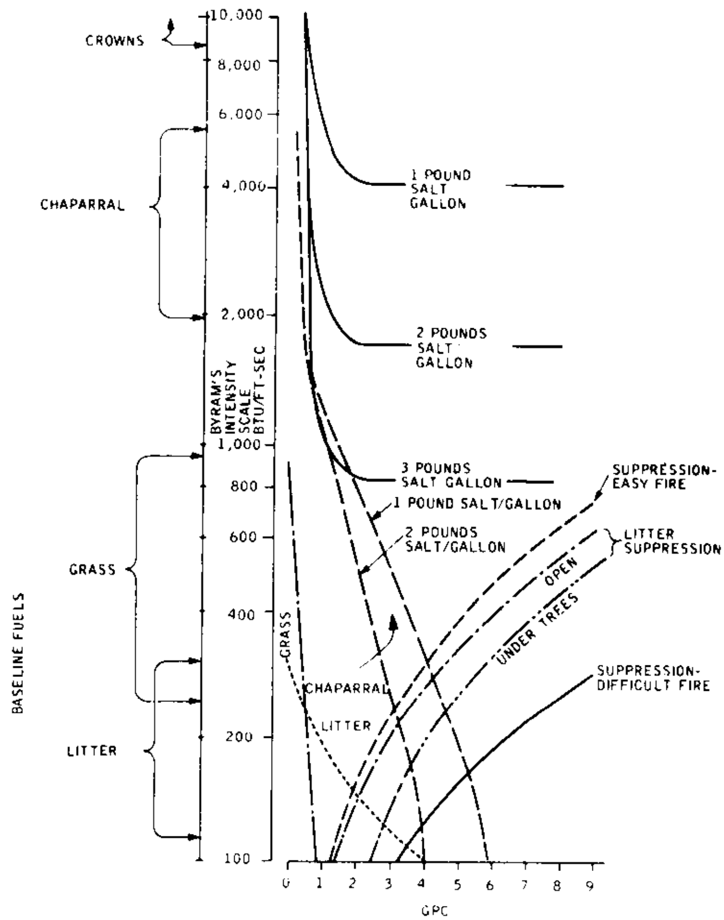


Figure 13. Quantity Effects of Various Retardants on Baseline Fires

Although the actual values in Figure 13 must be regarded as speculative, the order of effects shown is believed valid. Specifically, as the fire grows in intensity, the volume demands for suppression soon exceed the capability of the air tankers. At this point, treatment of the fuels in advance of the fire front becomes the only practical option. Subsequent direct attack, when the fire enters and is knocked down in the treated region, can then potentially extinguish the flame front.

Such sequential attack should be effective for most fires and, indeed, more effective than single passes with larger pattern concentrations. This results because there is a limit to the amount of retardant that a vertical fuel can contain. In the case of crown fires, it appears that the retardant damping action can only reduce the fire to some extent.

It is believed that both grass and litter fires are suppressible under most conditions in direct attack by a combination of suppressant and retardant actions.

On the basis of the above study, the following levels of retardant coverage may be specified as legitimate options for a retardant aircraft:

Grass	=	0.5 to 1.0 gpc (gallons per 100 feet)
Chaparral	=	4 to 5 gpc
Crowns	=	2 to 5 gpc
Litter	=	3 to 4 gpc

In addition, certain guidelines for pattern width, length, and the associated value of accuracy may be maintained.

- Where the fire is not suppressed, pattern width is of significant value. It determines the time over which the reaction front is delayed, the time required and time accuracy of the second (or third) pass attack. It establishes the ballistic accuracy with which the system can hit the fire front.

- Where the fire is suppressed, length alone dominates.

- When there is an option, the ability of a single aircraft to make two passes over the same area on a single flight is potentially of considerable value.

C. ACCURACY

In most situations, accuracy of pattern placement is an important factor (Figure 14) that influences both tank design and aircraft selection decisions. It is particularly important in direct attack, but remains generally significant in retardant missions as the placement of the pattern with respect to other drops or geographical conditions may well determine the success of the aerial attack.

To determine the effect of accuracy on tank design parameters and develop a data base for further consideration, an accuracy study was conducted. The results are summarized here in full recognition that a comprehensive study regarding specific aircraft and more detailed tank performance would be required to fully quantify the retardant bombing situation.

There are two conditions that significantly affect the ultimate accuracy of a system that also relate to design decisions. They are based on the availability of aircraft aiming aids or avionic support systems as follows:

(1) Without Avionic Support -- Under these conditions, pilot experience is the primary determinant of accuracy. The

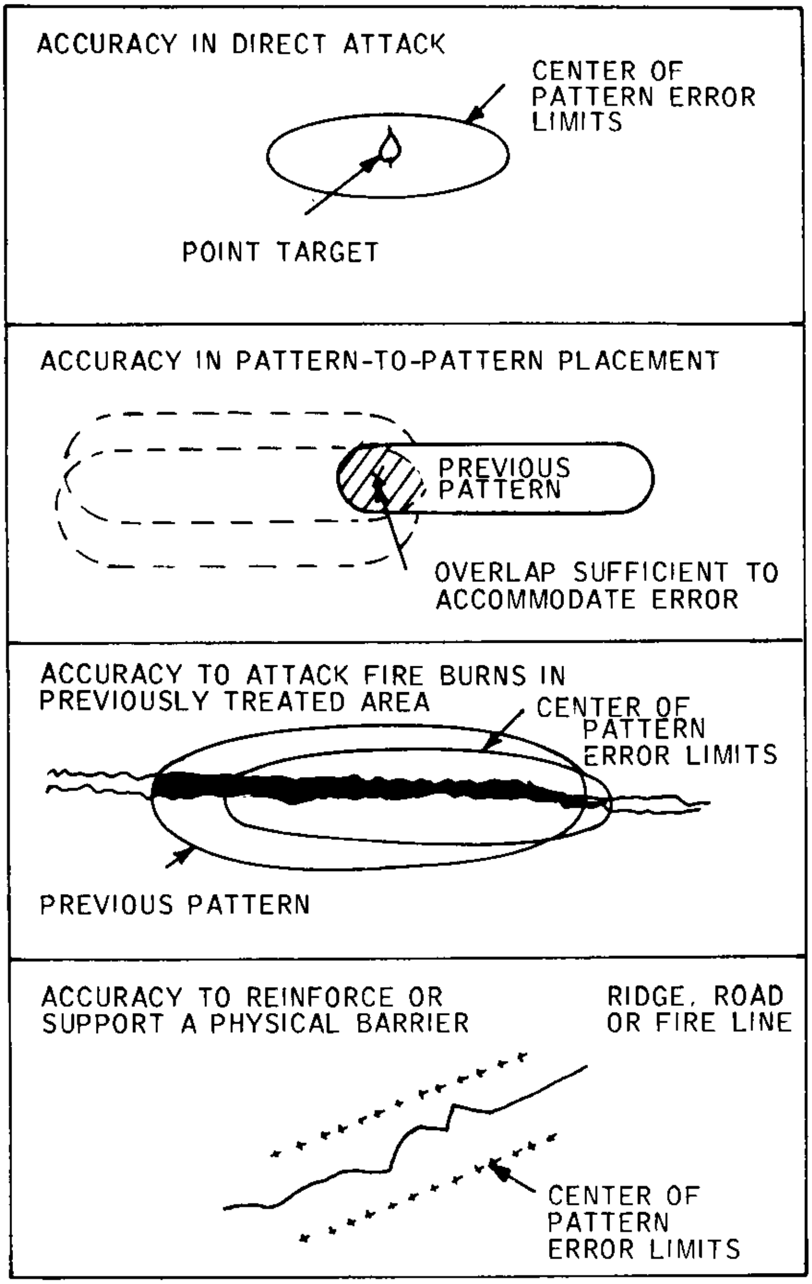


Figure 14. Delivery Accuracy is Important in Most Retardant Applications

visibility afforded by the aircraft (sight depression angle) and the maneuverability of the aircraft (allowable delivery altitude) maximize the pilot's ability to see the aimpoint at the time of retardant release. These values roughly determine the altitude limits above which the aimpoint passes out of view beneath the aircraft before the proper release point, with a consequent increase in release point uncertainty, as shown in Figure 15.

In addition, the condition implies that the tank system deliver an essentially constant and repeatable trajectory, regardless of the ground coverage requirements at issue. In this way, the pilot can develop a "feel" for the trajectory that contributes substantially to accuracy. The design for a standard trajectory or ballistic match imposes limits on the flexibility of the tank because trajectory modifications may be desirable in optimizing pattern controllability.

(2) With Avionic Support -- With aiming and trajectory aids, aircraft selection becomes decreasingly critical on visibility and maneuverability, and altitude limits for accurate delivery become less restrictive. Tank control parameters, including the modification of trajectory to optimize pattern coverage regardless of delivery condition, become more flexible with a consequent increase in effectiveness.

The first of these conditions represents most closely current practice, and was chosen for initial evaluation. It relates closely with the military problem of strafing or bombing and is consequently amenable to the same analysis. Although many of the characteristics are a function of the aircraft rather than the tank and gating system, capabilities of the retardant delivery system are best defined in the total context.

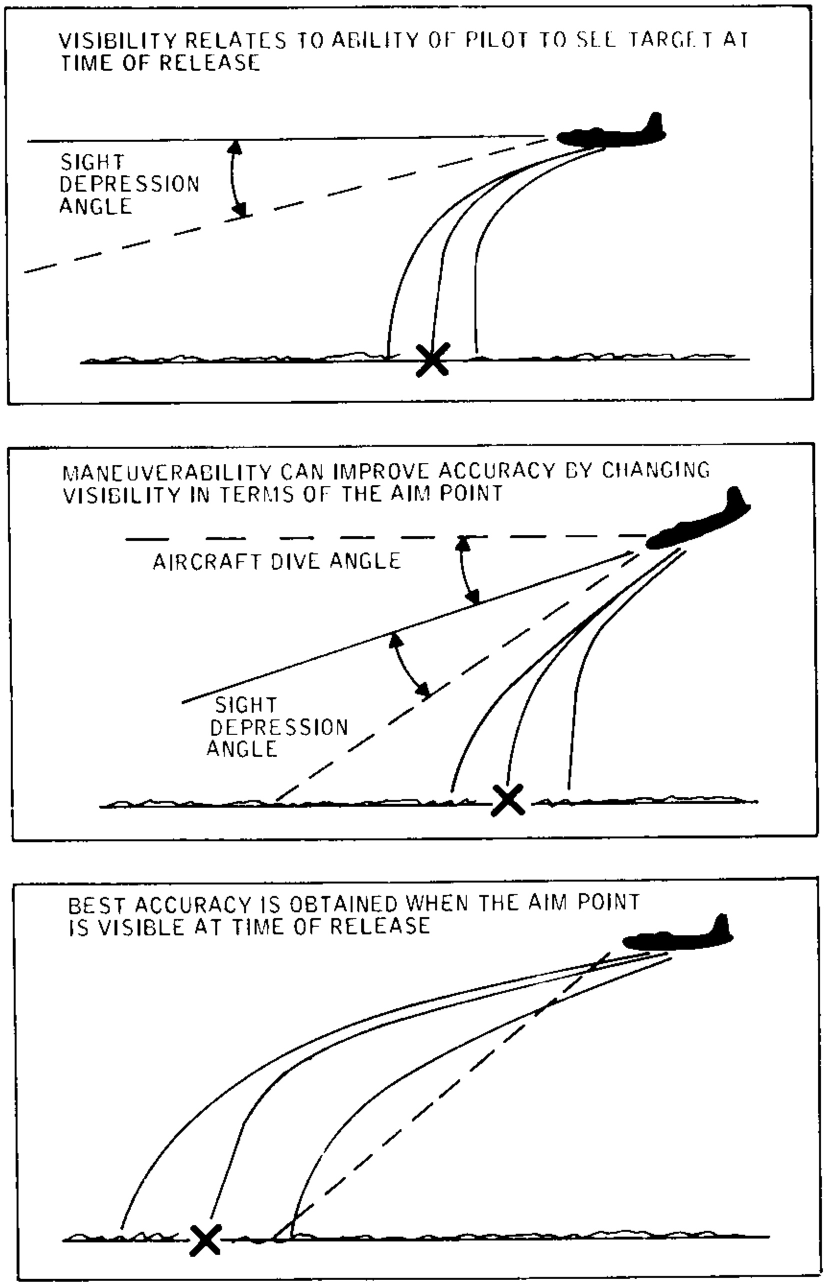


Figure 15. Effect of Maneuver and Visibility on Accuracy

What is a Delivery Envelope?

The technique used in the development of a delivery envelope is summarized in Figure 16. As shown in the figure, the first input necessary to determine the delivery envelope is the retardant trajectory or the line of flight followed by a hypothetical pattern center from release to the ground.

How Does Retardant Trajectory Affect the Delivery Envelope?

Examination of test data on existing systems (straight and level flight) shows that there is considerable choice in the type of trajectory that may be developed, and this is a choice made by selection of tank characteristics. (The actual trajectory is further modified by aircraft release conditions.) Detailed photo analysis was therefore conducted to determine the trajectories of two systems.

Two aircraft were selected from the Maranna tests. The Aero Union B-17 that produced one of the longest trajectories and the CL-215 that produced a more moderate trajectory were examined in detail. A third option, in which the breakup and consequent slowdown of the liquid mass was immediate was then extrapolated to allow evaluation of the full range of potential variation. The three trajectories are shown in Figure 17.

The effect of trajectory selection on the visible accuracy limit is readily examined in Figure 18. Note that there is considerable increase in the altitude over which the target is visible as the trajectory length or range value increases. The importance of aircraft visibility angles is also shown for a realistic range between 15 and 25 degrees. The significance of visibility indeed becomes more pronounced as the trajectory range increases.

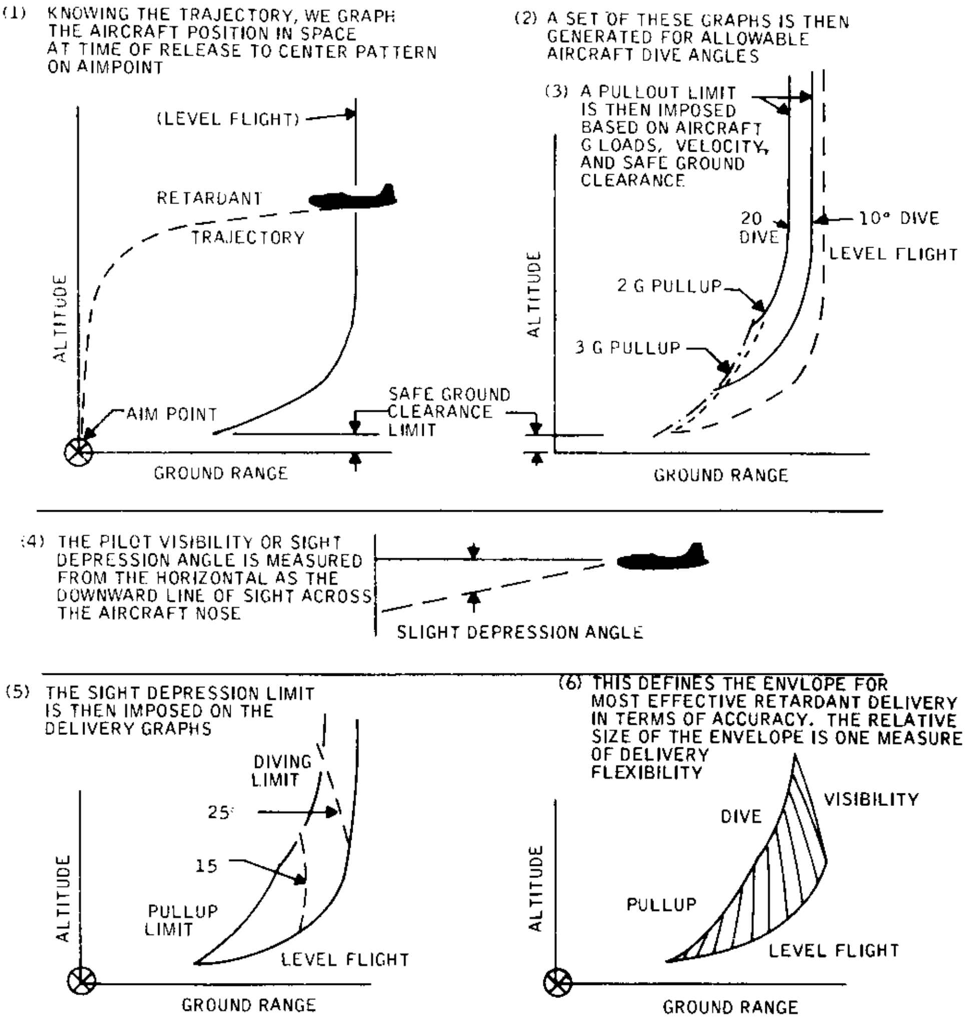


Figure 16. Definitions – Development of a Delivery Envelope

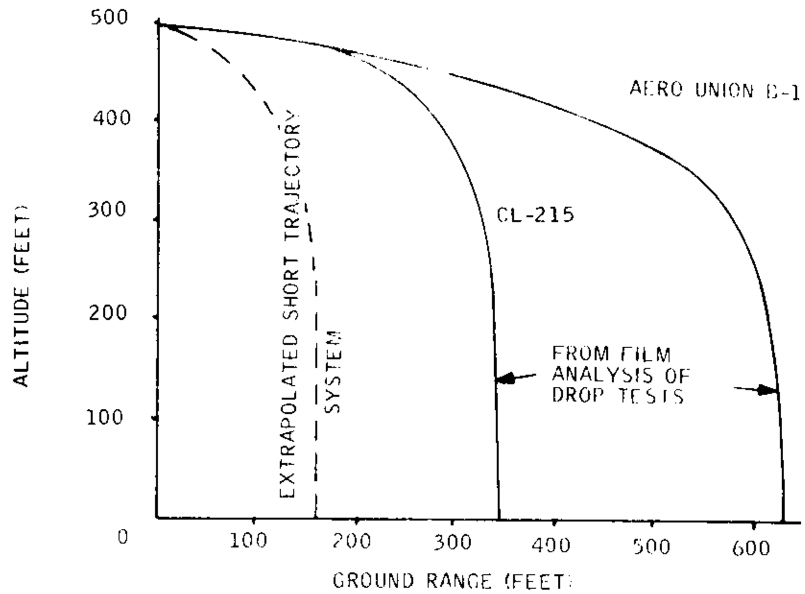


Figure 17. Nominal Trajectories Achievable from Various Tanking Systems

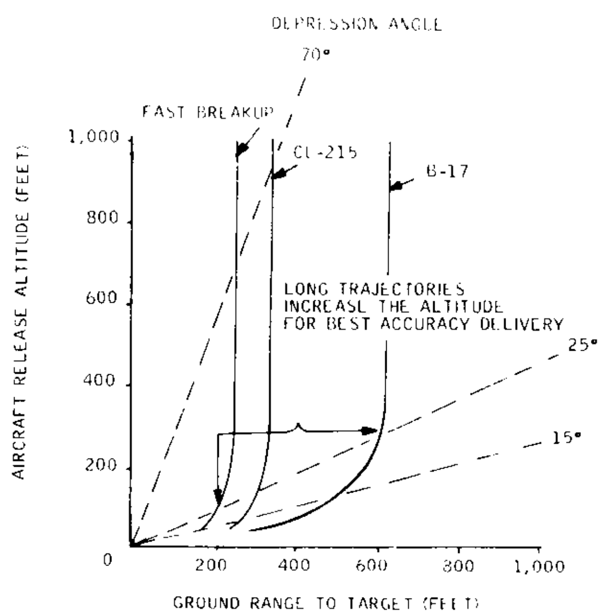


Figure 18. Effect of Various Retardant Trajectories on Visible Accuracy Breakpoint (Level Flight)

What is the Effect of Flying Above the Delivery Envelope?

The emphasis on visibility does not necessarily mean that retardant cannot be delivered effectively from above the altitude limit. It means that the target has passed below the aircraft nose, and a time interval must be estimated from this pass under to the release. The uncertainties associated with this time value reduce accuracy as shown in Figure 19.

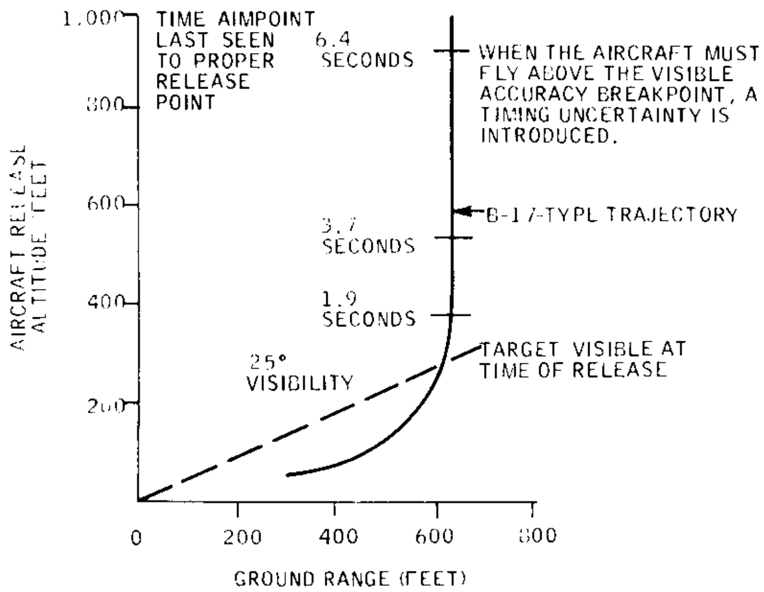


Figure 19. Accuracy Determinants Above the Visibility Limit

Probability of Hit

The delivery envelope is not in itself an accuracy prediction. To determine reasonable values of accuracy, a probability of hit must be generated. This is a highly complex calculation requiring the use of a number of standard computer programs and a considerable backlog of data developed and, in many cases, standardized by the military. The process is summarized in Figure 20.

PROBABILITY OF HIT IS A COMPLEX CALCULATION THAT SUMS UP A NUMBER OF UNCERTAINTIES, MANY OF WHICH HAVE LITTLE TO DO WITH THE TANK AND GATING SYSTEM.

SYSTEMIC UNCERTAINTIES

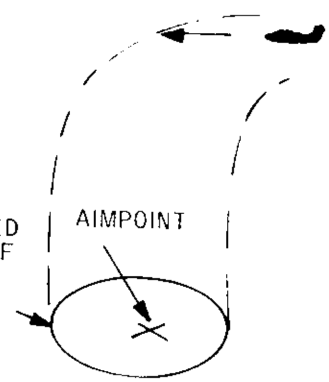
- GROUND SPEED
- ALTITUDE
- AIMING ERROR
- PILOT REACTION TIME
- TRUE LINE OF FLIGHT.

TANK AND RETARDANT UNCERTAINTIES

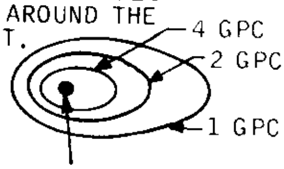
- TRAJECTORY VARIABILITY
- BALLISTIC ERRORS
- WIND
- EQUIPMENT RESPONSE TIME.

VALUES OF THESE UNCERTAINTIES, TAKEN FROM KNOWN DATA OR ESTIMATES, ARE TABULATED IN AN ERROR BUDGET.

THE COMPLEX SUM OF THE ERROR BUDGET YIELDS AN EXPECTED ERROR IN TRAJECTORY PLACEMENT CALLED A CIRCULAR ERROR PROBABILITY. IT IS USUALLY MEASURED IN BOTH RANGE AND CROSS RANGE.

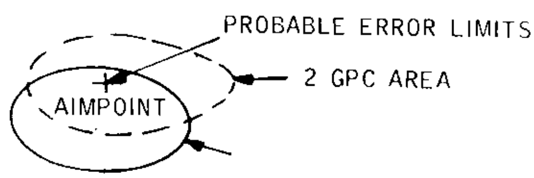


THE ACTUAL PATTERN IS A SERIES OF AREAS ORGANIZED AROUND THE NOMINAL IMPACT POINT.



A COMPUTER PROGRAM COMPARES THE PATTERN AREA AT ANY GIVEN COVERAGE AND ALTITUDE WITH THE EXPECTED ERROR.

- WHEN THE AREA IS LARGE ENOUGH TO ACCOMMODATE THE ERROR, A HIGH PROBABILITY OF HIT WILL EXIST.
- WHEN THE AREA IS SMALL WITH RESPECT TO THE ERROR, THE PROBABILITY OF HIT IS LOW.



WHEN THE PROBABILITY OF HIT IS ON THE ORDER OF 0.4 OR BETTER, A SYSTEM IS GENERALLY CONSIDERED TO HAVE SOME REASONABLE CAPABILITY.

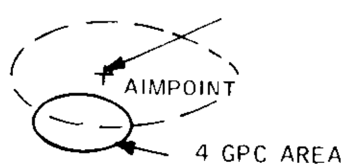


Figure 20. Definitions - Predicting the Probability of Delivering the Retardant on a Target

What is a Probability of Hit Envelope?

Just as the delivery envelope is generated by a range of allowable aircraft delivery conditions, an envelope of expected hit probabilities can be generated showing the expected values for a range of conditions as shown in Figure 21. In this case, wind establishes the upper and lower values. The curves are composites of dive and level flight values obtained from separate computer runs. Such data on a fully characterized aircraft system can be generated for use in mission planning. For purposes of this study, however, they were used to determine the effects of quantity, retardant form, and trajectory decisions on system performance.

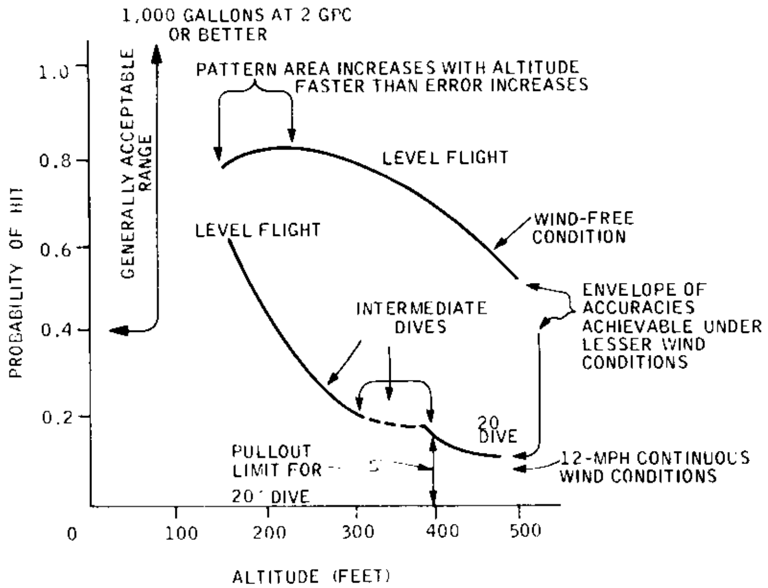


Figure 21. Interpreting the Probability of Hit Curves

What is the Effect of Aircraft Capacity on the Probability of Hit?

Figures 22 and 23 show the effect of salvo quantity on the probability of hit for comparable 1,000-, 2,000-, and 3,000-gallon deliveries under two wind conditions. Figure 24 is a crossplot of the wind data at a fixed probability of hit of 0.6, or delivery with a 60 percent chance of hitting the aimpoint. The data show that systems with 1,000 gallons or less are inadequate for high-altitude applications. However, they are usually small aircraft that can negotiate rough terrain to achieve low-altitude release. Nonetheless, larger quantities should be specified when the lower altitudes are not achievable under operational conditions. In addition, a true direct-attack capability at 4 gpc or better does not appear to exist below about 1,500-gallon capacity.

Conversely, the difference between 2,000 and 3,000 gallons is not nearly so pronounced. Consequently, capacities ranging from 2,000 gallons upward appear worthy of consideration for high-altitude capability.

The data also show that drop increments much less than 500 gallons are relatively ineffective in terms of accuracy. Thus, there is little value to the establishment of fixed tank increments below 500 gallons.

How Important is a Long Trajectory to Probability of Hit?

Figure 25 compares probability curves for a long-trajectory high-momentum delivery and a moderate trajectory system. They show that the long-trajectory system is generally superior in the wind case up to about 500 feet. This improvement in accuracy is mostly in the meaningful range, i.e., in a region where the probability of hit is 40 percent or better and is consequently of some significance. In the wind-free condition, this situation is reversed because the longer trajectory system has not yet achieved its full pattern

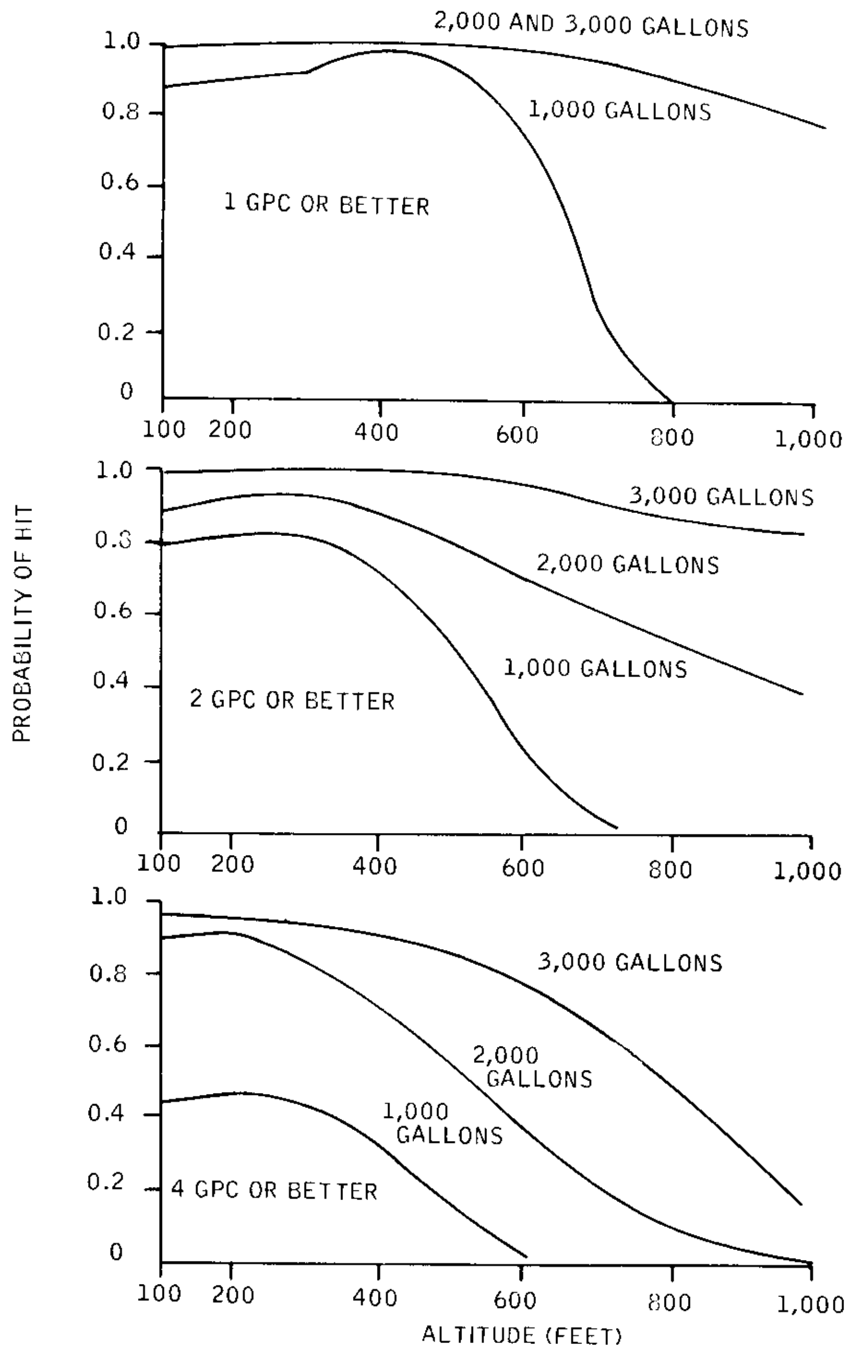


Figure 22. Probability of Hitting the Aimpoint for Various Salvo Quantities

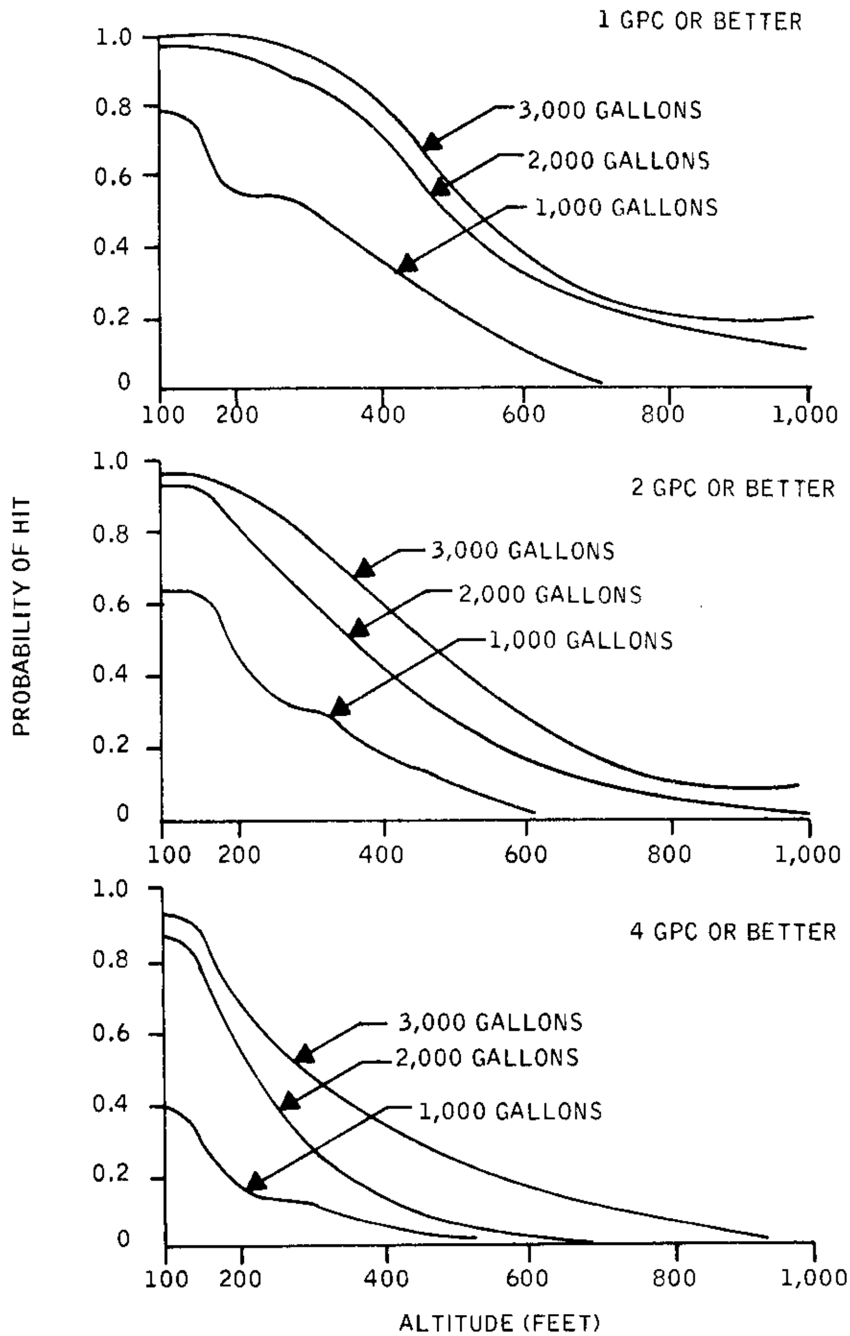


Figure 23. Probability of Hitting the Aimpoint for Various Salvo Quantities Under 12-mph Wind Conditions

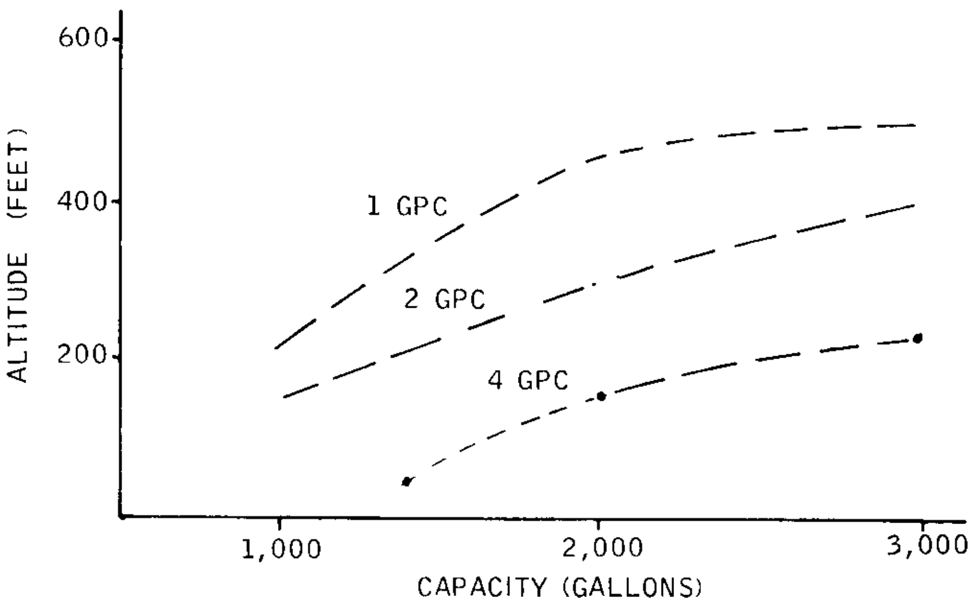


Figure 24. Allowable Altitude With a 60-Percent Probability of Hit Under Moderate Wind Conditions as a Function of Capacity

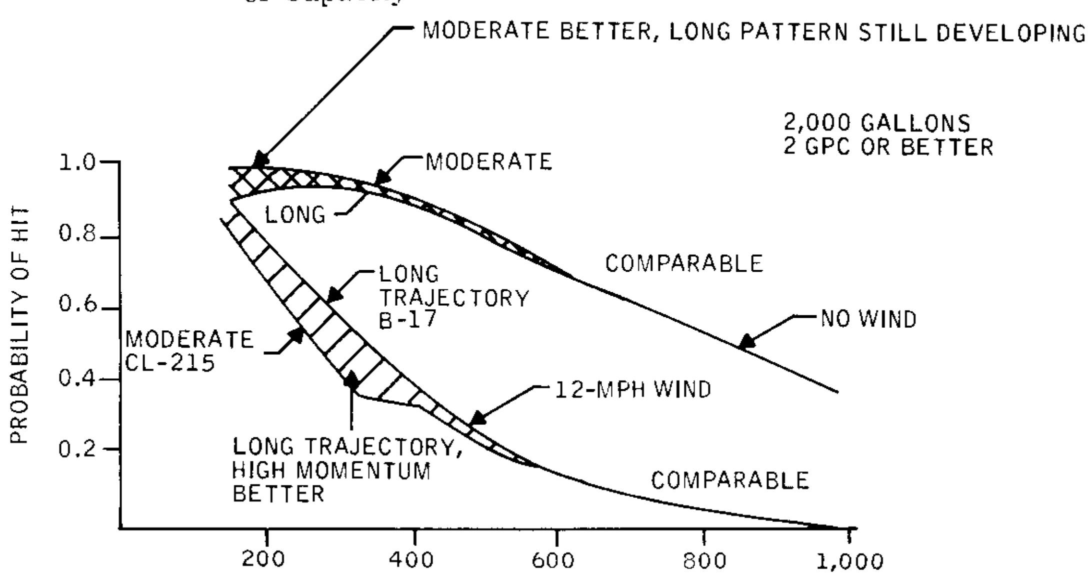


Figure 25. Comparison of Long and Moderate Trajectory Systems

expansion at low altitudes. The significance of this inversion is minor as both systems have a high likelihood of hitting the aimpoint under these conditions.

What Causes the Reduction in Accuracy Related to Wind?

The severe reduction in accuracy due to wind results from a combination of three effects:

1. Uncertainties in the aircraft flight path with respect to the aimpoint. This is represented by crabbing (in aircraft terminology) and also contributes to ground speed uncertainties. It is not controllable through the tank and gating system or the retardant characteristics.

2. Retardant Pattern Diffusion. A crosswind can potentially separate droplets of different sizes into diffuse bands in which smaller droplets are separated from larger ones by distances roughly proportional to their time of fall. This process would theoretically result in a wind-influenced reduction of useful pattern area, with a consequent reduction in accuracy. In test data, however, the evidence of this diffusion is minor. The fringe areas of the pattern do deflect, but there is little evidence that the meaningful pattern area is significantly changed. Although all tests were conducted in relatively low wind conditions, there is evidence in the study of rainstorms that support this observation. Specifically, smaller drops associated with large drops become entrained in the aerodynamic wakes of their larger companions and consequently have been shown to fall at velocities determined by the larger drops. Since diffusion thinning of the pattern requires differences in the time of fall,

entrainment phenomena will substantially reduce actual losses in pattern area, and they have been ignored in the analysis.

3. Retardant Pattern Deflection. The application of wind to the retardant cloud causes it to drift windward from the expected aimpoint. The amount of drift is related to the dominant drop size and the velocity of the wind. Based on the fall velocity of Phoschek® * drops taken from film analysis, the dominant drops are on the order of 1 centimeter in diameter. Wind deflection for these drops is sizeable as shown in Figure 26. The values can be reduced by causing the formation of larger dominant drops, either through rheological manipulation of the retardant or through contained delivery.

<u>How Much Will Contained Delivery Increase Accuracy?</u>

The use of a containerized delivery has been suggested to improve accuracy, particularly in the higher altitude release regions (see Section III. C). To evaluate this condition, Figure 27 was generated. The container was assumed to be ideally effective in generating its terminal coverage. It appears that systematic errors are dominant. Consequently the improvement afforded, although considerable, fails to bring the accuracy to an acceptable level in most cases. With the reduction in systemic errors with avionic support systems, this improvement could potentially become meaningful, particularly for smaller capacity aircraft required to achieve high coverage rates.

*Registered trademark of Monsanto.

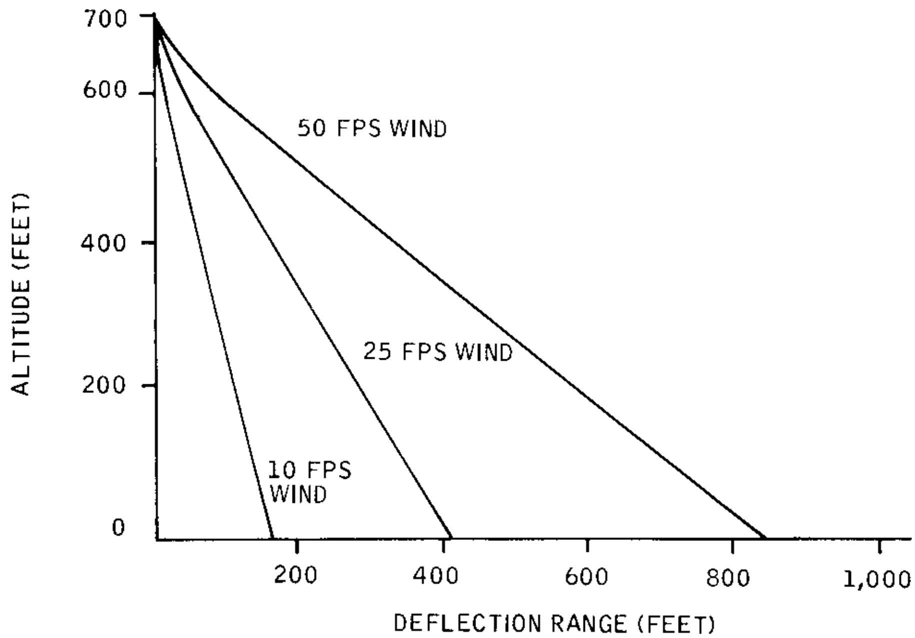


Figure 26. Wind Deflection on a One-Centimeter Drop

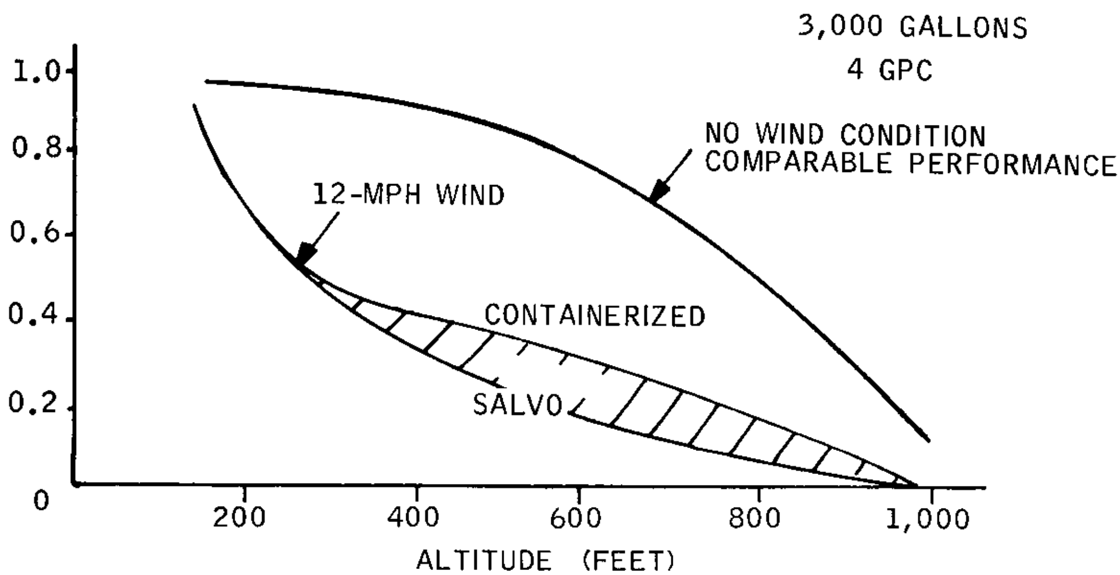


Figure 27. Comparative Accuracies of Containerized and Salvo Delivery

D. CONCLUSION

Although the substance of this study deals with tactics, the data used lack the precision necessary to make prescriptive statements on tactical policy. The intent rather is to order thinking on this problem in terms of the delivery system. Although the results are speculative, they show remarkable agreement with current thinking in retardant applications. The results also suggest that two passes are better than one in attacking a high-intensity fire because the long-term retardant effects, although not necessarily capable of extinguishing a fire, can knock it down to a point where direct attack can suppress it. Short-term retardant effects can finish the job when sufficient direct-attack knockdown is accomplished, or can be applied to achieve knockdown to a level amenable to direct attack. In other instances, such as against grass or litter, the combination of all three effects in a direct-attack mode appear desirable. Extension of these principles suggests that pattern width, placement accuracy, and duration of effects are quantitatively as important as the length of the fire line in planning sequential or coordinated attack.

We believe that studies to quantify and define the relationships between direct attack and line building by the agencies best equipped to conduct them can yield a significant improvement in fire control by air. It should be noted, of course, that the implementation of such tactical systems requires sufficiently accurate field information, coordination, communication, and training to realize the full potential of the delivery/retardant system that can offer these attack options.

III. RETARDANT FORMS

Previous discussions assessed the conditions of terminal effectiveness for two distinct tanker missions. The next step in the analysis is to relate these terminal requirements to the process whereby the retardant travels from the aircraft to the ground and the associated implications of the retardant form on the nature of the pattern and its survivability. Relationship of trajectory to terminal effectiveness, retardant rheology, and container delivery will be discussed in the following subsections.

A. RELATIONSHIP OF THE TRAJECTORY TO TERMINAL EFFECTIVENESS

Photo analyses of retardant drops shows that there are three basic parts to the retardant trajectory:

1. A period of travel during which the liquid mass, although changing, remains substantially intact. This portion of the trajectory gives us range that has been shown to exert a significant influence on delivery accuracy.

2. A second period during which the retardant breaks up, losing velocity rapidly and forming the meaningful portion of the retardant cloud.

3. A third stage during which the formed cloud falls in an essentially steady-state manner, depending on the completeness of breakup achieved in the second phase.

The phases of the trajectory have substantially different uses in the mission spectrum as shown by the matrix of Figure 28. They suggest different types of delivery and consequently different tanking parameters for the two missions of direct attack and line building.

↑ HIGHEST MOMENTUM ↓
↑ BEST ACCURACY ↓
↓ BEST DISPERSION
↓ SAFEST DELIVERY

	DIRECT ATTACK	LINE BUILDING
HIGH CONCENTRATION, DROP ALTITUDE A	MOST FAVORABLE AGAINST SMALL BUT INTENSE FIRES OR FIRES IN TIMBER CANOPIES. BEST WIND PENETRATION. MOST REPEATABLE TRAJECTORY. MOST HAZARDOUS TO GROUND PERSONNEL.	POOR LINE-BUILDING CHARACTERISTICS BECAUSE OF POOR DISPERSION.
AFTER INITIAL BREAKUP, DROP ALTITUDE B	USE WHEN MORE AREA COVERAGE IS REQUIRED AT LOWER CONCENTRATIONS THAN AT DROP DISTANCE A. MAY NOT PENETRATE STRONG CONVECTION COLUMN.	GOOD LINE-BUILDING CHARACTERISTICS NEAR A FIRE FRONT. LESS DRIFT THAN WITH DROP DISTANCE C.
CLOUD DISPERSION, DROP ALTITUDE C	PROBABLY ACCEPTABLE AGAINST LARGE LOW-INTENSITY FIRES IN LOW WIND CONDITIONS.	MOST FAVORABLE FOR BUILDING CONTINUOUS LINE FROM HIGH ALTITUDES UNDER LOW WIND CONDITIONS WHEN ACCURACY IS NOT CRITICAL.

Figure 28. Comparison of Delivery Conditions for Direct Attack and Line Building

Based onthe above analysis alone, it would appear that the design problem was to develop tanks that maximize the length of the intact trajectory. This also maximizes the distance below the aircraft of the high-momentum portions of the cloud and the accuracy of pattern placement. Line building would then be achieved simply by selecting appropriately higher altitudes. This indeed is a legitimate conceptual option. It will maximize the altitude at which successful direct-attack missions can beconducted and provide some order of high-altitude line building.

Unfortunately, other evidenceshows that the efficiency of line building is in a sense inversely proportional to length of the deep penetration trajectory. This results from two factors. First, losses occur during the high-velocity phase of the trajectory that detract from meaningful recovery in two ways. These losses are velocity dependent. One form results in fog-like droplets that evaporate before ground impact. Although modeling of conventional stripping shows these to be a small fraction of the volume, the fraction increases steadily with time after flow is established. The other losses are the result of surviving droplets formed by breakup phenomena at an insufficient rate to generate a continuous pattern. Consequently, fast breakup systems can be shown to maximize the amount of material contained in the meaningful pattern area.

The second factor that reduces the efficiency of deep penetration systems in high-altitude line building is in the time rate of pattern change in the so-called steady-state region of the trajectory. Figure 29 shows that preservation of the high momentum produces a cloud that is still changing rapidly as a function of altitudes. This trend is suggested by Maranna test data, although the number of samples over the full altitude range is insufficient to yield a positive assertion.

A more analytic way to evaluate this condition is shown in a normalized plot of thepattern change (Figure 30). Even though the data analysis is somewhat limited by lack of drop data in the higher altitude range of interest, there is some theoretical basis for expecting this condition to occur.

Classical drop formation theory asserts that there is an optimum steady-state condition for a liquid drop in free fall. It occurs when the drop terminal velocity results in a pressure that is in equilibrium with the drop internal pressure substantially determined by the rheological properties of the fluid. The maximum steady-state raindrop has been shown to be about 0.5 centimeter. It is reported that Phoschek ® XA produces a maximum steady-state drop of about 1 centimeter. Indeed cloud terminal velocities estimated from films suggest Phoschek ® droplets on the order of 0.5 to 1 centimeter in the final region of the trajectory. Such droplets have relative low evaporation loss characteristics.

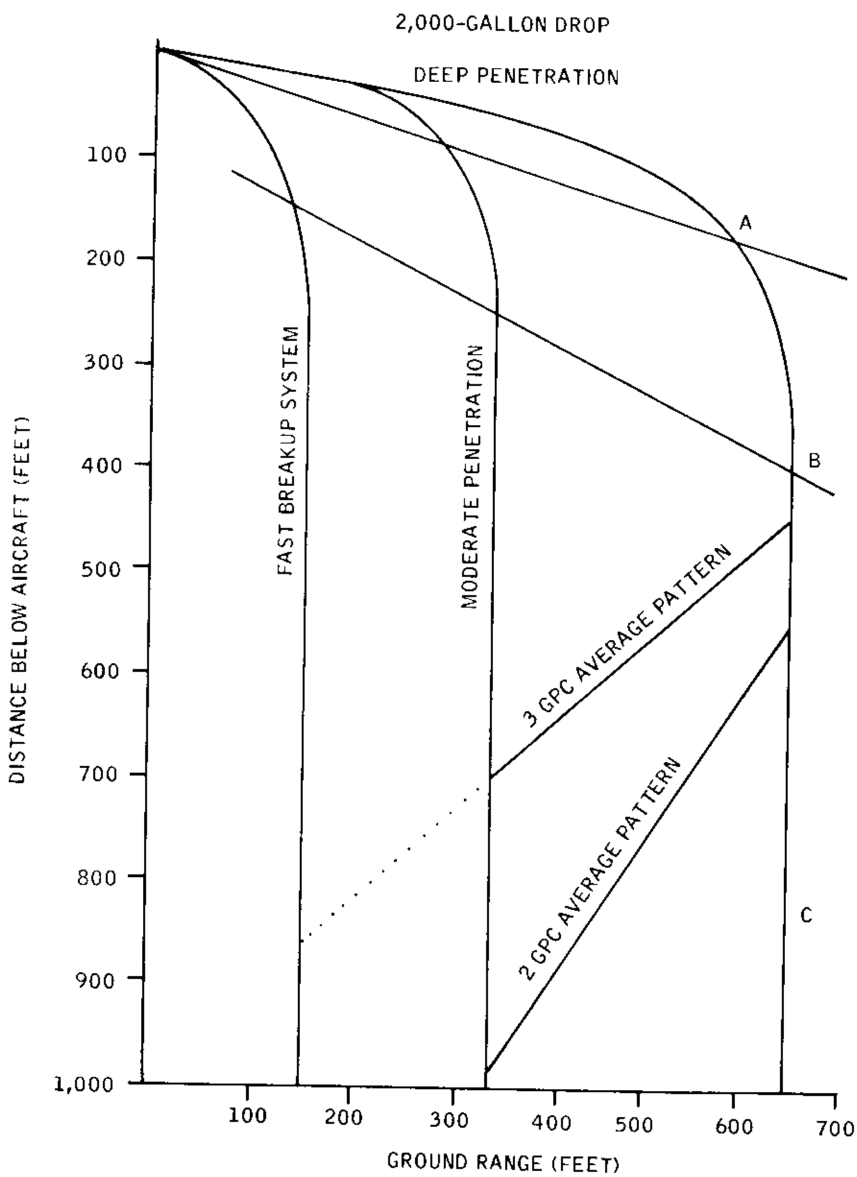


Figure 29. Effect of Retardant Trajectory on Ground Coverage Levels

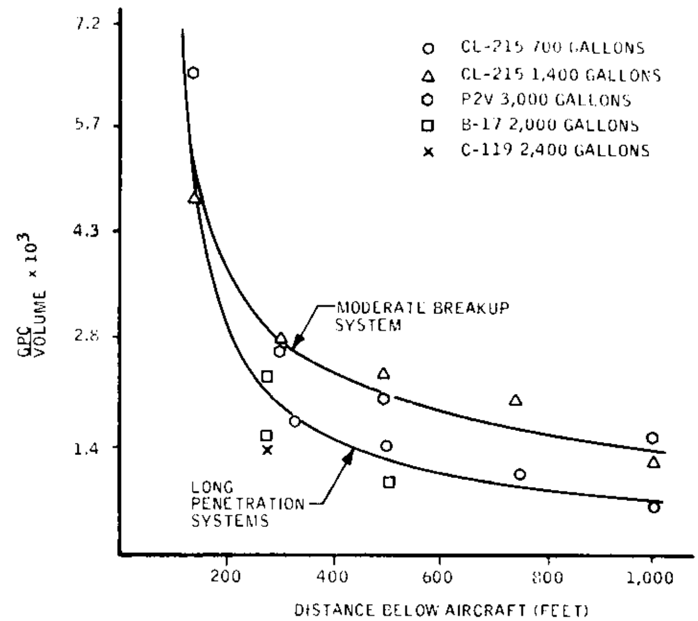


Figure 30. Normalized Pattern Change as a Function of Altitude

If droplets are larger than this value or traveling at velocities higher than their terminal velocity, they will continue to break up by one of three techniques conventionally known as: stripping, coaring, or varicose instability. The net result is continuous migration toward smaller droplets until a steady-state condition is reached.

Consequently, any excess of momentum after the primary breakup has substantially offset the aircraft velocity vector will result in continued degradation of the pattern value and substantially smaller size in the terminal condition. Thus, the maximum steady-state value would be expected to occur if the forward velocity was dissipated and breakup was complete before the downward velocity exceeded the velocity of the maximum steady-state drop; i.e., fast breakup would be expected to provide a maximum altitude resistance in the pattern.

This analysis leads to a second conceptual proposition that is equally valid for a certain spectrum of operations. Specifically, it may be stated:

Design to achieve a maximum steady-state momentum condition.

It can be achieved by two fundamentally different techniques:

- Manipulation of retardant rheology
- Containerized delivery.

B. RETARDANT RHEOLOGY

1. Baseline Retardant

The actual chemistry of retardant formulations, or improvements thereto, is not the province of this contract, except insofar as they dictate delivery system parameters. A good delivery system must be adaptable to retardent improvements as they are developed. (This is particularly true because the operational life of an aircraft is long under the typically low annual usage rates.) Nor can a good delivery system be predicated on a state-of-the-art improvement in retardant composition. Consequently, we have selected Phoschek® XA as a baseline retardant representative of a good, currently operational material embodying most of the characteristics contributing to superior performance. This selection does not imply that other operational retardants are inferior; in some instances, depending on mission limits and target fuel types, they can be shown to have advantages.

2. Retardant Improvements

It is impossible to conduct a study to evaluate air attack delivery systems without making observations on the nature of retardants and potential means to improve them. The state of the art with respect to the design of non-Newtonian fluids supports the contention that almost any specifiable characteristics desired can be designed into a retardant system. This includes the possibility of fluids that perform differently in the loading pump, the release environment, the liquid mass breakup stage, drop formation, and subsequent interaction in the fuels. The problem remains then to specify with reasonable precision these desired characteristics. This effort could account for a substantial program in itself, yielding major rewards in terms of improved effectiveness for retardant systems.

3. Survival, Tank Performance

In addition to retardant characteristics functionally related to the fire or fuels, there are characteristics that must be preserved to enhance handling, delivery, and subsequent survival during the trajectory. In some cases, these additives have no effect on the fuels (such as corrosion inhibitors; in other cases they are beneficial, such as the iron oxide dies that render patterns visible to the pilots and function (potentially) as opacifiers generally believed to be of value in conventional fire-fighting fluids. Fortunately, most of the qualities desired for fuels coverage for fire attack are compatible with those characteristics desired for release. For example, long polymers, used in some retardants as a thickening agent, have been shown to orient under flow, reducing turbulence and consequently wall friction in pipes. This is an advantage in loading and ejecting the material. These polymers have also been said to add strength and consequently thickness to films applied to vertical fuel surfaces.[7] In addition, viscosity has a demonstrated effect on spray-suppression of fires[4] while damping out high-frequency instabilities that contribute to small drops in the breakup of the liquid mass after release from the aircraft.

4. Drop Size

In the initial view of vertical fuels coverage, the proposition of designing an optimum drop in terms of the collision cross-section of the fuels was examined. This approach to drop size specification yields results similar to those found for insect control, with a resultant importance of achieving relatively small drop sizes. There are two things wrong with this approach in the retardant application. First, it suggests a very fragile cloud that exhibits considerable perturbation under relatively quiescent meteorological conditions and that has a finite liquid life (due to evaporation) with little likelihood of surviving air drop from altitude. Second, there is an implicit assumption that only the upward surfaces with respect to a plane of particles can be coated. (In actuality, particulates are recovered from the leeward side of coated objects, but the quantities recovered are very small.) It should be noted, in addition, that the optimum spray for a cloud supported in the trees is less than 200 microns, with anything larger said to be useless.[8] This suggests that only particles above 0.2 millimeter in diameter are captured by the vertical fuels.

Subsequent studies show that fuels are most effectively coated by a combination of dynamic impact and subsequent drip and run. The resultant splash and flow show a relatively good capability to cover all fine fuel surfaces, with the possible exception of broad leaves. This can be observed in dense trees such as Douglas Fir during a prolonged rain or duplicated by dropping retardant on complex fuel-like structures.

The ability of droplets to recombine on a fuels plain imposes a theoretical lower limit on drop size, i.e., wherein the kinetic energy of impact is sufficient to break interfacial tensions between the two droplets. If we approximate this condition by asserting that the kinetic energy of impact must equal the surface energy of the drop, size can be expressed by:

$$r v^2 \rho = 6 \sigma$$

where r is the drop radius, v is the drop velocity, ρ the liquid density and σ the surface energy. Using Stokes law to estimate velocity in terms of drop size, the diameter (d) of the drop (in mils) to meet these conditions is:

$$d \approx (3\,\sigma/4\rho)^{1/5}$$

For water, this suggests that droplets much less than 2.25 millimeters in diameter, are too small to assure recombination on impact. To evaluate the ability of retardant droplets to cover an area on impact, 5-millimeter drops were released from an eyedropper and recovered on a sheet of paper after about 30 feet of free fall. (This was an uncontrolled experiment in that retardant characteristics other than those at issue were not thoroughly measured.) Splash pattern data were then calculated as follows:

	Splash Diameter (Centimeters)	Splash Area (Cubic Centimeters)	Film Thickness (M llimeters)	gpc Equivalent	Equivalent Film Thickness (Inches)
Ink	2.0	3.1	0.2	0.5	0.0078
Phoschek® * XA	.8	6.1	0.1	0.25	0.0039
Firetrol® ** 100	2.4	4.5	0.13	0.35	0.0051

The surface area expansions accounted for only a small portion of the available energy:

Surface area x Surface tension = Surface energy

	Surface Area (Cubic Centimeters)	Units	Expended Kinetic Energy (Ergs)	Available Kinetic Energy (Ergs)
Ink	6.2	72	450	26,000
Phoschek XA® *	12.2	62	760	27,800
Firetrol 100® **	9.0	78	860	31,000

*Registered trademark of Monsanto.
**Registered trademark of Chemionics Industries.

It appears, therefore, that there is always an excess of kinetic energy for the surface energy required to expand the retardant drop. The difference taken off in heat, mass transfer, the work of adhesion, and other factors is far more significant in determining drop size.

It is interesting to note that the 5-millimeter water drop produced an equivalent coverage level of 0.5 gpc, with an equivalent film thickness of 0.0078 inch. One-half gpc is the approximate level that Germond analyses* suggest as the optimum container splash pattern to yield an average pattern coverage of about 2 gpc. Conversely, it is equivalent to the Grah-Wilson film thickness parameter for chaparral-like vegetation; consequently, some thinner value might be desirable. It is also interesting to note that ink was the least efficient in terms of creating surface, and that the two retardants were comparable. It would, however, take a far more lengthy study with considerably more experimentation to draw meaningful conclusions.

Energy available to create area from the falling drop in some portion of the kinetic energy of impact

or

$$K\, mV_t^2/2 = mV_L^2/2 \text{ or } (K) \text{ impact energy} = \text{lateral energy}$$

where

K is a dominating efficiency
m is the drop mass
V_t is the vertical terminal velocity
V_L is the resultant lateral velocity.

*Section II, C.

Since the masses involved in the drop and subsequent splash are the same, the problem is essentially one of relating the impact velocity to the equivalent lateral velocity. For spheres, the terminal velocity approaches a limit value (for water about 900 centimeters/second. Conversely, the lateral velocity (used here as a scalar value of energy) continues to increase as a function of the drop volume (r^3). This suggests that there is a crossover above which the available energy is insufficient to create the desired expansion. The pure value can be estimated several ways and yields relatively large drop size values, but this means little because energy-coupling coefficients dominate the problem as shown by the drop splash experiments. Specifically, both retardants could benefit from somewhat larger drops, whereas ink produced an area coverage close to that we might specify to achieve the requisite coverage.

Using the experimental splash data to calculate the efficiency constant, K, the graph of Figure 31 was generated based on the approximation $K \sqrt{\text{coverage level (gpc)}} = \text{drop diameter}$. Although this is an extremely simplified approximation, it suggests that drop sizes on the order of 0.5 to 1.5 centimeters are close to optimum for materials of these rheologies.

It is significant that rheology characteristics that tend to increase the stable free-fall drop size may themselves resist the lateral forces that develop the splash pattern. In this respect, thixotropes that act like water at the high shear rates of impact should offer the best area increase. It is also true that as size is increased from rheological controls, the expandability of the drop splash becomes limited and the true contained material that splashes like water after the container fractures will yield better values.

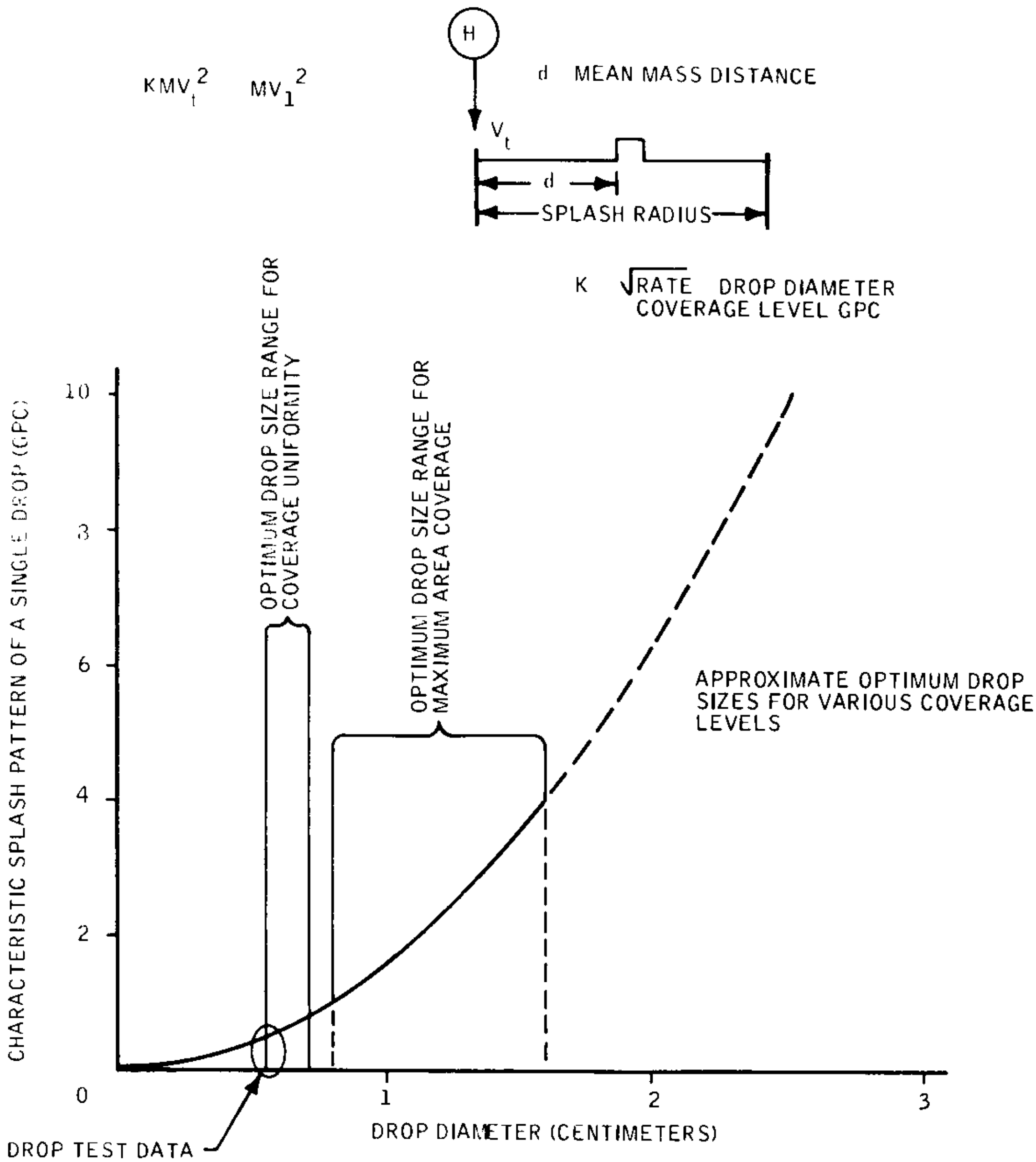


Figure 31. Estimate of Optimum Drop Size Based on Impact Energy to Lateral Energy

5. Ice

Ice has been suggested for retardant usage because of its:

- Superior cooling capability
- Superior airdrop survivability.

The cooling capacity yields about 20 percent more cooling per weight than water because cooling in the fire environment is dominated not by the heat of fusion but by the heat of vaporization. (This advantage is somewhat less if salt water/retardants are considered.)

Ice can take forms ranging from flakes to hailstones. For flakes, the time of fall is long compared to the melt time, but this ratio reverses as the area/mass ratio of the shape decreases.

Preliminary evaluation indicates that, even assuming a high melt rate, a hailstone 1.6 inches in diameter will lose only 50 percent of its solid volume in a drop of 1,000 feet. However, traversing a 10-foot flame in 0.1 second, this hailstone will only transfer 7.4 gram-calories from the flame. Nor will the hailstone be effective on aerial fuels because no more than 50 percent of the volume is available as liquid assuming no loss from stripping. The solid stone will simply penetrate the aerial fuels.

Nevertheless hailstones may be effective against litter as the solid will deliver a thin layer of retardant to the floor beneath the canopy.

The ice flake has a potential advantage in preforming uniform droplets. Figure 32 shows schematically the relationship of ice crystals to slowdown and the melt time to form essentially predesigned manufactured droplets of uniform size.

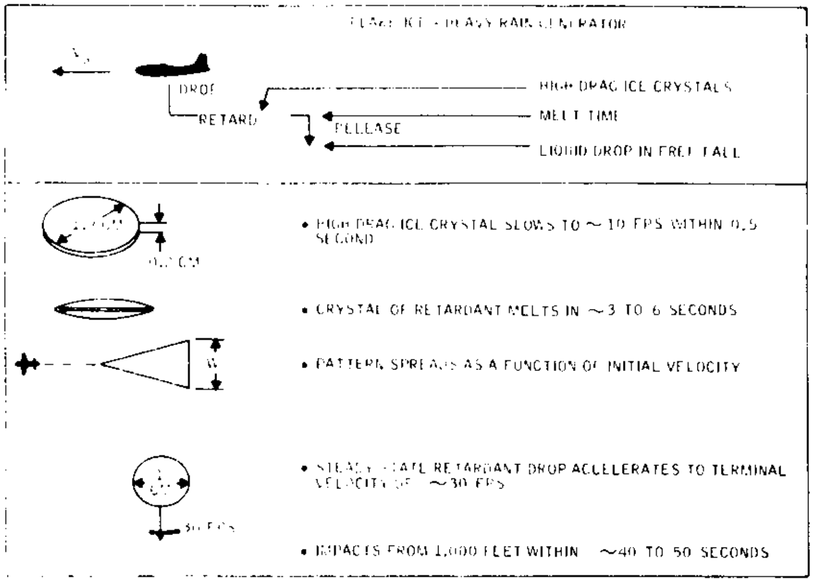


Figure 32. Relationship of Ice Crystals to Slowdown and Melt Time to Form Droplets of Uniform Size

Consultation with North Star Ice Equipment Co., Seattle, Washington, on high-rate ice making equipment shows an approximate linear relationship of equipment cost to rate on the order of $1,700 per ton per day. The cost of ice runs at about $1 per ton, or about $0.022 per gallon. The equipment cost is compared with aircraft delivery rates in Figure 33.

It is apparent from these data that practical equipment cost values must be based on a three-for-one production-to-use basis, in other words, 24 hours of production to support an 8-hour fire day.

The marked point on the vertical scale represents a large portable unit with a 180-ton-per-day capacity. This equipment can be mounted on two flat-bed trucks, costs $300,000 plus truck costs, and is potentially leasable during the fire season. Such equipment could be used on remote location for helicopter support. However, the relatively low rates compared with helicopter operations, and the uncertainty of the location for remote operations prior to the fire,

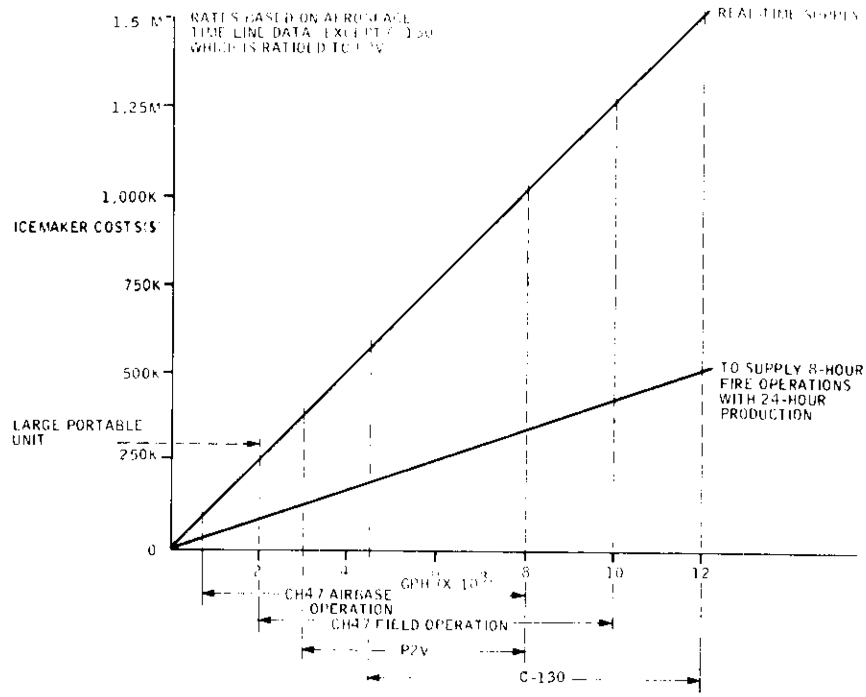


Figure 33. Icemaker Equipment Costs to Support One Aircraft

suggest that it is impractical because substantial quantities of the first day's capacity must be trucked in or additional units must be supplied. Since first-day operations are critical, it does not appear practical to consider this equipment for operation from the field. This is not a severe limitation because the ice concepts have little value in the helicopter delivery conditions.

North Star ice-making equipment is not the only equipment that could be considered, but it is a well designed, high-rate ice maker that produces flake ice and has the ability to handle salt water (presumed equivalent to retardant). It was not considered necessary to determine competitive equipment costs because it appears that a large cost reduction would be required to achieve a practical fixed facilities cost. Specifically, the cost of the ice-making equipment to support one P2V would range from 2 to 3 times the cost of the aircraft.

C. CONTAINER DELIVERY

A methodology for concept formulation of contained drops was developed. Two independent aspects of the investigation were recognized and defined: the operational and the logistic.

The operational features of prime interest were:

- Retardant dispersion technique
- Container size
- Container design.

1. Dispersion Techniques

Retardant dispersion techniques for this level of study were defined as natural and forced. Natural dispersion is that obtained by releasing the entire container volume to the atmosphere or allowing it to break on impact without energy input to break it up or impose some initial velocity. Forced dispersion is defined generally as a technique for increasing the horizontal spread of retardant beyond that obtainable by natural means. Enhancement of vertical spread was considered less important because gravity would provide this feature in any dispersion mode.

Two specific forced dispersion concepts were established for additional definition. The first concept consists of spherically symmetric dispersion from a central point as would be obtained by a gas expanding within a volume of retardant. This concept should be amenable to simple modeling to determine the critical variables and the degree to which uniform coverage can be obtained. The second concept consists of a nozzle or a collection of nozzles located around the container surface to provide lateral dispersion. The container would require pressure to provide flow through the nozzles. Again, the concept should be amenable to simple modeling.

In both concepts, dispersion was considered to be of low energy to prevent making an aerosol of the retardant with consequent excessive evaporation.

2. Container Size

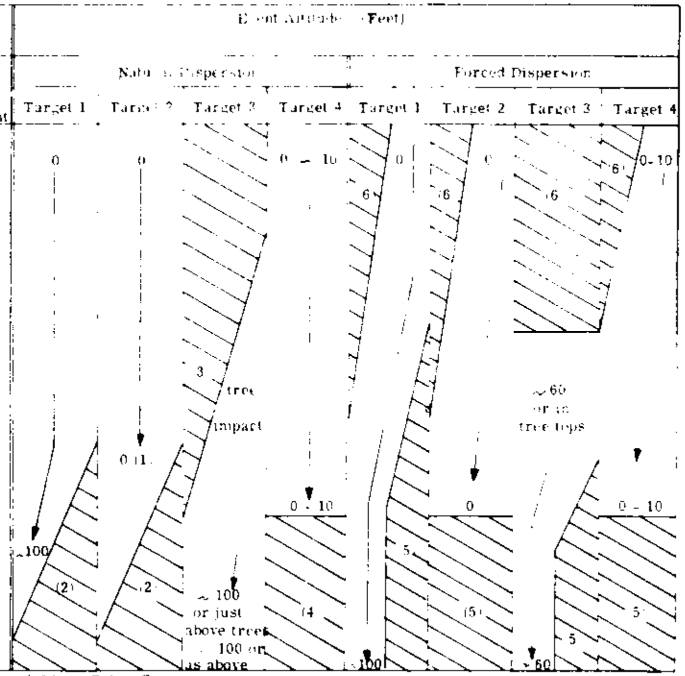
The size of the container was found to be the most significant independent variable. The event altitude, container design, target effects, and logistic aspects can most easily be discussed in terms of container size. The size range considered was an unrestricted as possible to allow broad understanding of the effects of its variation. The lower limit was approximately 0.5 gallon because previous work had already considered smaller containers. A 100-gallon container was chosen as an upper limit because it is the largest container that could be considered as movable and stowable in an aircraft.

Estimates of the operational aspects of the generalized container concept as dependent on size are summarized in Table I. These estimates were somewhat subjective because they were assessed prior to detailed evaluation using target effects models. The following paragraphs summarize the rationale presented in Table I.

The number of containers for a full aircraft load was approximated on the basis of a weight rather than a volume limit. These numbers have a very large range, depending on the size of the individual container. As stated earlier, the logistic aspects have not been considered in detail, and consequently the question, for instance, of stowage of 10,000 half-gallon bags in the C-130 has not been addressed.

Table I. Operational Characteristics of Container Concepts

Container Size (Gallons)	No. of Containers For Full Aircraft Load			Container Design	
	C-130	P2V	CH47	Material Estimate	Parasitic Weight Percent Total Weight
0.5	10,000	6667	3960	3-mil Polyethylene	1
1.0	5000	3333	[illegible]	5-mil Polyethylene	2
5	1000	667	396	Molded Polyethylene	3
10	500	333	198	Fabric Reinforced Plastic	4
50	100	67	40	↓	5
100	50	33	20	Rigid Wall Structure	6

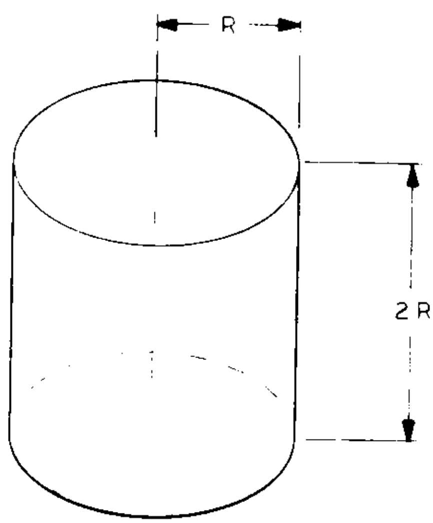


Target 1-Grass, Target 2-Chaparral, Target 3-Douglas Fir Crowns, Target 4-Litter Below Crowns.

NOTES:
(1) Shaded areas relate compliance over the size spectrum.
(2) Based on low capture cross section to horizontal dispersion and high capture cross section to vertical dispersion.
(3) It is assumed that large volumes are not as efficient as small volumes in dispersion by splash.
(4) Very small volumes will probably have a low crown impact frequency and are impractical in comparison to large volumes for air eventing techniques.
(5) Small volumes have better chance of getting through crowns. Additionally, the capture cross section to horizontal dispersion is probably too large to make large volumes feasible.
(6) The efficiency of forced dispersion probably decreases with increasing size of container.
(7) Forced dispersion hardware costs probably make very small container sizes not cost effective.

Preliminary material estimates are specified in the container design column. The material specified is sufficient to support the associated volume of retardant, but in general is not sufficient to support a stack of containers. Estimates are based on the tensile stress developed in filled cylinders as given in Table II Comparative strengths of polyethylene are given in Table III The parasitic weight estimate is based on a simple pillow bag for the 0.5-gallon volume. For the larger sizes, a subjective increase is shown to account for structural features required for reinforcing and handling.

Table II. Maximum Tensile Stress in Filled Cylinders



Volume, V (gallons)	2R (inches)	Tensile stress, T (pounds/inch)
0.5	5.28	0.27
1	6.65	0.43
5	11.38	1.26
10	14.35	2.00
50	24.5	5.85
100	30.8	9.25

Table III. Comparative Strengths of Polyethylene Film

Film Thickness (Mils)	Tensile Strength (Pounds/inch)
1	0.6
1.5	0.9
3	1.8
5	3.0

NOTE: Based on 600-psi ultimate at 90 degree elongation for low-density material.

In projecting the most appropriate event altitude for each container size as a function of dispersion mode and target, the following qualitative guidelines generally apply. (The term efficiency is defined as the area covered to the desired retardant density gpc divided by the potential area coverage. The potential area coverage is 100 times the container size in gallons divided by the density desired. This concept of efficiency takes into account the disadvantage of either too sparese or too dense coverage.)

1. The efficiency of natural dispersion due to impact (splash) decreases as the volume of the container increases. Moreover, the impact surface must be fairly flat, hard, and impervious to obtain good coverage by splash.

2. The event altitude at which the dispersion efficiency is maximum will vary with container size and generally is higher for larger sizes.

3. Increase in velocity will increase dispersion.

These guidelines, together with the four fuel characteristics, were applied in an attempt to establish ranges of event heights as shown in Table I

3. Logistics

Figure 34 shows the volumetric requirements for various delivery rate capabilities. It represents the storage volume required to supply one day's operation by a single aircraft. The line showing the storage for rigid filled or self-filling containers represents the total volume (in the case of filled containers), or the dunnage (container) volume for self-filling devices. Separate storage of the retardant in the latter case would approximately double the total. Compressible foam containers considerably reduce this space allocation to containers.

Rates of delivery for current air and helitankers range from about 20 to 8,000 gallons per hour for an 8-hour flight period. Aircraft of primary interest in this study, however, provide potential rates of 700 to 12,000 gallons per hour. Further, the high-altitude capability sought should extend the fire fighting day to almost 24 hours.

From the standpoint of this study, two values are of interest: (1) the time to achieve the first load; (2) the ability to resupply at rates compatible with aircraft delivery. The daily or 24-hour delivery capability is not of major

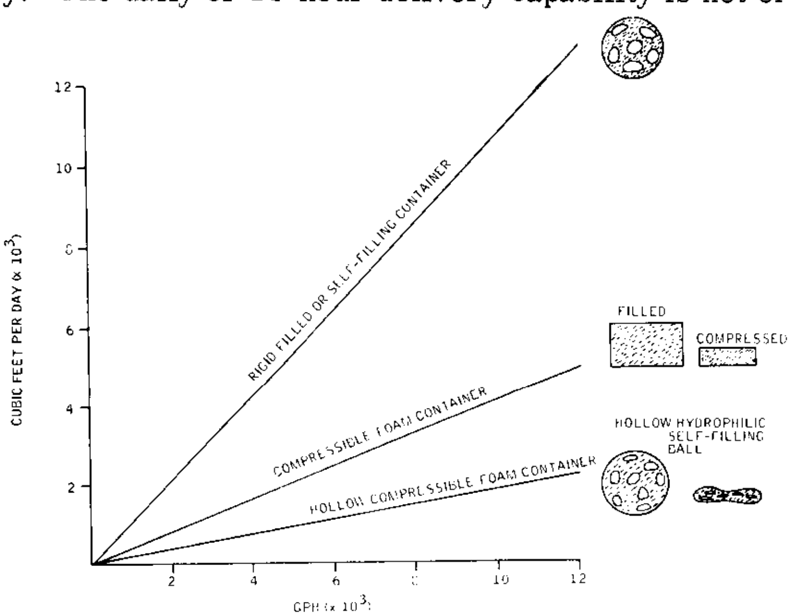


Figure 34. Volumetric Requirements for Various Rate Capabilities

interest because more effective delivery will potentially reduce the total volume required to suppress all but the most severe fires. It is nonetheless realistic to assert that the total volume to suppression will be reduced in direct relationship with the rate of application in the early stages of fire operations. The key rate data are tabulated for the baseline aircraft below:

Aircraft	Load	Rate Capability* Minimum (gph)	Rate Capability* Maximum (gph)
C-130	4,500	4,500	12,000
P2V	3,000	3,000	8,000
CH47 A	1,800	700	8,000
CH47 B	1,800	2,000	10,000

*Rates based on Aerospace data, except C-130 is ratioed to the P2V.

A - Operating from permanent base

B - Operating from remote base.

Using the above factors, there are several significant values to consider in evaluating the resupply rate capability of containerized delivery:

(1) Time to achieve first load

(2) Amount of equipment to resupply at rate

(3) Cost of equipment to resupply at rate

(4) Amount of equipment plus storage to resupply at 3:1 ratio

(5) Cost of equipment and storage to resupply at 3:1 ratio.

These value considerations reflect various tactical options or resupply conditions. Factors (1), (2), and (3) reflect the practicality of setting up a remote station when the fire situation arises (i.e., with equipment brought in from a central location to either the operational airbase or a remote helitanker reloading point) and apply to the first day of operation. Items (4) and (5) reflect on the practicality of a fixed installation plus a 16-hour storage reserve, with equipment permanently installed or brought in on standby for the fire situation.

The fixed cost of ground-based equipment for producing expendables for use in fire retardant delivery is, in general, an insignificant contribution to the cost of delivered retardants, although it is a factor in the decision to implement a given system. The reason for this is that the equipment is not heavily used. It is typically required to provide about 100 aircraft loads per year, requiring a maximum of about 300 hours per year of operation compared to 2,000 hours in single-shift production during one year. Consequently, the equipment becomes obsolete before it wears out. Arbitrarily using a 20-year obsolescence rate, the fixed equipment costs may be prorated over 2,000 aircraft loads to provide a worst-case cost estimate. Under these conditions, $1 million fixed initial expenditure would result in only a 15-cent increase in the delivered cost of a gallon of retardant. This increase is easily offset by small potential increases in effectiveness. On the other hand, to equip 10 bases with facilities costing $1 million each would clearly be prohibitive. It is, therefore, concluded that initial equipment costs should not be prorated into costs on a per-gallon basis, but carried as a separate (approximate) evaluation factor on which decisions to accept or reject a given concept can be made.

4. Patterns

A canister can protect the retardant fluids in high-altitude delivery so that losses are minimized, and can provide a method of using thin retardant that could be advantageous in certain fuels. From safety considerations, the small container has many advantages over larger sizes. Thus, the main emphasis was on the small container.

One of the additional requirements on the patterns other than density is the need for a continuous line. Therefore the contained system must be capable of producing the required densities with the continuous treatment requirement. How these two requirements of coverage and density relate is the first element of the study.

This idealization is shown in Figure 35. An actual canister breakup will be spread over an irregular area after breakup or release, and it is convenient to assume that the rate can be represented as a symmetrical shape as shown in Figure 35a. The next step in idealizing the breakup is the cylinder shown in Figure 35b. This idealization is for a coverage area (A) and for a rate (g) in gallons/foot^2. Thus to design a contained system, these two parameters are required for the single canister; alternately, to evaluate a known system, these two factors will relate the performance of a single canister to the pattern developed with such a system (Figure 35c).

The development by Germond[9] can be modified for the retardant delivery and pattern simply by changing the appropriate terms. If each canister has the right circular cylinder representation with effective radius(R), then for any small portion of a target of radius (R) to lie outside the effective area of the canister, that canister must land at a distance as great as R + r from the center of that portion. If each canister is as likely to strike at one point inside the target as another, then the probability (P) of this small area remaining untouched is:

$$P = 1 - \frac{\pi(R+r)^2}{C}$$

where C is the area of the vegetation target.

The probability (P_N) that all N canisters miss this area is:

$$P_N = P^N$$

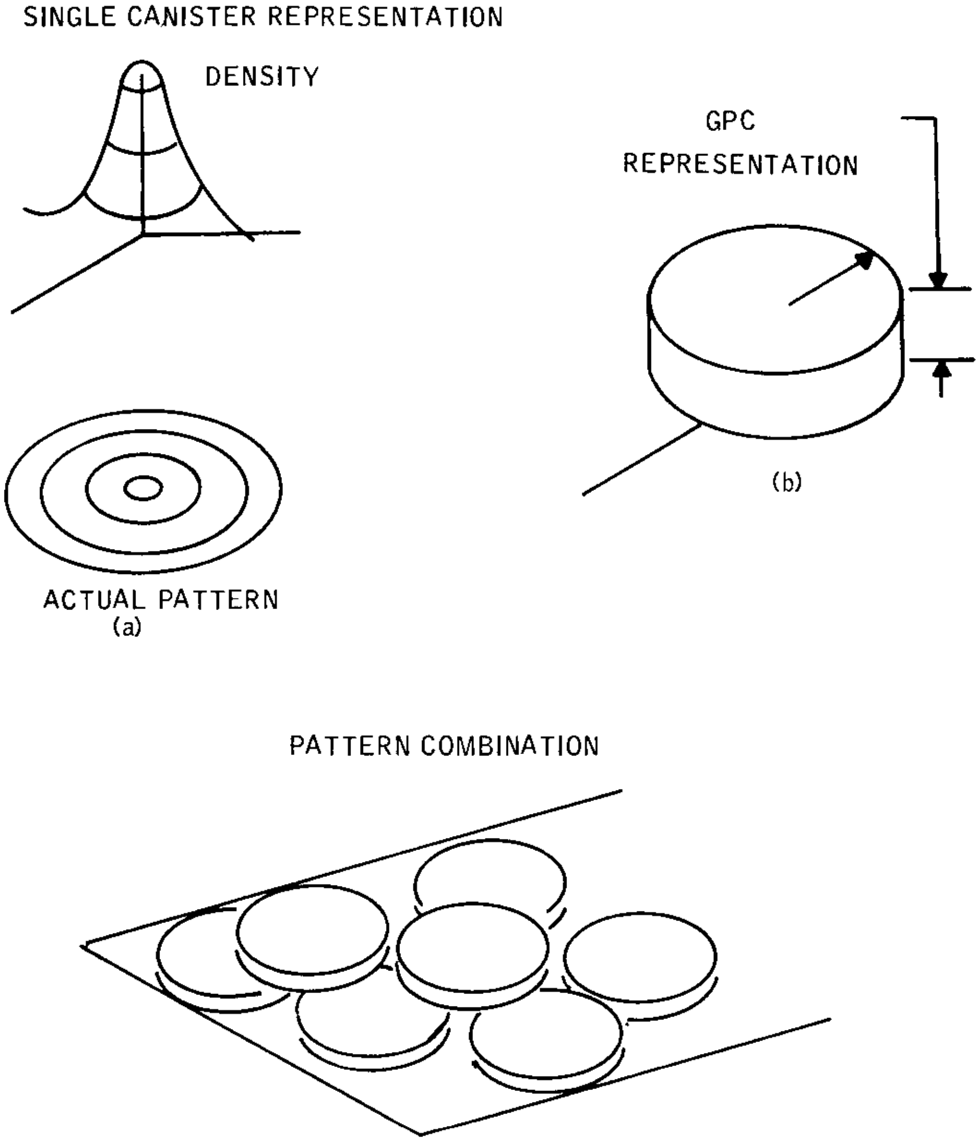


Figure 35. Representation of Continuous Coverage by Means of Individual Splash Patterns

Assume that the target comprises a number of small areas, and if the possibility that the target area is covered without overlap is not considered, then the number of such small areas is $C/\pi r^2$. The expected number of these small areas not covered is:

$$\left(\frac{C}{\pi r^2}\right)(P_N), \text{or } \frac{C}{\pi r^2}\left[1 - \frac{\pi (R+r)^2}{C}\right]^N$$

The expected area not covered by retardant is the product of this quantity and the area of these small sections

$$E \text{ (uncovered area)} = C \left(P_N\right), \text{or } C\left[1 - \frac{\pi (R+r)^2}{C}\right]^N$$

If these sections are very small, the number increases without limit; however the expected area uncovered will approach a limit

$$E \text{(uncovered area)} = C\,[1 - \pi R^2/C]^N$$

which can be approximated by $C\,e^{-NA/C}$ if the area for each canister is small compared to the total area:

$$E \text{ (covered area)} = C\,(1 - e^{-NA/C})$$

To apply the Germond formula, consider the coverage of a vegetation stand (C) with canisters of a known area (A) so that the fraction untreated is 1.0 percent:

$$0.01 = e\,\frac{-NA/C}{C} \text{ so that}$$

$$NA/C = 4.61$$

This means that the number required is:

$$N = (4.61)(C)/A$$

Normally, the treatment of vegetation stands is specified in terms of gpc, and to modify the Germond formula for this requirement, consider the two possibilities that can be used to define continuity of pattern:

- Minimum rate of retardant application is the equivalent continuous level; i. e., a pattern has a minimum of 2 gpc with 2 percent coverage.

- Average rate of application is the equivalent average rate to the continuous level, i. e., average rate of 2 gpc with 2 percent coverage.

Of these two possibilities, the easiest requirement to meet is the latter, and this would limit over-treatment of the bulk of the pattern specified by the first definition. With this specification, the average rate in the pattern is:

$$G = N\, g\, A/C$$

where

g = rate of a single canister
A = area of a single canister
N = number of canisters
C = pattern area.

The ratio of G/g is the value of the exponential set by the fraction covered.

This relationship is useful in relating the optimum pattern area for a single canister of known size. Figure 36 shows the relationship for three pattern application rates.

Some of the important factors from this graph are:

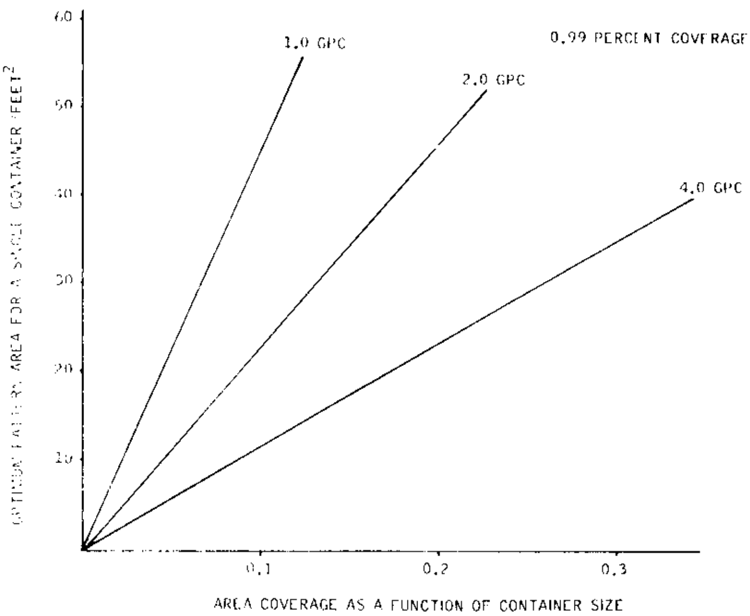


Figure 36. Area Coverage as a Function of Container Size

- The average level in a pattern has distinct pattern breakup for the single canister; e. g., a 0. 1-gallon container must be capable of covering 46 square feet at 1 gpc, or 11. 5 square feet at 4 gpc.

- A compromise value at 2 gpc is probably the way the container would have to be designed.

- Spreading of the fluid over the area for optimum pattern size is appreciable. At 23 square feet this would be a continuous thickness of t = 23. 1/(144) (23) = 0. 007 inch.

- The key issue in implementing such a concept is an inexpensive method of dispersing the retardant on impact.

Another key issue in contained delivery is the extent to which a dispersing system can distribute retardants in the vegetation stand. A canister that distributes cargo on impact by lateral motion can be inhibited within a stand. As an example of this kind of reduction in spread, Honeywell has data indicating the reduction in lateral motion as follows:

Environment	Relative Travel
Lawn	1.00
Light Pine Forest	0.74
Heavy Forest	0.32
Savanna	0.54

The matter of breakup in the vegetation stand could be studied with the Honeywell Munition Canopy program; however, there is sufficient information on this type of entry to suggest that there are significant problems in producing breakup in aerial vegetation. It appears that contained delivery would be applied mainly to special purpose conditions that required delivery of a thin retardant on low-level fuels under a canopy.

5. Concept Evaluation

Some specific drop concepts and assessments of their characteristics appear in Appendix A. In general, they appear to be unnecessarily complex, involve a heavy penalty of parasitic weight and are unduly expensive. However, the plastic pouch, delivery of dry salts, and airburst container may be considered further.

a. Plastic Pouch -- Contained delivery in plastic bags requires either a central packaging facility or an on-line pouching operation. Rates of current automatic equipment for filling and sealing baggies are shown with aircraft rate capabilities in Figure 37. Current rates were estimated as a straight line between two data points, 400 one-ounce packets per minute, and 30- to 60-quart pouches per minute. The time-limiting factor is the time to heat-weld and cool the seal by impulse sealing, dielectric, or radio frequency techniques, depending on the material.

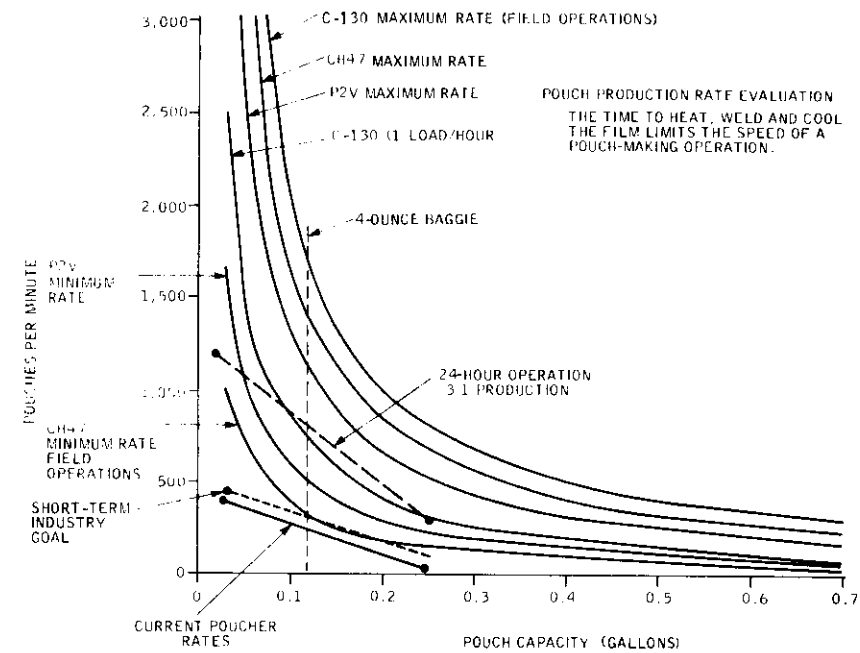


Figure 37. Poucher Equipment Production Versus Aircraft Rate Capability

The analysis shows the capability of a single-head poucher. Approximate cost is $12,000 per poucher. To support a P2V at maximum rate would require an initial expenditure of about $26,000 per aircraft if the 4-ounce, on-line bagging approach is selected. These costs do not appear prohibitive, although the amount of equipment to support a helicopter in field operations probably makes the approach impractical for this application.

b. <u>Delivery of Dry Salts</u> -- Since fire retardation in a long-term sense is based on the concentration of salt on the fuel, a considerable increase in coverage potential theoretically can be achieved in terms of payload weight. This is shown in Figure 38 as a function of the increase in area as the salt approaches 100 percent of the retardant weight.

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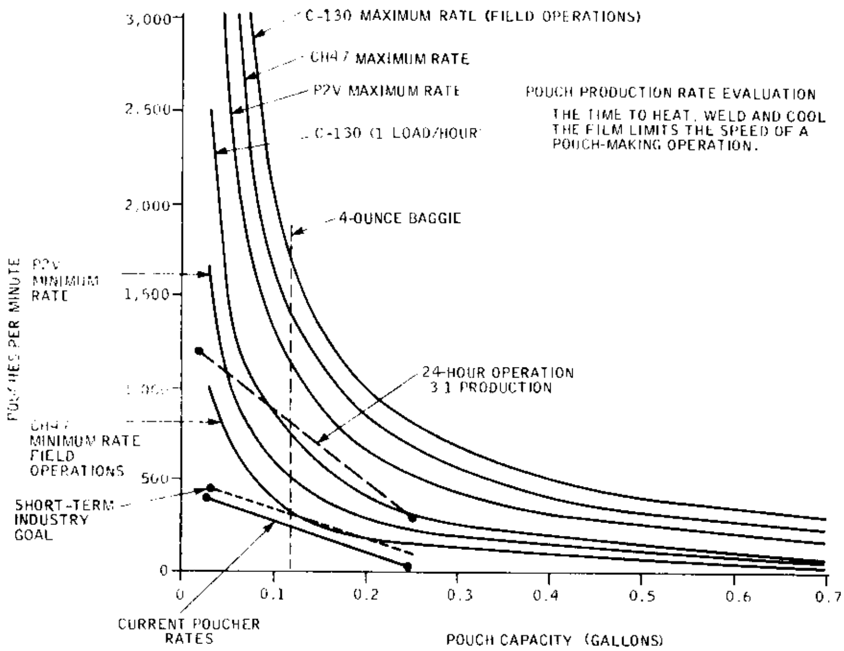

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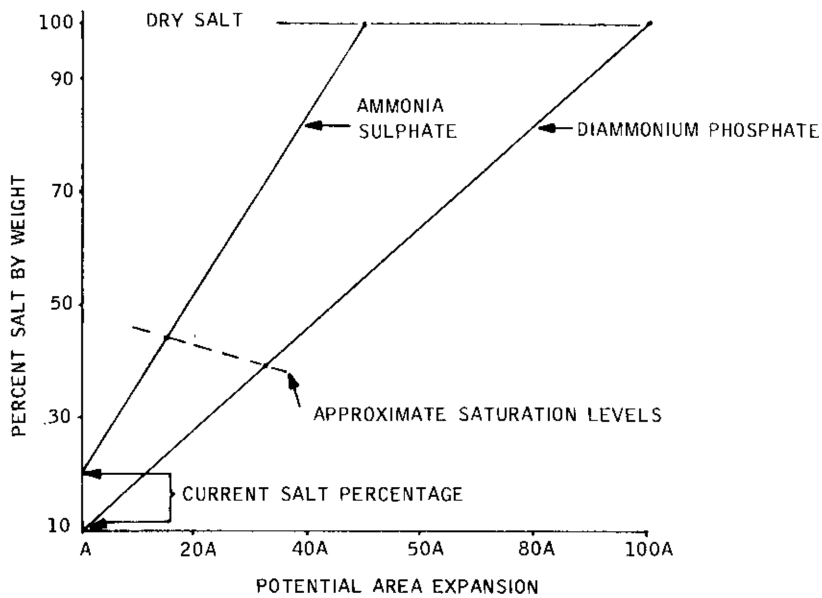


Figure 38. Potential of Dry Salt Fog Generator

Since dry salts ground to particle sizes with a coating affinity for fuels will settle slowly and drift considerably, such systems are limited to groundburst containers. The principle is shown in Figure 39. Energy must be imparted to the salt at impact to fracture the load. Three techniques have been used for this type of operation in the past: implosion, in which a converging explosive shock wave breaks up the powder mass; explosion, in which the shock energy moves outward; and the expanding cylinder, in which two cylinders rapidly separating bring air shocks into the contained mass. Implosion is generally the best method for generating the desired cloud, but is the most expensive to implement. Explosion is next in efficiency, but shares the explosive hazard of the implosion device. The cylinder is least efficient, but offers the potential for nonhazardous operation.

Key issues are the ability of a dry salt (without liquid binders) (1) to attach to the fuel surfaces, (2) to achieve sufficient crosswind spreading through the fuels to accommodate the volume released efficiently, and (3) to be safe. It

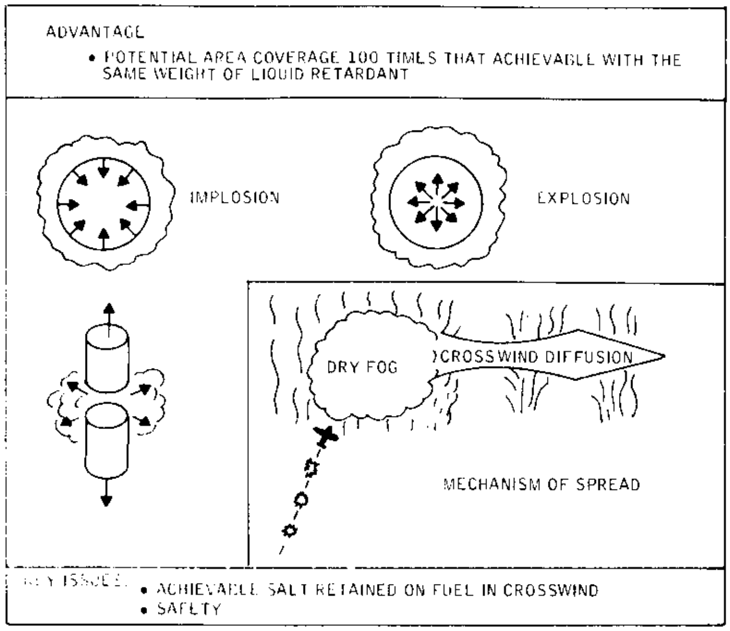


Figure 39. Dry Salt Fog Generator

is also possible that such a device could be used as the equivalent of an aerially disseminated dry fire extinguisher, with the products drawn into the fire by convection.

If wetted salt is required to achieve fuel adhesion, liquid aerosol generation (Figure 40) may also be considered. However, in the low-humidity, high-temperature environment conducive to fire activity, small liquid particles will soon become dry salt with the same limitations as the dry material.

The primary difficulty in achieving appropriate area coverage with dry salt or liquid aerosol containers is the amount of area expansion required, i.e., up to 100 times that required from a similar volume of conventional retardants. This requirement is difficult enough with the concentration currently employed. The techniques are therefore rejected in terms of the current study.

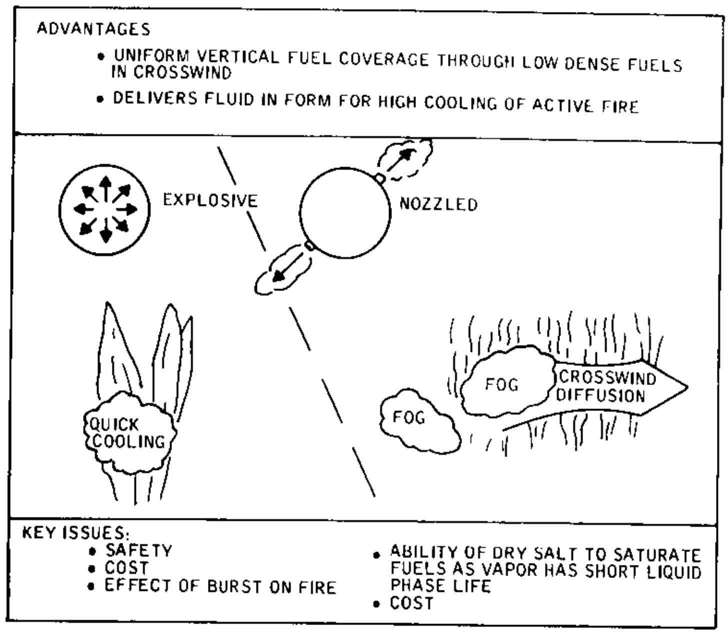


Figure 40. Liquid Fog Generators

c. Airburst Containers -- The airburst container, a large container of the type shown in Figure 41, essentially creates a small salvo drop at an altitude some distance below the aircraft.

The concept was advanced for the following reasons:

- Ability to offset aircraft velocity prior to exposing the retardant.
- Ability to reduce exposed time of fall and consequently aerodynamic losses and wind errors.
- Ability to deliver from unmodified tail-loading aircraft using cargo drop techniques.

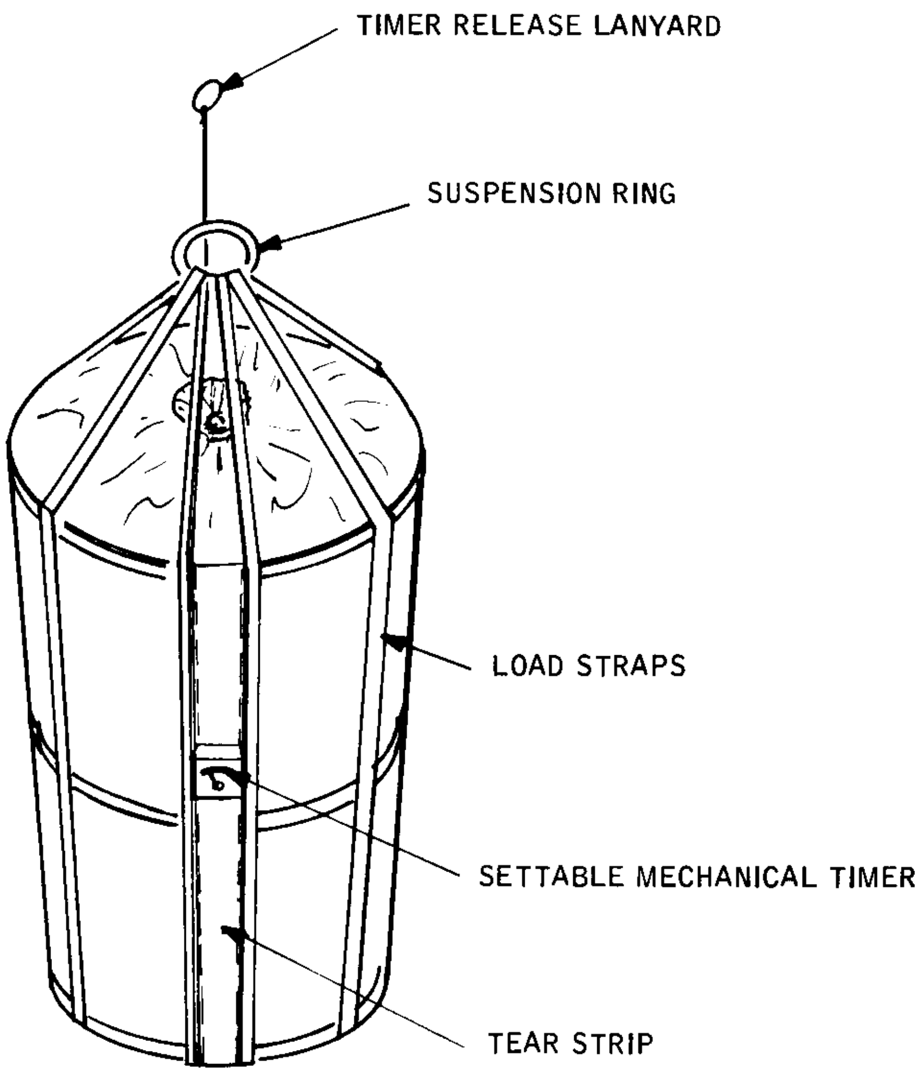


Figure 41. Airburst Container

It is rejected for near term applications for the following reasons:

- Protection of the retardant from aircraft velocity is not a significant value. Indeed, the velocity at opening must be sufficient to generate pattern area expansion.
- The generation of uniform patterns from relatively large containers results in considerable overlay.
- Accuracy, though potentially achievable in a range sense and essentially unaffected by crosswind, cannot be achieved at higher altitudes with the relatively narrow patterns thus developed.
- Potential ground safety problems require failsafe and consequently expensive timing operations.

D. CONCLUSIONS

The fundamental issue in the tradeoff between containerized and cascade delivery resolves itself to the basic question:

> Is the improvement in accuracy, survivability, and momentum afforded by containerized delivery sufficient to offset potential inefficiencies in meeting terminal requirements, and if so does it justify the potential complication of logistics?

The results of a number of conceptual and analytical studies on this issue are summarized in Figure 42. In the hierarchy of terminal retardant forms, the following conclusions are justified:

- Fog-like coverage effective in crop spraying produces a fragile cloud that will not survive altitude, nor does it yield the capability to drip and run that is important for uniform coverage of vertical fuels.

- Logistics limits associated with contained delivery are easily offset by small cost effectiveness increases in all but remote base operations.

- Use of stored-energy containers to enhance splash patterns for containers imposes unique ground-handling procedures for safety, precluding their acceptability.

It is concluded that containerized delivery is comparable with the capabilities of advanced cascade, where 4-gpc coverage must be achieved from altitudes above 800 to 1,000 feet for large-capacity aircraft or for smaller aircraft that must fly high.

Because most of the full range of delivery requirements can be achieved using existing retardants, emphasis in the near term should be placed on advanced cascade and rheological improvements. The additional capability of containerized delivery from very high altitudes should still be considered in the future, particularly if sophisticated aiming capability is included in the aircraft.

		RETARDANT FORM		LOGISTICS PENALTY	SURVIVABILITY	MOMENTUM	FUEL'S COVERAGE	UNIFORMITY OF COVERAGE	
IMPACT ENERGY	RHEOLOGICALLY DETERMINED	FOG-LIKE	1 MICRON TO 2 MILLIMETERS		MINIMUM	NONE	FAIR	POOR	UNACCEPTABLE
		RAIN-LIKE	3 MILLIMETERS TO 1 CENTIMETER	NONE	GOOD	FAIR	NEAR OPTIMUM	NEAR OPTIMUM	BEST FOR 1 TO 4 GPC, MODERATE WIND
		HAIL-LIKE	2 CENTIMETERS TO 5 CENTIMETERS	NONE / MODERATE		FAIR / EXCELLENT	NEAR OPTIMUM / FAIR	POOR	BEST FOR 4 GPC PLUS OR HIGH WIND
	PHYSICALLY CONTAINED	CONTAINED	6 CENTIMETERS TO 10 CENTIMETERS	MODERATE	EXCELLENT	EXCELLENT	FAIR		
STORED ENERGY		AEROSOL CONTAINERS	8 CENTIMETERS TO 10 CENTIMETERS	MAJOR			POOR	MODERATE	UNACCEPTABLE
		BURSTING CONTAINERS	8 CENTIMETERS TO 10 CENTIMETERS						UNACCEPTABLE

Figure 42. Terminal Retardant Form

IV. MODELING OF RETARDANT DELIVERY

In this section, the physics of retardant breakup will be discussed, along with the modified Mac Phearson simulation, Weibull pattern characterization, and methods for extended models.

Understanding of the physics of retardant breakup involves several complex hydrodynamic instabilities occurring both simultaneously and in phases. Figure 43 traces the stages of operation.

First, door opening shapes the emerging fluid. Drag deceleration deflects the fluid and introduces amplifying instabilities of two types -- Taylor instabilities on the front surface and Helmholtz instabilities on the lateral or side surfaces[10][11]. Taylor instability causes the fingering effect on the front of the liquid mass. Helmholtz instability produces the wave-like motion on the sides of the mass. The emerging liquid surface also expands to the sides near the front and becomes effectively shorter as flow replaces some of the deceleration. The amplitude of the Taylor instability increases with time until air pressure on the front surface breaches the liquid mass causing a series of reactions that end in the explosive-like breakup of the liquid. Rheological properties of currently used retardants damp out higher frequency instabilities and cause formation of larger droplets than would be produced with water alone. The rheological properties also help establish the time to breakup.

Management of this process by proper design of tank parameters to achieve desired delivery modes is the basic objective in improving cascade delivery.

This section describes the physical and mathematical basis for a first principles approach to generalized simulation of the phenomena and the empirical model simultaneously developed for relating tank performance parameters to

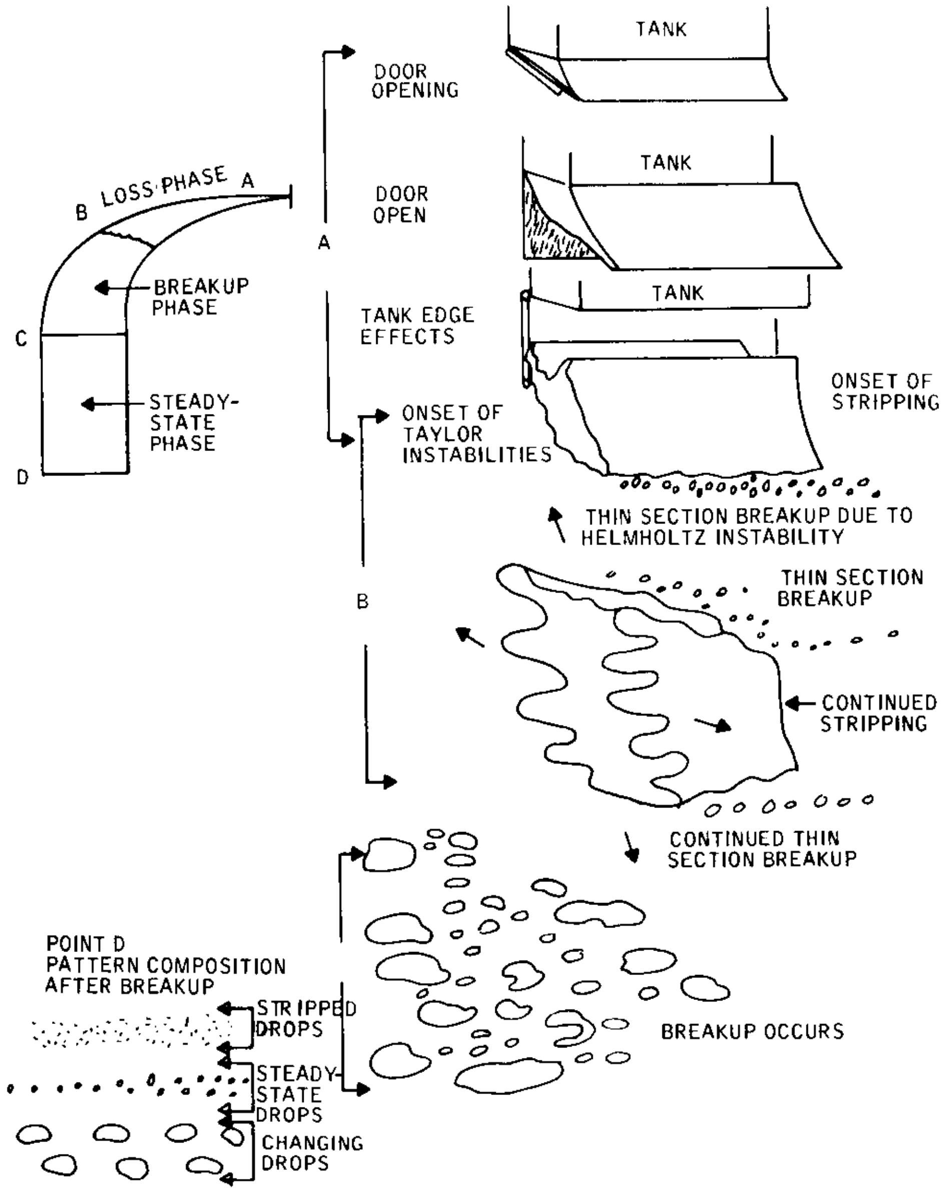


Figure 43. Schematic Representation of the Breakup Process

pattern formation. The empirical model was developed because certain aspects of the physical representation are currently intractable mathematically. There is, however, a traceable similarity between the simulation model and the theoretical treatment.

A. PHYSICS OF RETARDANT BREAKUP

The theoretical understanding of the hydrodynamic process outlined above differs significantly from the intuitive view in two significant respects, both of which are supported by the physics involved and considerable study of actual test results. These differences are:

1) The application of classical stripping or atomization theory (represented by Taylor-Priestly stripping from the outer surfaces of the mass) is not a dominant effect. The amount of material stripped is related to the relative velocity between the retardant mass and the surrounding air flow. The mass loss due to this phenomenon is not a significant portion of the released volume.

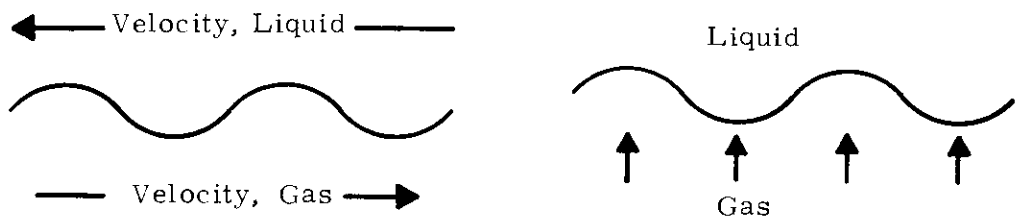
2) The breakup process is an acceleration-dominated phenomenon. Although the accelerations are small compared with those associated with shock dynamics, their effect is shock-like due to a nondimensional Bond number relationship[12]. This number is a ratio of inertial forces to surface tension forces. The Bond number theory suggests that small drops subject to very high accelerations and very large drops subject to small accelerations behave similarly.

When these two factors are realized, the visually perceived characteristics of a retardant are substantially accounted for as are most of the measured values associated with the process.

1. Interfacial Instabilities

(Primary Reference - J. Birkhoff, Garrett, 1. "Helmholtz and Taylor Instabilities" American Math Society Conference on Hydrodynamic Instability and 2. "Taylor Instability and Laminar Mixing").

The dominating mode of breakup is due to the growth and interaction of two instabilities on the interface of fluids in relative motion. These are commonly called Helmholtz and Taylor instabilities. Flows are illustrated in the following sketch.



Helmholtz Instability
(Instability of Vortex Sheets)

Taylor Instability

The theory of instability is based on the normal mode concept that develops oscillation of the surface as a linear superposition of normal modes. A linear differential equation is formulated to represent the magnitude of the amplitude of the kth normal mode, i.e.

$$\frac{d^2\,(A\,(t)\,)}{dt^2} = A\,(t)\,S\,(k)$$

where $A\,(t)$ is the amplitude of the kth mode and $S\,(k)$ is a real function.

For the surface to be stable, i.e., the oscillations do not build up in amplitude with increasing time, it is necessary that $S\,(k) < 0$. This linear or perturbation theory amounts to a Fourier integral representation of the initial small disturbance in terms of the normal modes.

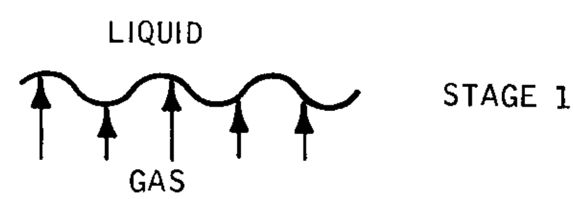
An initial sinusoidal disturbance goes through three successive stages:

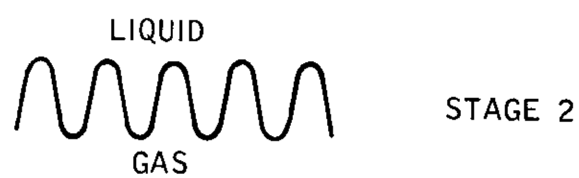
(1) Perturbation stage: the small initial amplitude grows exponentially

(2) Transition stage: the sinusoidal shape of the perturbation is lost and the amplitude continues to grow

(3) Asymptotic stage: a new mode of equilibrium develops.

These stages are shown in the following sketch.





PENETRATION BY AIR COLUMNS AT UNIFORM VELOCITY PROPORTIONAL TO $\sqrt{a - g}$ STAGE 3

The perturbation stage can be analyzed by using Kelvin's formula for S (k):

$$S(k) = \frac{\rho \rho' k^2}{(\rho + \rho')^2} (U - U')^2 - \frac{\rho - \rho'}{\rho + \rho'} (g - a) k - \frac{\sigma k^3}{\rho + \rho'}$$

where $k = 2\pi / \lambda$ is the wave number, U, ρ, U', ρ' are the velocities and densities of the fluids, σ is the surface tension, and a is the acceleration.

Three qualitative conclusions follow from this formula:

1. The relative tangential velocity of Helmholtz instability is a destabilizing influence.

2. Acceleration from lighter to denser fluid is destabilizing if its magnitude exceeds gravity.

3. Surface tension is a stabilizing influence.

These conclusions can be applied to the retardant breakup process as follows:

1. Helmholtz instabilities on the periphery of the fluid mass give rise to a stripping process on the boundary layer of the fluid mass. This effect can be estimated by the Taylor model[13][14]:

2. Taylor instabilities require a positive quantity in the second term of Kelvin's formula, that occurs when the component of gravity acceleration is less than the drag force on an elemental area of the retardant mass. The onset of instability occurs after the liquid mass has undergone major deformation due to aerodynamic shaping.

3. The fluid properties considered in the above model are density and surface tension; however, it can be shown that viscosity is purely a retarding property in that it reduces growth rate of unstable waves and thereby adds damping.

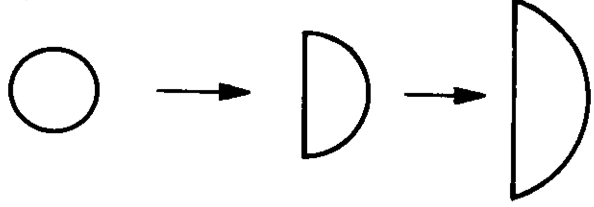
4. Calculation of the shape of the fluid mass during the asymptotic stage where the spike and bubble formation occur is only possible by means of complex computer techniques with limited applicability.

The Taylor instabilities have two additional states, the spikes have a Helmholtz instability and a final statistical asymptotic stage wherein the formation of droplets has been shown in some simulations. Only qualitative estimates of these kinds of phenomena are possible at the present time.

2. Free Boundary Fluid Mass Deformation

Tank and gating system parameters affect ultimate instability and breakup by influencing the shape of the initial fluid mass that is expected to have a great effect on the characteristic time for the onset of Taylor instability. This geometrical description of the fluid mass and its transformation to the onset of instability is at present untractable mathematically for rectangular tanks and multiple-tank arrangements. We may note, however, the geometrical effects on acceleration in the range of interest is substantially a function of tank length (or in a more general case, the instantaneous hydraulic head with respect to the velocity vector) as shown in Figure 44.

There is considerable evidence that deformation due to aerodynamic forces does occur, even though it is occluded in actual drops by the products of stripping. These types of deformation occur in bubbles rising in liquids and in water droplets in shock waves. Evidence of this phenomena in retardant delivery is in the photographic change of size in the intact fluid mass in large quantity drops. In particular, a 2000-gallon drop from the Aero Union B-17 increased in measured appearance approximately tenfold before breakup occurred. This increase in size can only occur if the same sequence of events occurs as shown below:



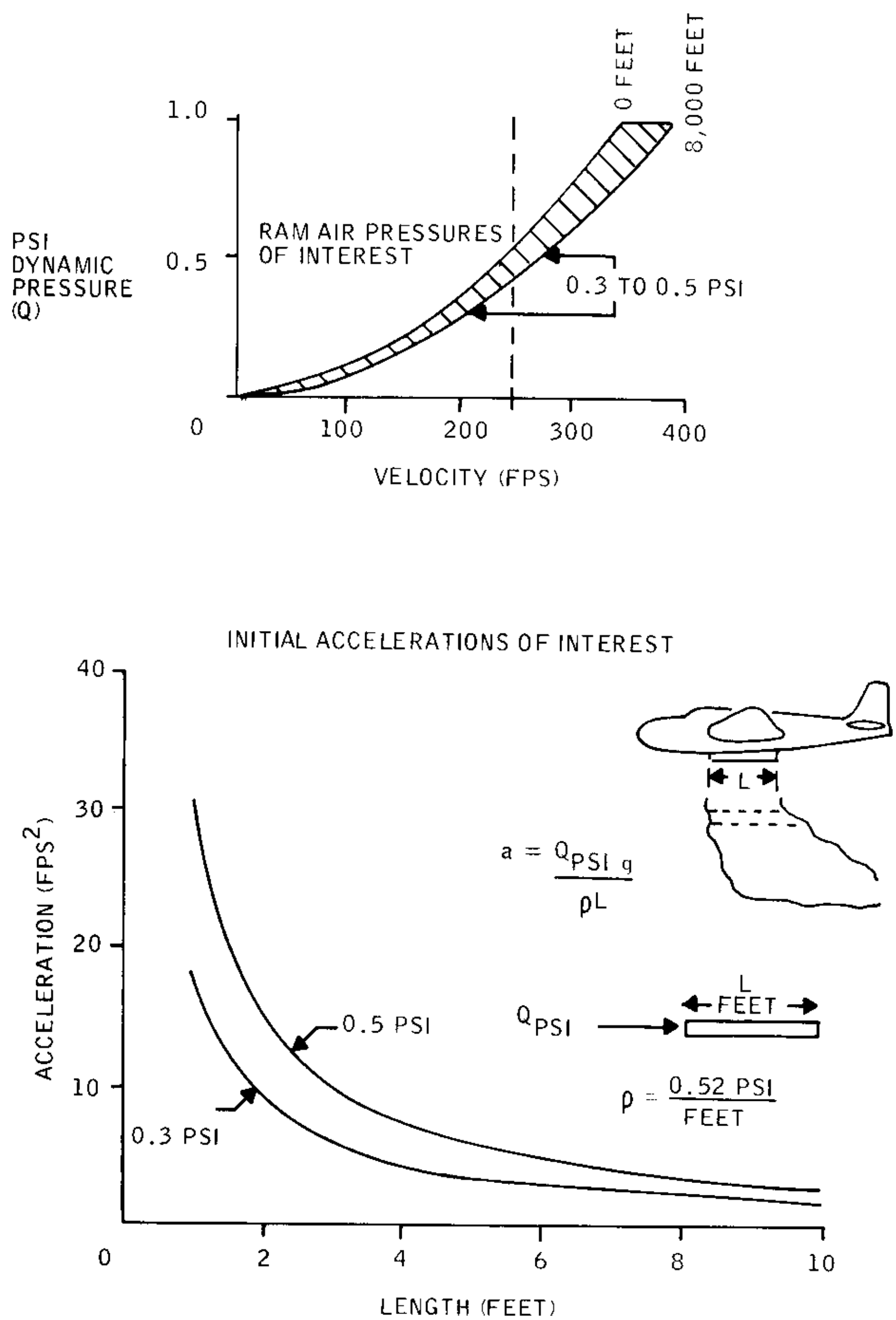


Figure 44. Accelerations of Interest

Specific evidence of this deformation in the same detail as in water droplets is not available due to the complexity of experimentation. This explicit information would be desirable to ensure complete confidence on the correspondence between retardant delivery and similar phenomena.

The real difficulty is the obscuration caused by the Helmholtz-related stripping processes. Because this type of behavior has been documented in several other situations that have similar aerodynamic conditions, and explicit evidence has been produced for these conditions, it will be assumed that the same phenomenon exists in retardant delivery.

The mathematical model for the surface deformation of bubbles was analyzed by Taylor[15]. He showed that the shape would be spherical on top of the bubble so that pressure on its surface is constant. This requires that the pressure due to flow equal the gravity component.

By Bernoulli's equation this is:

$$q^2 = 2gX$$

where X is the depth below the highest point, q is the fluid velocity relative to the bubble, and g is the acceleration due to gravity. Wind tunnel experiments on lenticular bodies verified that the pressure distributions were essentially those of spherical bodies.

Experimental evidence of the change of shaoe was obtained by Lane and Green[16], Engel[17], and by Simpkins and Bales[12]. The Lane and Green data were obtained on water drops at terminal velocity, the Engel data and the Simpkins data at supersonic velocity. Thus, there is a great body of evidence on the distortion of fluid masses in the airstream.

3. Droplet Trajectories

Three factors are important in droplet trajectories of retardants:

- Stripping and instability or breakup mechanisms
- Terminal velocities
- Effects of winds.

In the effects of these factors, the application of data from other droplet studies can be used with more assurance. The Weber and Bond numbers are a measure of the stability of a drop, and the breakup time can be estimated from the formulas of Wolfe and Anderson or from Bell Telephone studies[18]. Terminal velocity depends on the drop coefficient that relates to stable drop size and the amount of flattening. The effects of wind are easily predicted with simple spherical models because the effect will be large. (Refer to Figure 26.)

The Weber number is the ratio of the aerodynamic pressure to the surface tension pressure:

$$W_E = \frac{\rho_a \, U^2 r}{\sigma}$$

If the aerodynamic pressure is replaced by inertia pressure the Bond number results:

$$B_o = \frac{\rho_L \, r^2 g}{\sigma}$$

The Bond number is related to the Weber number by

$$B_o = \frac{3 \, C_D W_E}{8}$$

where C_D is the drag coefficient of the droplet.

ρ_a = air density

U = relative velocity

r = radius of equivalent sphere

σ = surface tension

ρ_L = Liquid density

Hinze has examined the deformation of a water droplet in potential flow and has developed formulas for the maximum deformation in terms of Weber number[19]. This maximum deformation was used to calculate the values of Weber number at which droplet breakup occurred using the data of Merrington and Richardson[20]. Except for very high viscosity materials, the value of W_E critical is approximately 10. For fluids with very high viscosity that have terminal velocities appreciably higher than raindrops, the application of the W_E critical of 10 can be in error. The effect of the aerodynamic pressure in deforming the drop, the droplet natural frequency of oscillation, and the loss of velocity of the droplet in the airstream all can change the breakup process for high viscosity fluids. This case is worth studying for fire retardants.

Assuming that the anomalous case does not happen with retardants, the breakup process is found to be in one of three states[21]:

- Stripping mode
- Transition mode (both stripping and bag breakup)
- Bag breakup.

Bag breakup occurs at low velocities, whereas stripping occurs at *higher* velocities. (See Figure 45).

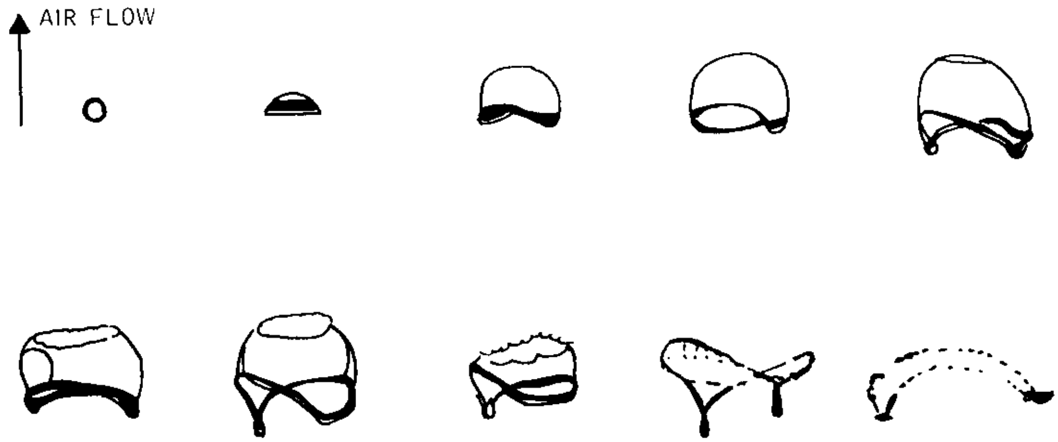


Figure 45. Bag Breakup (16)

The breakup time has been estimated by Wolfe and Anderson as:

$$t = \frac{d}{(A^2 + BP)^{1/2} - A}$$

where

$A = 16\eta/d\rho$

$B = 2/\rho$

$P = \frac{1}{2}\rho_a u^2 C_D - k\frac{\sigma}{d}$

and

C_D = drag coefficient = 1

k = constant = 2

d = drop diameter

η = viscosity of drop

ρ = density of drop

ρ_a = density of gas flow

σ = surface tension of drop

u = velocity of gas flow

The comparison of observed and predicted breakup times is shown in Figure 46.

Terminal velocities of retardant droplets in the final stages are comparable to those of water droplets based on calculations in the photos. Although the precision of such estimates is doubtful, the maximum advance of broken up material is on the order of 40 fps. This implies that droplet sizes are probably larger than water droplets (see Figure 47). Experimental evidence of this phenomenon under controlled conditions is needed.

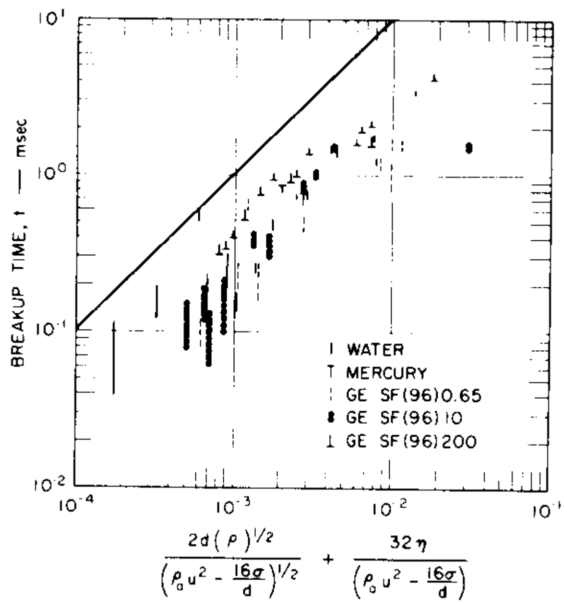


Figure 46. Comparison of Wolfe and Andersen Theory with Experimental Breakup Times(21)

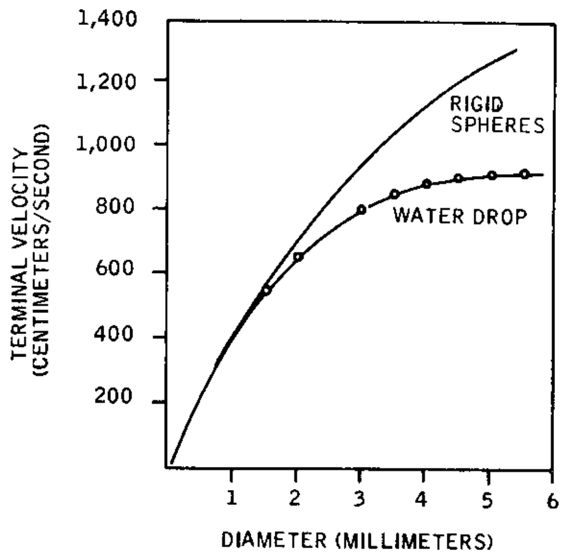


Figure 47. Terminal Velocities of Spheres of Unit Density and of Water Drops Falling in Air at 20°C and 750mm Hg Pressure

Data on water droplets is available from several sources, and it is summarized in Table IV.

4. <u>An Approximate Physical Method</u>

The work of the Bell Telephone Laboratories[18] on raindrop breakup provides new insight into retardant liquid mass breakup. Application of the theory gives an estimate of the time for development of the instabilities and the time for this transition event to be completed. More importantly, it gives a technique for viewing development of the instability on an accelerating fluid mass in an airstream without resorting to completely artificial mathematics such as a plane interface with random sinusoidal perturbations.

The theory starts with a liquid mass of spherical shape accelerated by a gas dynamic flow field that is analyzed for stability in terms of normal modes. These normal modes are either stable, quasi-stable, or unstable depending on a critical Bond number calculation. The next step examines an initial value problem that combines the aerodynamic and acceleration forces to show the fluid breakup criterion in terms of Bond and Weber numbers.

Table IV. Terminal Velocities of Water Drops in Air at 20°C and 750 mm Hg

Diameter of Equivalent Sphere (mm)	Terminal Velocity (cm/sec) Porton	Laws	Gunn and Kinzer	Average
0.1	-	-	27	27
0.2	-	-	72	72
0.25	100	-	95	97.5
0.5	201	-	206	203.5
0.75	305	0	305	305
1.0	402	-	403	402.5
1.5	540	551	540	543.7
2.0	645	658	649	650.7
2.5	726	741	741	736.0
3.0	790	806	806	800.7
3.5	837	852	852	847.0
4.0	872	886	883	880.3
4.5	898	910	901	903
5.0	909	925	909	914.3
5.5	913	930	915	919.3
6.0	915	930	-	922.5

The kinds of events that a liquid mass exhibits when a suddenly applied pressure distribution is introduced are the following:

- The fluid mass vibrates with stable oscillations that are dominated by the effects of surface tension
- A quasi-stable region of oscillations in which the vibrations of the fluid mass take an appreciable amount of time to develop
- An unstable region that produces breaking in a short time.

Concurrent with the development of these oscillations, the fluid mass is deforming due to the applied pressure distribution. Thus the event of fluid breakup is dominated by these two effects.

These events can be characterized by the density ratio and by the Weber and Bond numbers:

- For Weber numbers in low range $7 \le W_E \le 50$, the fluid mass deforms with time. The flow results in the so-called bag or umbrella-like response.

- Above the lowest critical value of Bond number of 11.2, the drop is unstable to small disturbances. The Bond number for rapid unstable growth is the order of 10^5. In the quasi-stable region (B_o between 11.2 and 10^5), the fluid mass deforms due to aerodynamic pressure distributions in time, and the effect of accelerations is to produce surface waves on the windward surface. (Taylor instability developing).

- The mass loss due to stripping has the effect of increasing the drag, and for Reynolds numbers in the region of 10^4 the drag coefficient can be estimated to be 2.5.

- Instability does not occur for normalized time less than unity,

  $$t^* = (\rho_a/\rho_L)\ t\ U/r$$

  where

  P_a = air density

  P_L = liquid density

  t = time

  U = velocity

  r = radius of equivalent sphere.

- The onset of Taylor instability is approximated by $t^* = 22\, B_o^{-1/4}$

- The estimated breakup time is $t^* = 65\, B_o^{-1/4}$

These formulas have been applied to the retardant mass as shown in Figure 48.

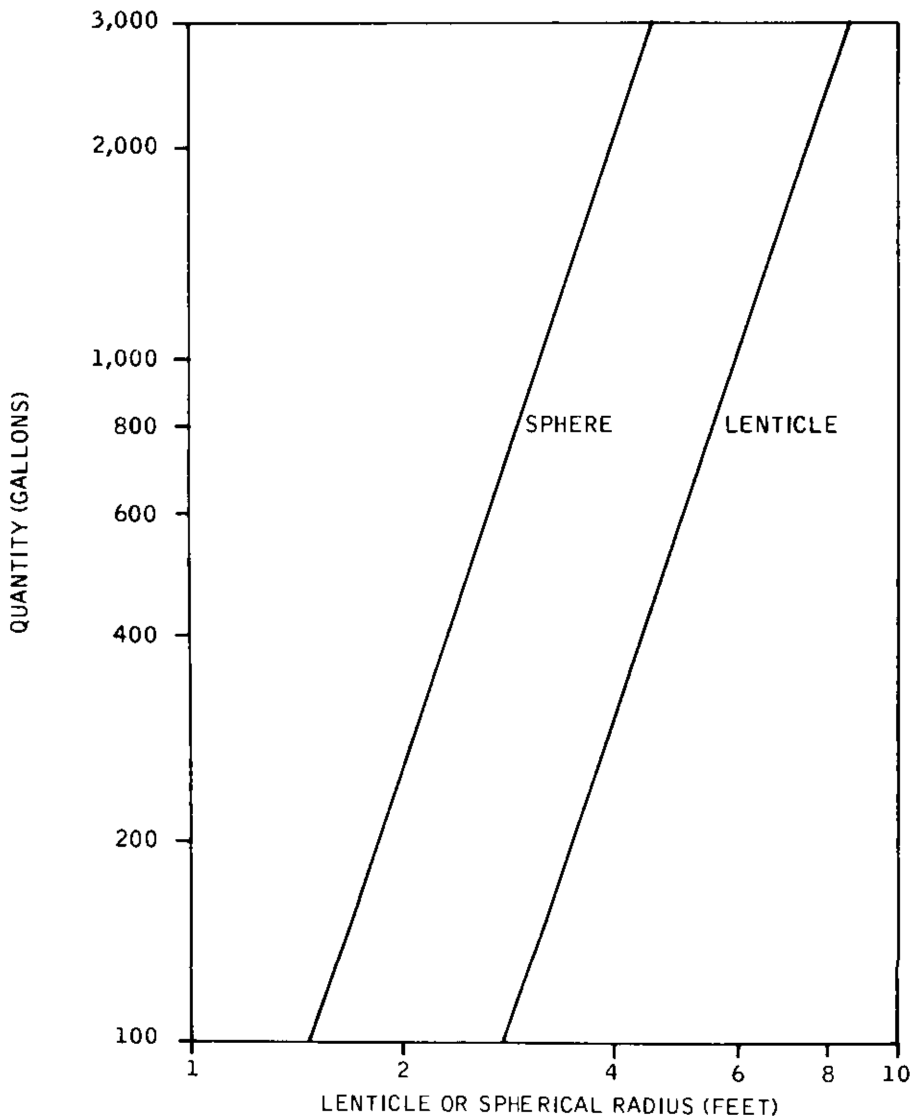


Figure 48. Spherical or Lenticular Radius Versus Quantity

Weber number calculations are shown in Figure 49.

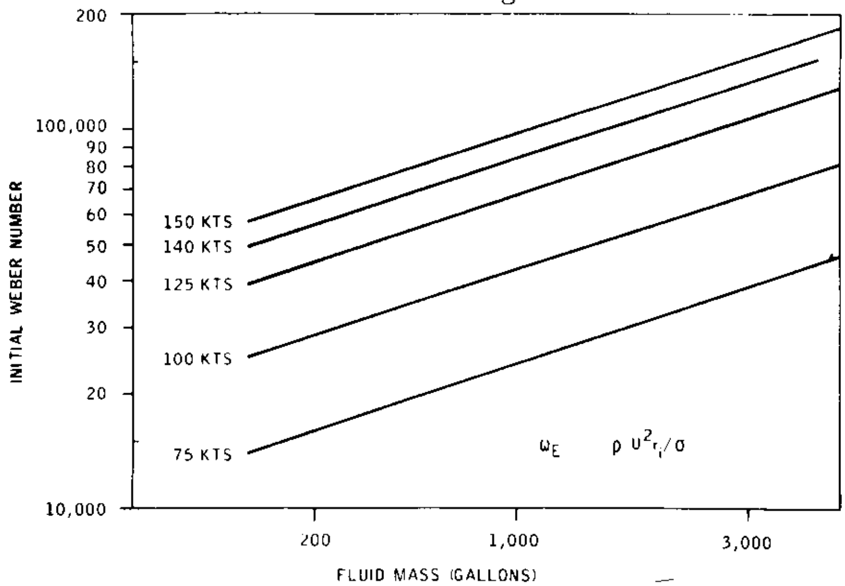


Figure 49. Weber Number versus Initial Quantity in Gallons

Bond number calculations are based on $B_o = 3/8\ C_D\ W_E$ where $C_D = 2.5$. The value of the Reynold's number exceeds 10^6, which is larger than the experimental results of Simpkins and Bales. (Figure 50).

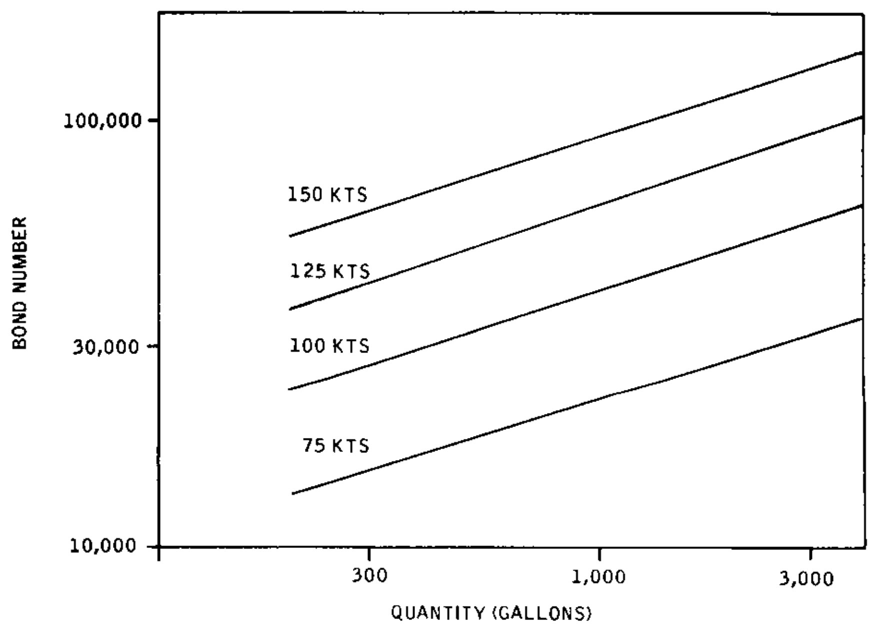


Figure 50. Bond Number versus Quantity

The expected time for breakup based on $t^* = 65\ B_o^{-1/4}$ is shown in Figure 51. Actual predicted time is shown, i.e.:

$$t = \frac{r_o\ t^*}{\epsilon^{1/2}\ U}\ , \quad \epsilon = \frac{P_G}{P_L}$$

where

P_G = density of gas

P_L = density of liquid

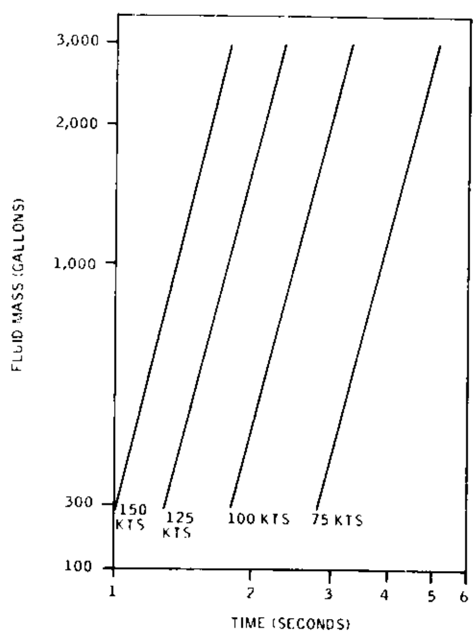


Figure 51. Breakup Time Versus Quantity

These times have been compared with film studies of B-17 Aero Union and PB4Y2 drops. If one adds the time required to discharge the fluid mass from the tank, comparable results are obtained.

	Exit Time	Calculated Breakup Time	Total Time	Observed Earliest Breakup Time
B-17 2,000 gallons	1.1	2.09	3.19	2.75
PB4Y2 1,200 gallons	1.9	1.85	3.75	3.5

The significance of this calculation is that the travel of the intact fluid mass before the breakup process occurs can be estimated from the discharge and the quantity of fluid released. Other tank and gating parameters could be a perturbation about this predicted travel. The fact that flow out of the tank and quantity are such important parameters is not obvious, and the combination of this bond number representation and the MacPhearson tank simulation could be the most important conclusions of this study.

B. THE MODIFIED MacPHEARSON SIMULATION

A basic objective in this program was development of a computer model of tank release that would allow traceability of tank design characteristics into the pattern. This objective was further emphasized with the selection of advanced cascade as the primary technique for improving performance.

The baseline model selected was a computer simulation of TBM performance originally developed by MacPhearson in 1967[(22)(23)(24)].

In two stages of refinement, MacPhearson calibrated the empirical portions of the model to reflect TBM delivery of water at a fixed altitude and showed in preliminary form that the modeling approach was extendable to retardants. The basic simulation was reprogrammed for current high-speed computers and modified slightly to generate a program that yields practical answers to a variety of tank design questions.

1. Overview of the Simulation

Figure 52 shows schematically the operation of the simulation. Internal shape details of the tank and door-opening size and rate are entered into the computer. Velocity at time of release and flow rate are then calculated. The flowing retardant volume is divided into packets representing fixed time increments. Each packet ($\dot{Q}_i$) is then flown on a point-mass trajectory from its emergence on the aircraft flight path until it is completely broken into droplets and loses its identity as a liquid mass. The mass converted to droplets over the trajectory is tabulated in space for each packet. The results are then tabulated to form a distribution of the retardant over the range into which it falls. Summation of packets along the range produces a marginal distribution. A final subroutine can display the predicted pattern as an isopleth of coverage contour lines similar to that used in recovering pattern data from actual tests. The following subsections describe an example case using the 700-gallon release from a CL-215.

2. Flow Rate

The first subroutine of the MacPhearson simulation calculates the volume flow rate as a function of time using the inputs of tank geometry and door-opening rate as shown in Figure 53. The equations used are strict Bernoulli, with an efficiency constant that was found in early model checkout to be approximated by a value of 0.85. The door-opening rate, however, has been used as a floating variable in the achievement of pattern matches with the marginal distribution. The floated value is within a few tenths of a second of the values recorded from films and is believed to be within reasonable limits of uncertainties. (Calibration of this part of the simulation with measured values is recommended as a means of reducing modeling uncertainties prior to availability of data from the proposed experimental tank.)

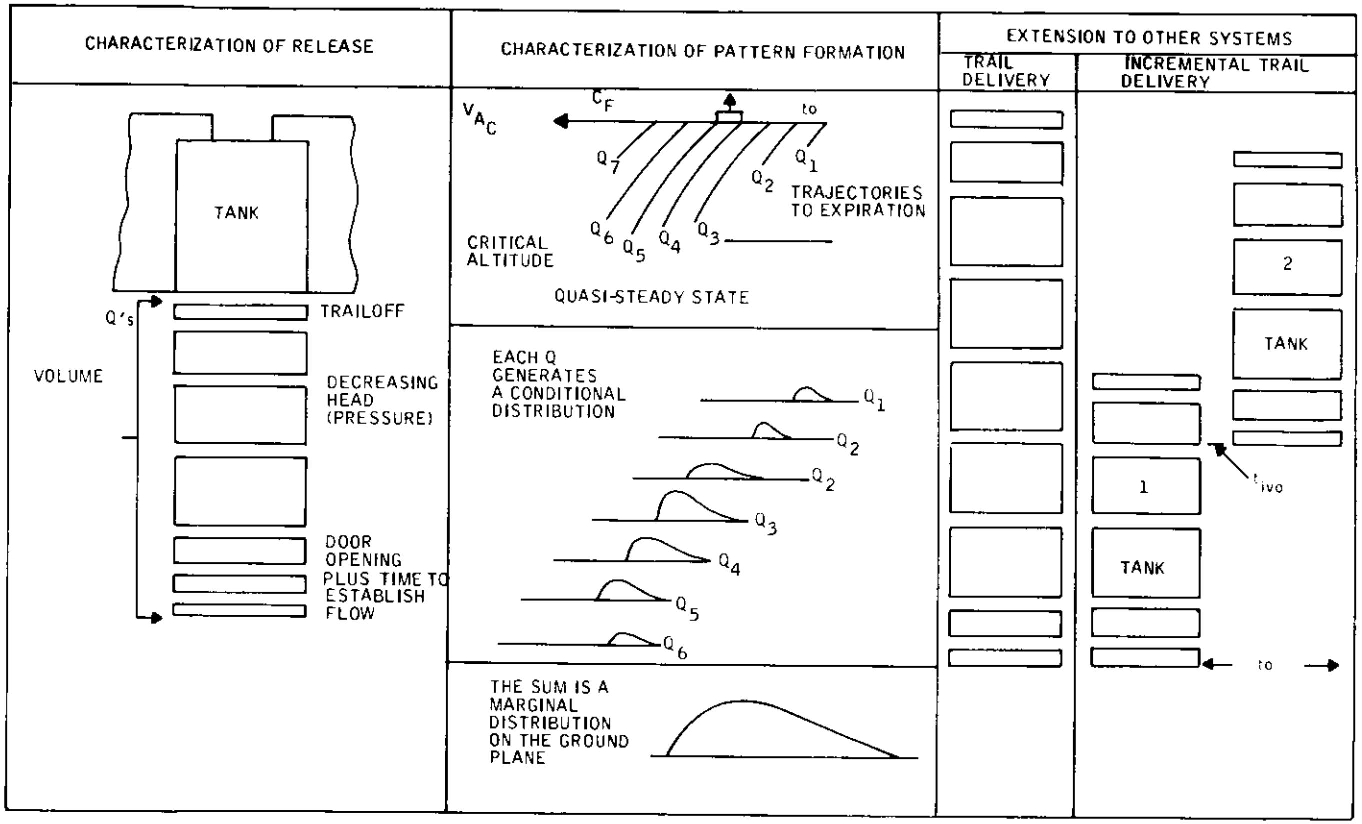


Figure 52. Delivery Characterization

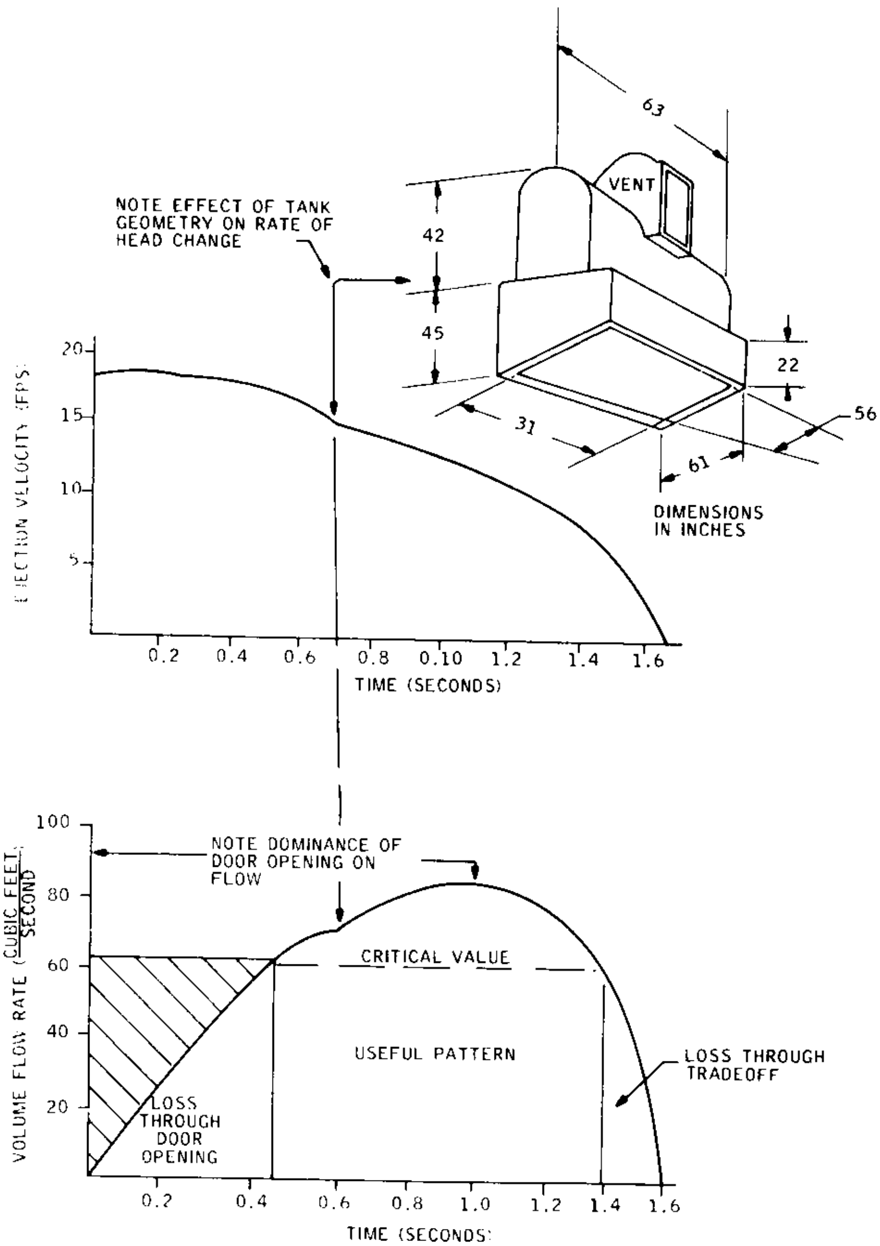


Figure 53. Ejection Velocity and Flow Rate from MacPhearson Simulation (CL-215) 700-Gallon Drop)

Examination of Figure 53 shows the effect of door-opening rate on the early portions of the delivery, as well as a dip in the flow rate introduced by a sudden change in tank geometry. The net result of these tank characteristics can still be seen in the predicted pattern, and evidence of their effect can be found in actual pattern data. The useful pattern can also be grossly related to a critical flow rate, i.e., a rate that must be maintained at a given altitude to achieve adequate coverage.

The flow rate simulation provides considerable direct visibility of the effect of various tanking parameters on flow rate. Flow rate curves were generated for single tanks from the CL-215, Aero Union B-17, PB4Y2, C-119 and P2V. (The full set of flow rate curves is presented in Figures 55 through 60.) Figure 54 shows a direct comparison of tank types normalized by the initial tank capacity. This shows the wide range of flow management in tested tanking systems, from the fast release B-17, through the restricted flow of the PB4Y2, to the trail tank delivery system of the Aero Union B-17. It is interesting to observe that the C-119, P2V, and the B-17 (Intermountain) are approximately equivalent systems in terms of flow rate on a normalized basis.

3. Marginal Distribution

The next subroutines of the MacPhearson simulation convolute the flow rate curves into a marginal distribution on the ground plane. This distribution can then be compared with the actual marginal distribution developed in flight tests. Figure 61 defines the marginal distribution as it is derived from pattern plots. Each quantity increment is flown on an independent trajectory from its release point to extinction (Figure 62). The distributed mass from each quantity increment is tabulated as a function of travel as shown in Figure 63.

The rule for quantity disintegration is the only major departure from the second of the two original MacPhearson simulation studies. It is:

$$\frac{d\ Q_i}{dt} = \frac{K_1}{Q_i} \quad e^{K_2 t}$$

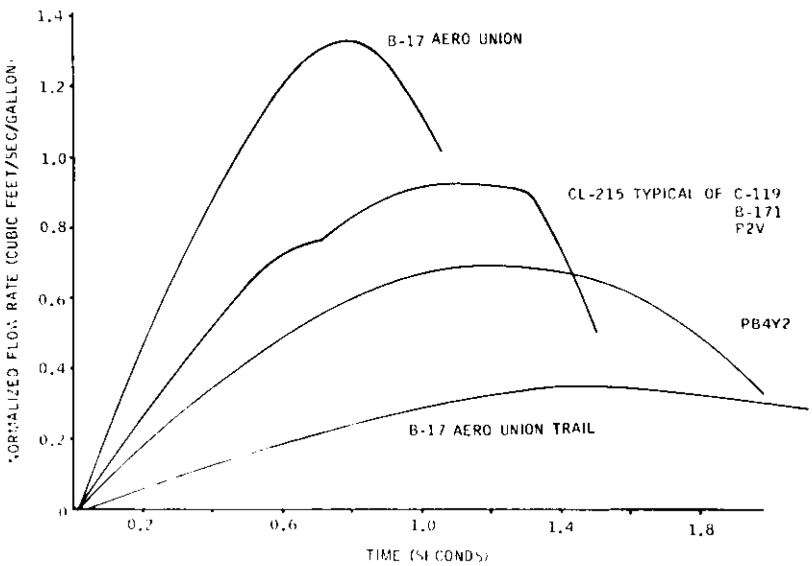


Figure 54. Normalized Flow Rates from Seven Tank Options

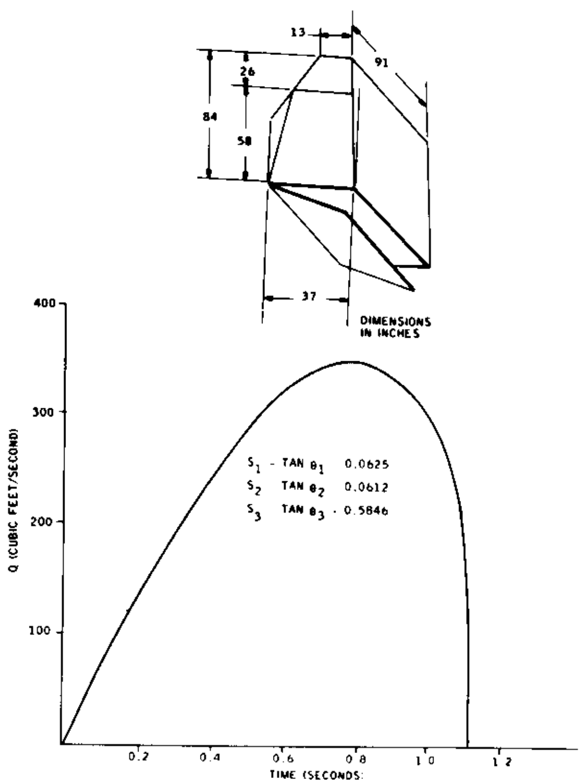


Figure 55. Flow Rate, B-17 Tank

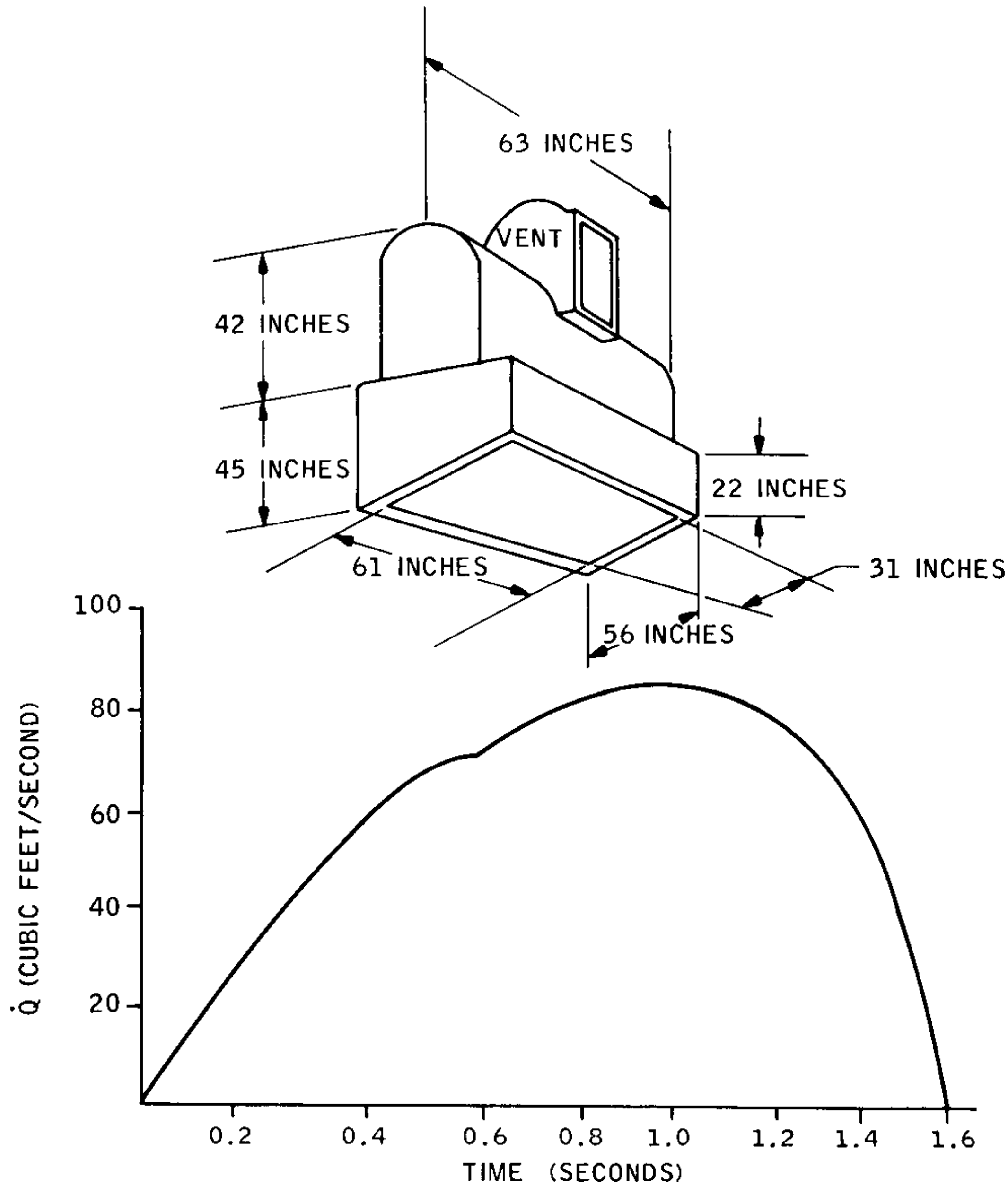


Figure 56. CL-215 Flow Rate

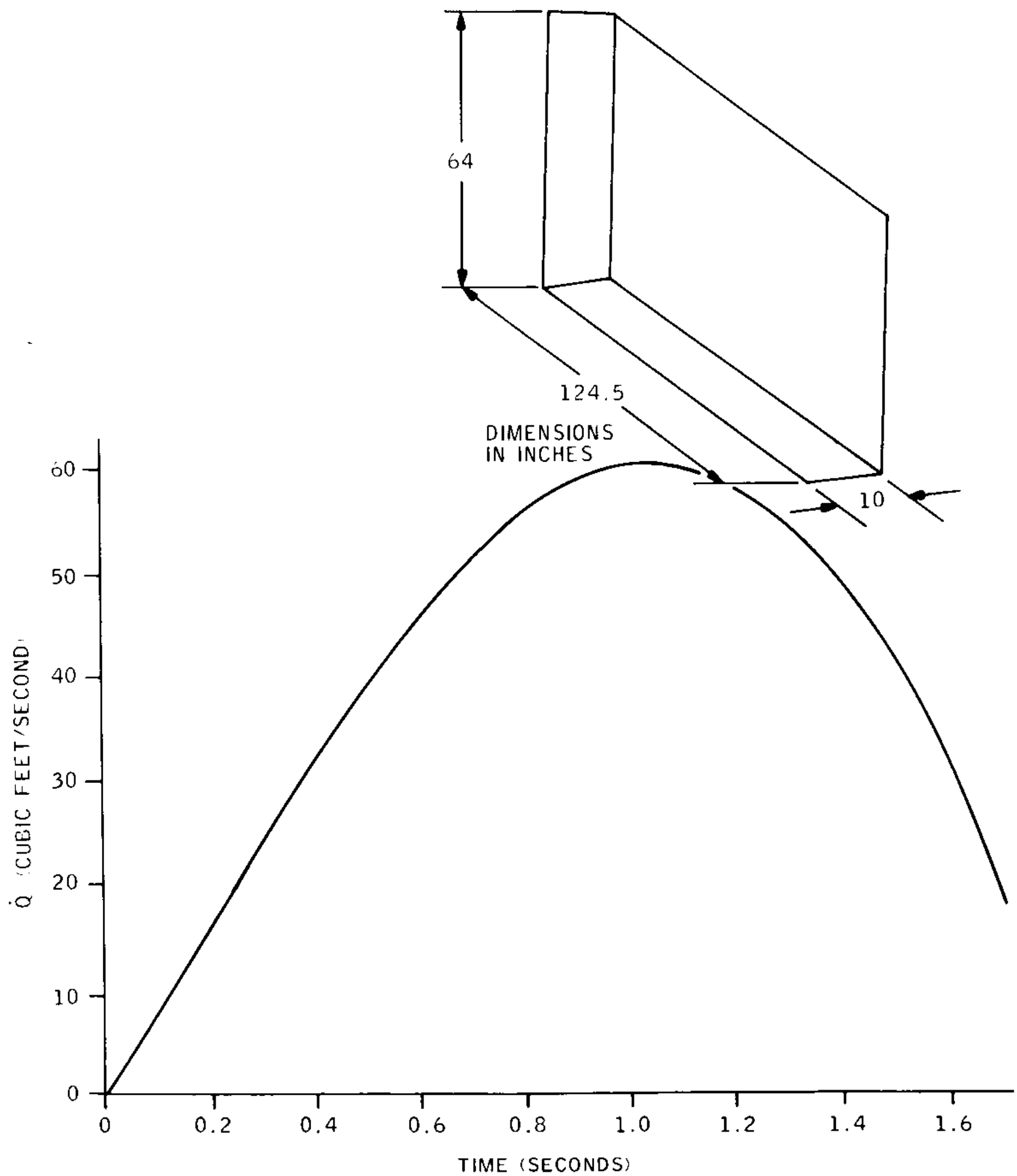


Figure 57. P2V Flow Rate

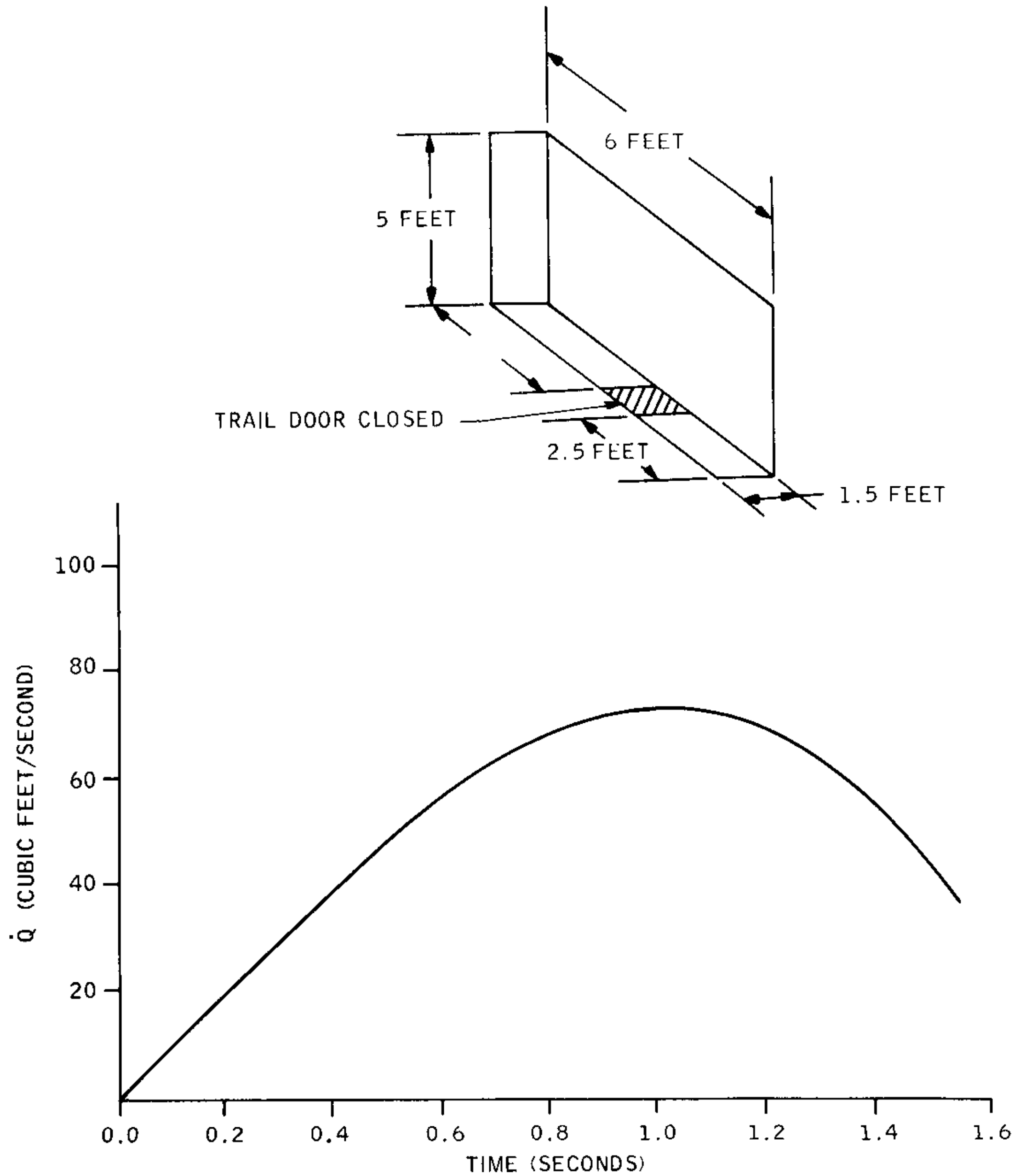


Figure 58. C-119 Flow Rate

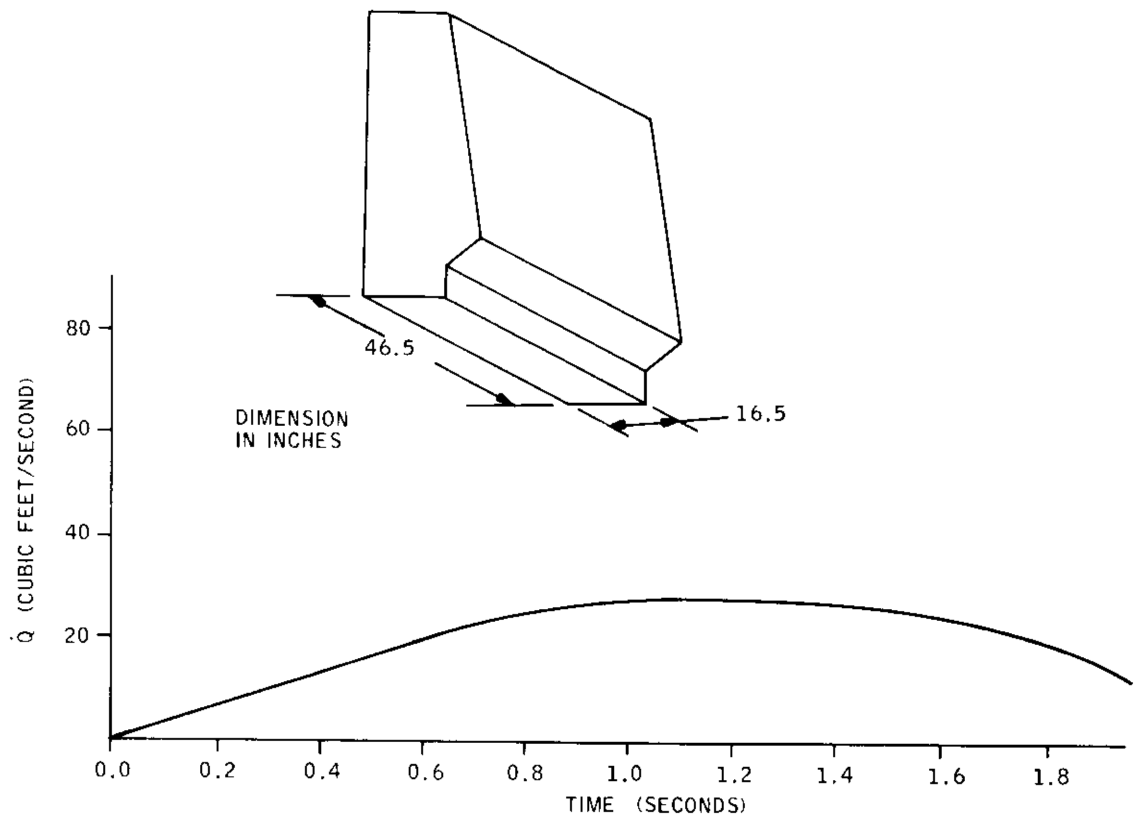


Figure 59. PB4Y2 Flow Rate

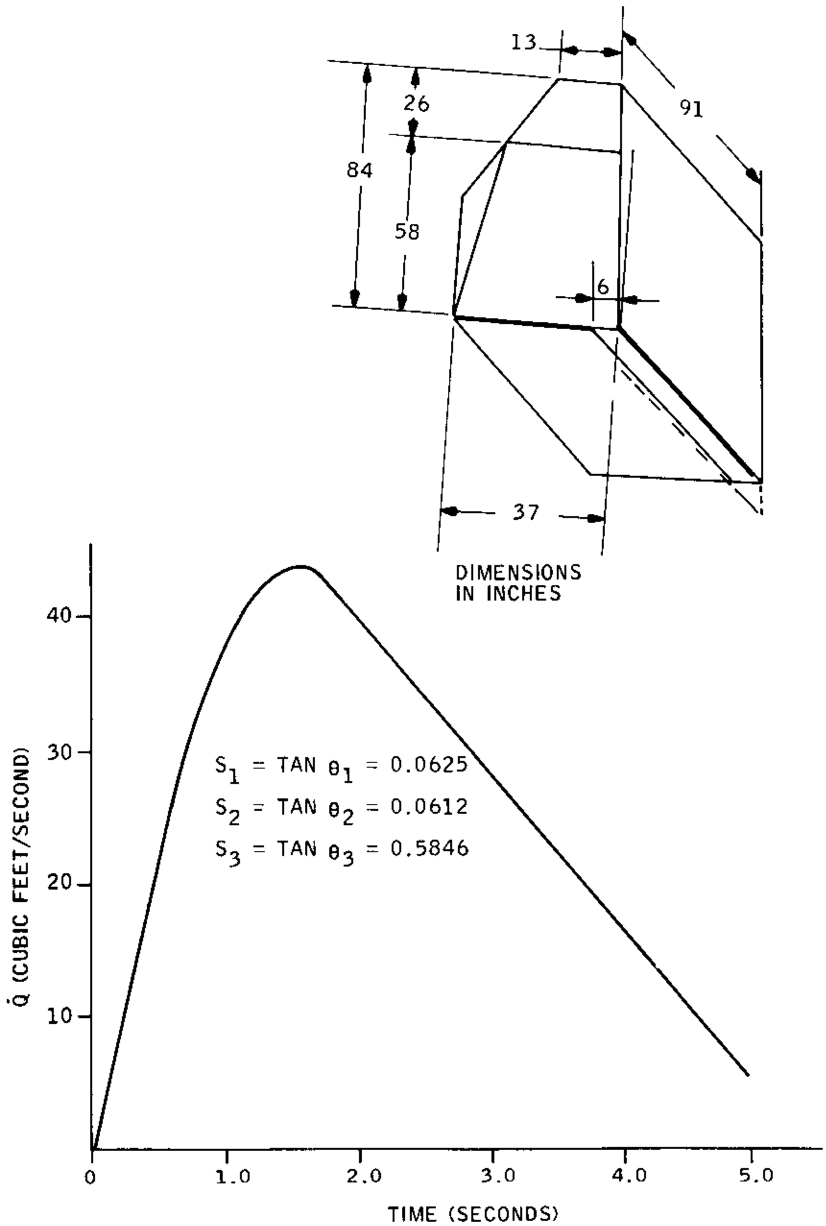


Figure 60. B-17 Trail (Aero Union) Flow Rate

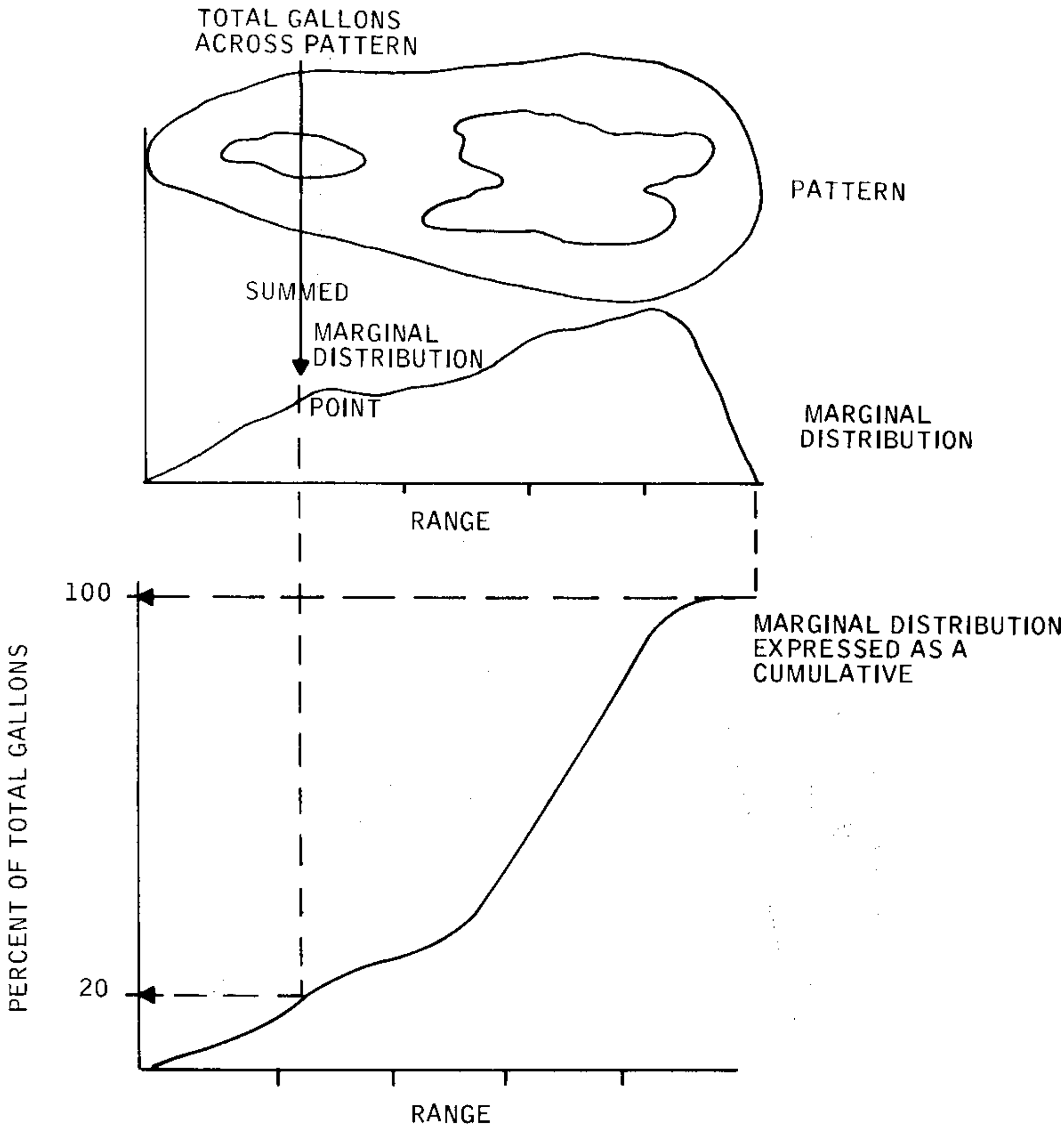


Figure 61. Calculation of Actual Pattern Marginal Distributions

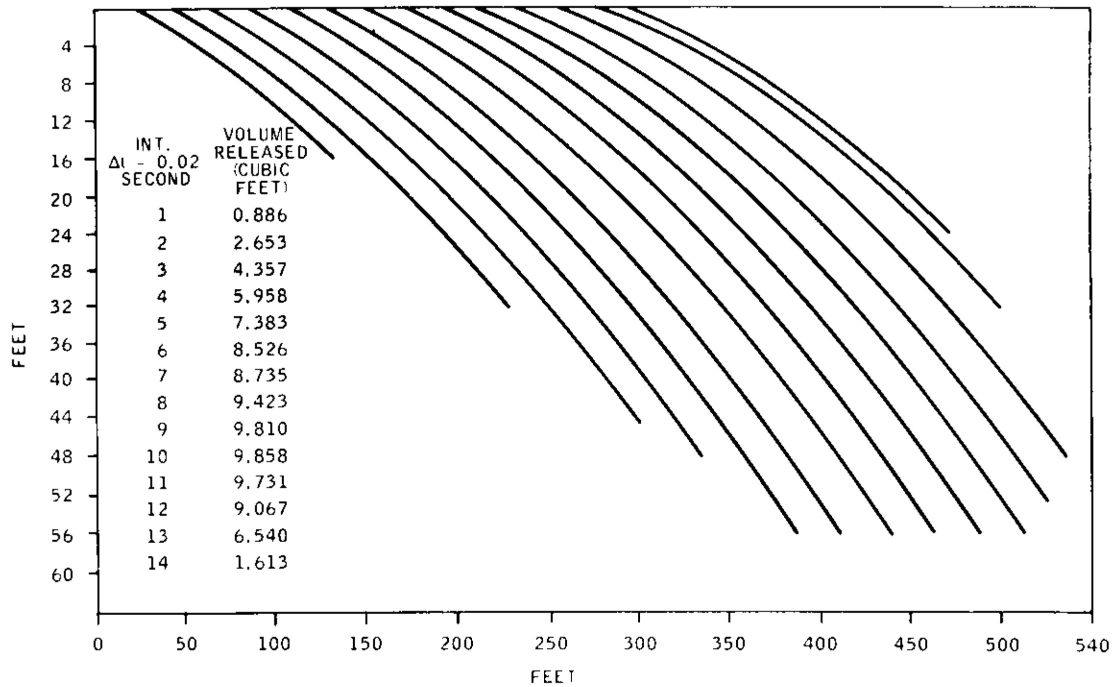


Figure 62. MacPhearson Trajectory Display (CL-215)

where Q_i is the volume of the i^{th} packet and the K values are calibration constants. The rule generates a mass disassociation rate that varies exponentially with time. This rule is supported both by observed phenomena and our quantitative understanding of physics of breakup.

Although the two constants might be expected to vary from tank to tank, good fits to most test data have been achieved with K_1 at a fixed value of 4 and K_2 at a fixed value of 12.

The next step of the simulation accumulates the mass values of Figure 63 on a ground plane as shown in Figure 64, which for convenience of analysis is usually displayed as a cumulative distribution (Figure 65). This allows direct comparison with the marginal distribution taken from test results.

TOTAL (CUBIC FEET	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500	525	550
1,708	0.453	0.459	0.292	0.259	0.198	0.045																
3,192	0.001	0.094	0.170	0.274	0.441	0.711	0.680	0.617	0.205													
5,137		0.004	0.063	0.109	0.171	0.278	0.449	0.732	1.202	1.245	0.757	0.126										
6,693			0.007	0.350	0.086	0.135	0.217	0.354	0.575	0.734	1.544	1.804	0.988									
8,426				0.010	0.045	0.074	0.118	0.191	0.305	0.503	0.804	1.343	2.171	2.628	0.234							
10,150					0.013	0.043	0.069	0.110	0.176	0.246	0.465	0.755	1.244	2.229	3.317	1.640						
10,393						0.020	0.045	0.074	0.116	0.189	0.303	0.499	0.797	1.329	2.128	2.908	1.966					
11,297							0.025	0.045	0.072	0.118	0.138	0.306	0.495	0.796	1.330	2.154	3.534	2.735				
11,644							0.001	0.029	0.046	0.076	0.121	0.197	0.315	0.512	0.634	1.376	2.237	3.646	2.251			
12,428								0.003	0.034	0.051	0.811	0.131	0.212	0.339	0.550	0.896	1.466	2.402	3.945	2.315		
10,199									0.007	0.038	0.057	0.089	0.144	0.231	0.375	0.606	0.993	1.622	2.614	3.153	2.401	
9,662										0.012	0.044	0.067	0.104	0.267	0.268	0.435	0.695	1.142	1.393	3.735	2.301	
7,857											0.026	0.069	0.102	0.158	0.256	0.410	0.660	1.070	1.714	2.579	0.414	
TOTALS	0.454	0.457	0.532	0.702	0.954	1.306	1.604	2.155	2.738	3.454	5.120	5.386	6.572	8.189	9.292	10.425	11.571	12.119	12.422	11.032	3.334	
PERCENT	0.004	0.004	0.005	0.006	0.009	0.012	0.015	0.020	0.025	0.031	0.046	0.049	0.059	0.074	0.084	0.094	0.105	0.110	0.112	0.100	0.035	
CUMULATIVE PERCENT	0.004	0.008	0.013	0.019	0.028	0.040	0.055	0.075	0.100	0.131	0.177	0.226	0.285	0.395	0.443	0.537	0.642	0.752	0.864	0.964	1.000	

NEW
STRIPPING
EQUATION

$V_{A\,F}$ 125
4 0.341
NO PRESSURE

Figure 63. MacPhearson Mass Distribution Display (CL-215)

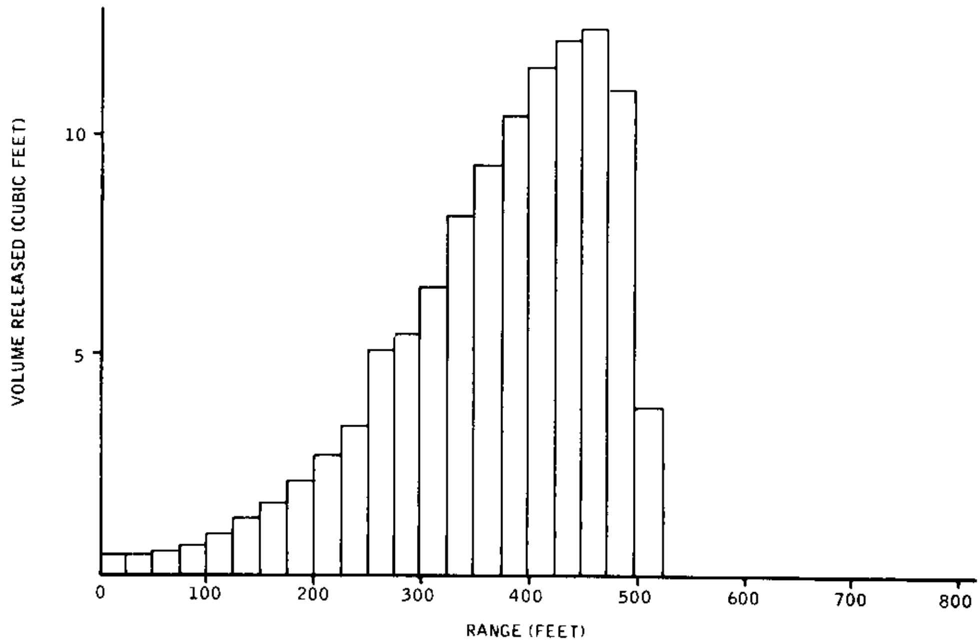


Figure 64. MacPhearson Marginal Distribution Display (CL-215)

Figure 65 shows a good match with actual results with the CL-215 drop. (Figures 66 through 71 compare the predicted with actual marginal distributions generated over a range of conditions.)

In general, the matches are surprisingly good considering expected effect of release geometry on trajectory values and different forms of tank addition used in the actual tests. Extension of the analysis to the other tanks indeed suggests the technique is valid in assessing the effects of tank characteristics of hypothetical or conceptual tanks.

The data also suggest that in order to determine more precisely the effect of parameters not specifically included in the simulation, actual flow data on the existing tanks and/or the conduct of tests on an experimental tank are required.

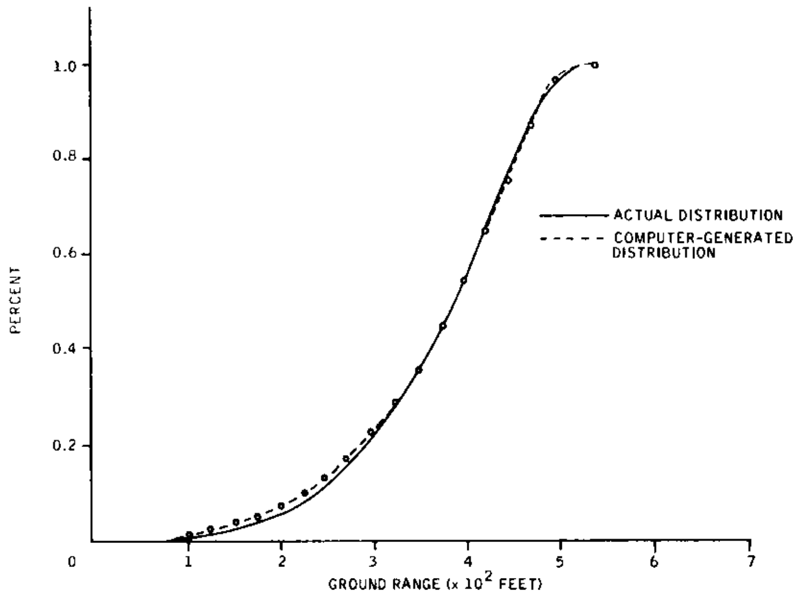


Figure 65. MacPhearson Cumulative Marginal Distribution Display (CL-215)

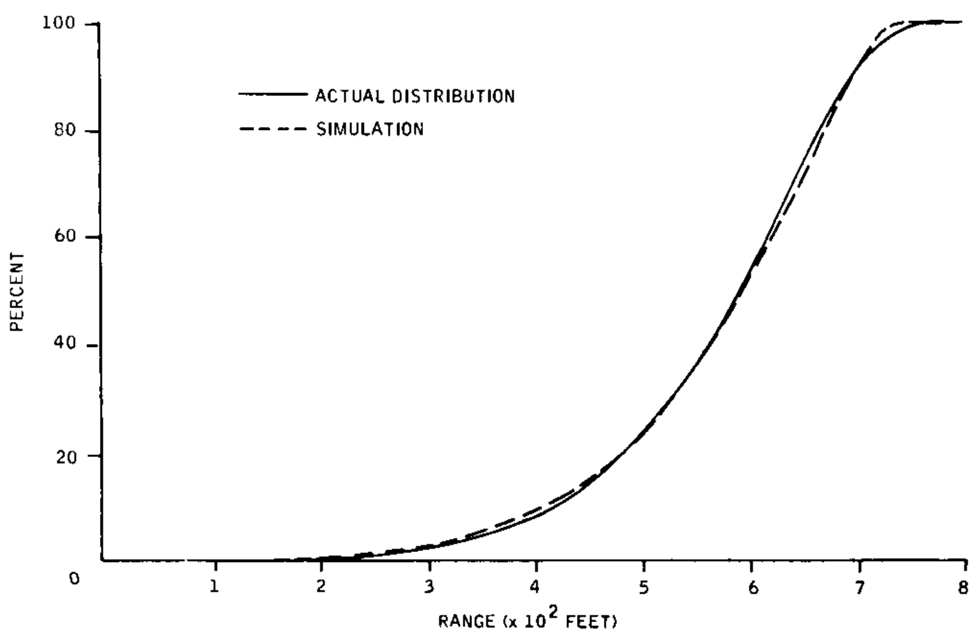


Figure 66. Marginal Distributions Obtained for Aero Union B-17A

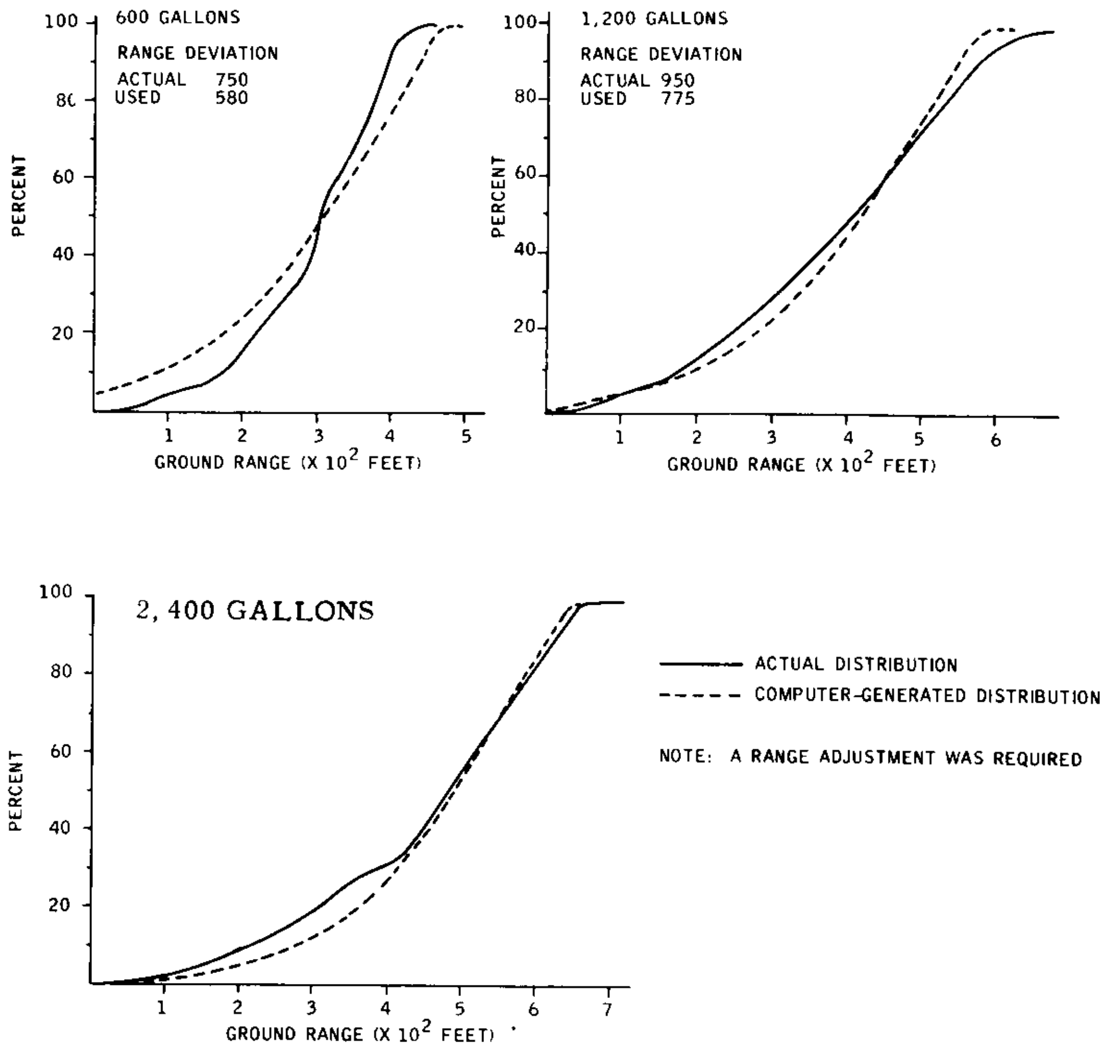


Figure 67. Marginal Distributions Obtained for the PB4Y2 at 500-Foot Altitude

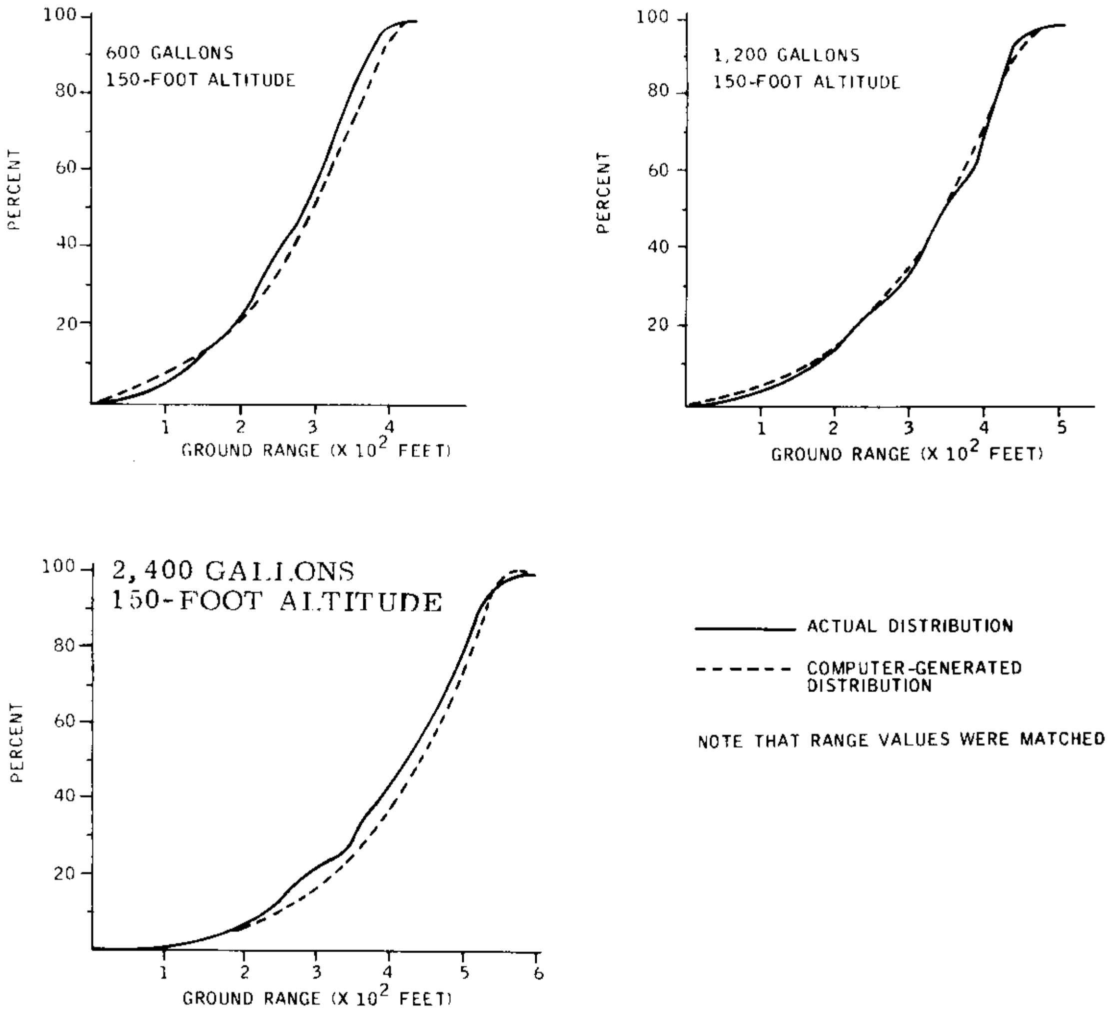


Figure 68. Marginal Distributions Obtained for C-119

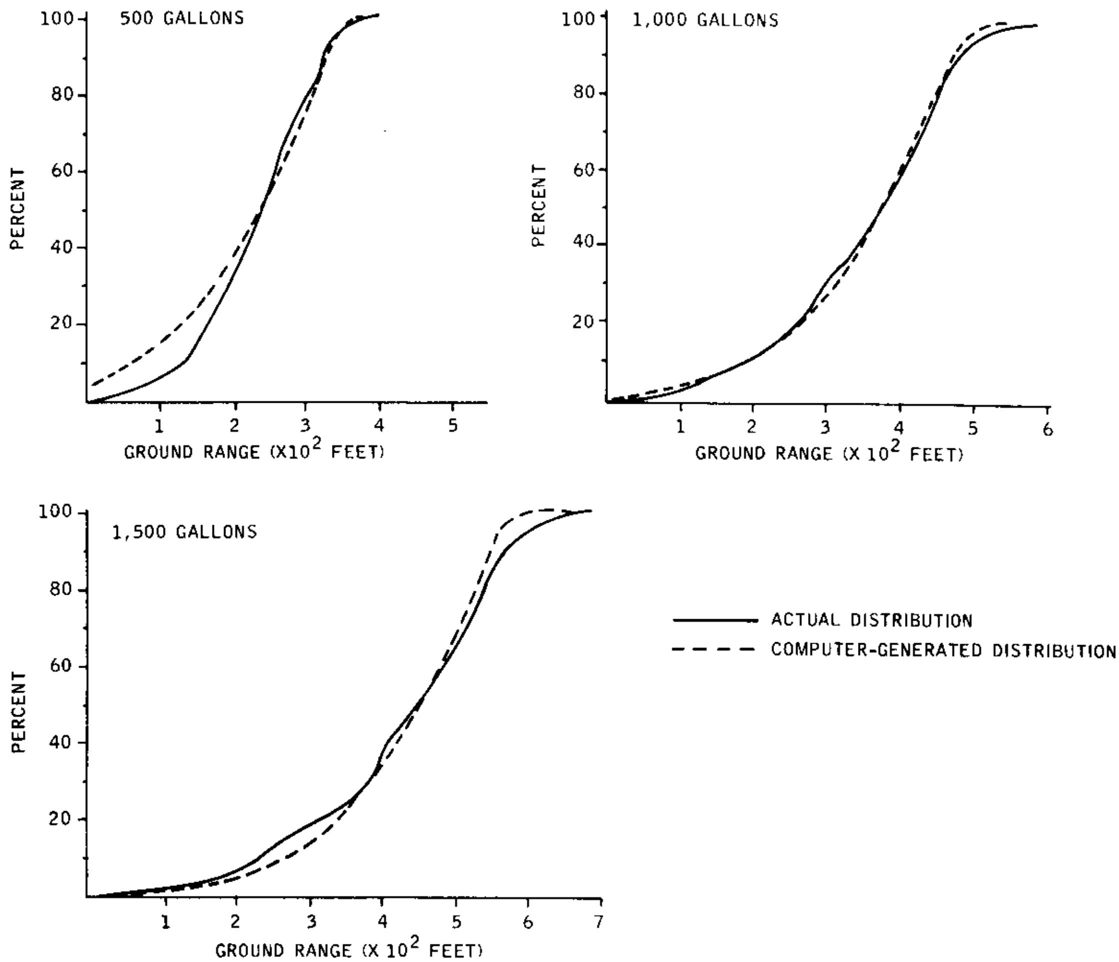


Figure 69. Marginal Distributions Obtained for the P2V at 300-Foot Altitude

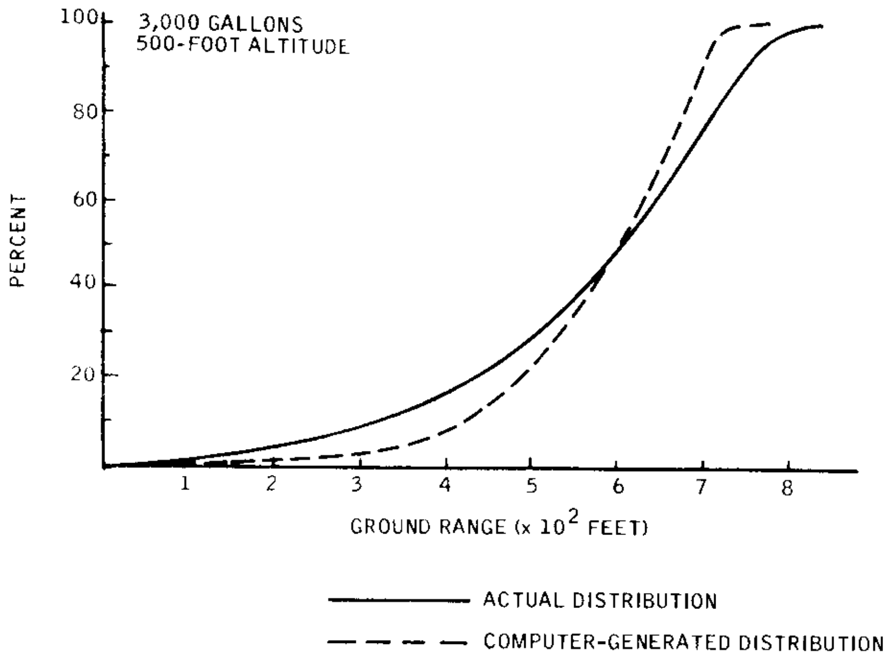


Figure 70. Marginal Distributions Obtained for the P2V at 500-Foot Altitude

I. Cross-Range Development

In discussions with the Forest Service, the desirability of extending the simulation to cross-range and subsequently pattern isopleth plots in the manner that actual test data are displayed was determined.

To develop the isopleth from the predicted marginal distribution, a normal cross-range distribution has been typically assumed. This technique works [illegible] as shown in Figure 72. It is essentially similar to that used for cross-range pattern development in MacPhearson.

Figure 73 shows patterns generated from the CL-215 simulation by applying a normal cross-range assumption to the marginal distribution. The symbols [illegible] show increases in density moving toward the center of the pattern. Figure 74 shows the resulting profiles. The three patterns represent an increase in altitude over a range of interest where a perturbation in flow rate, due to tank geometry, renders the pattern relatively sensitive to altitudes.

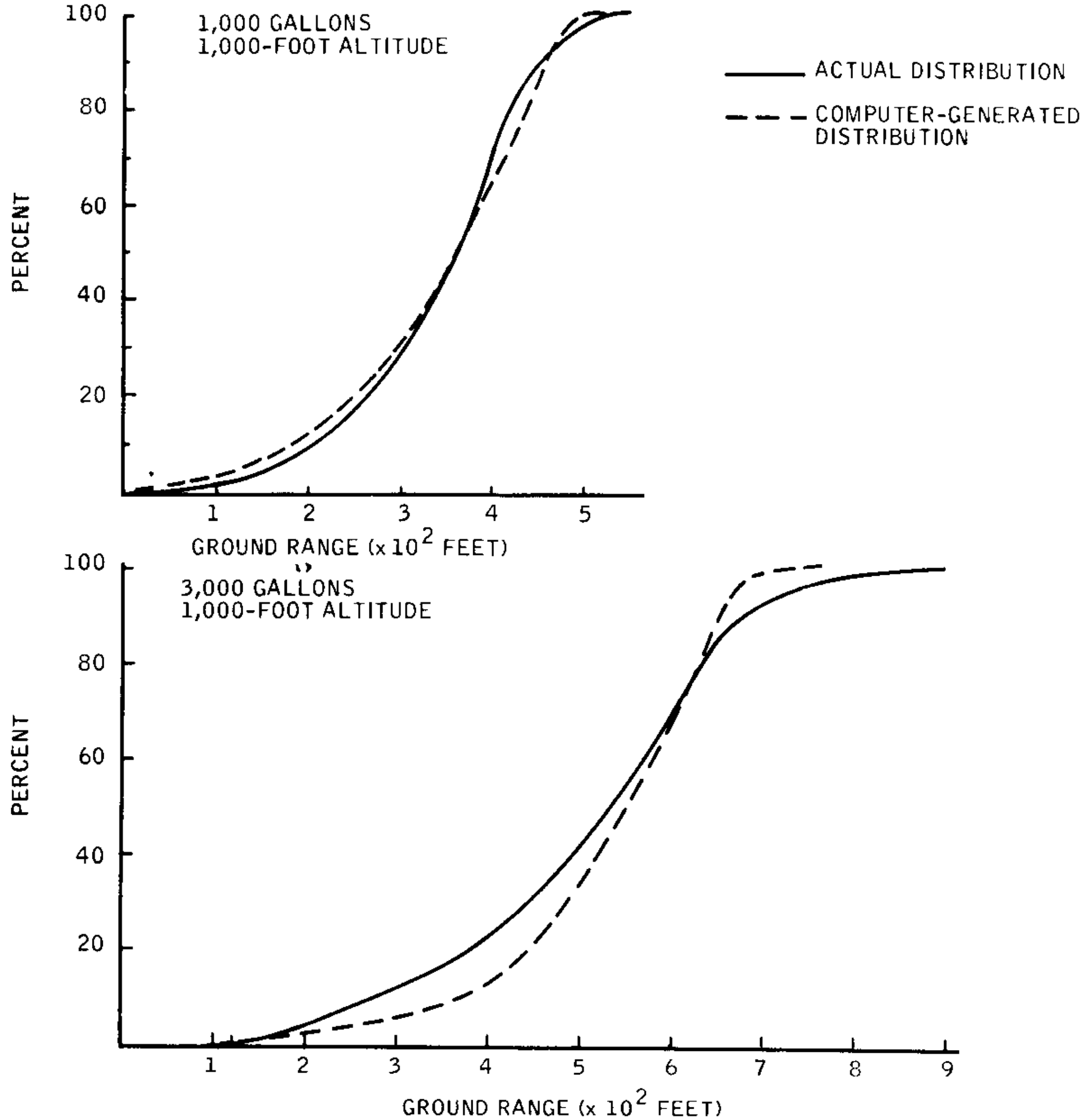


Figure 71. Marginal Distributions Obtained for the P2V at 1, 000-Foot Altitude

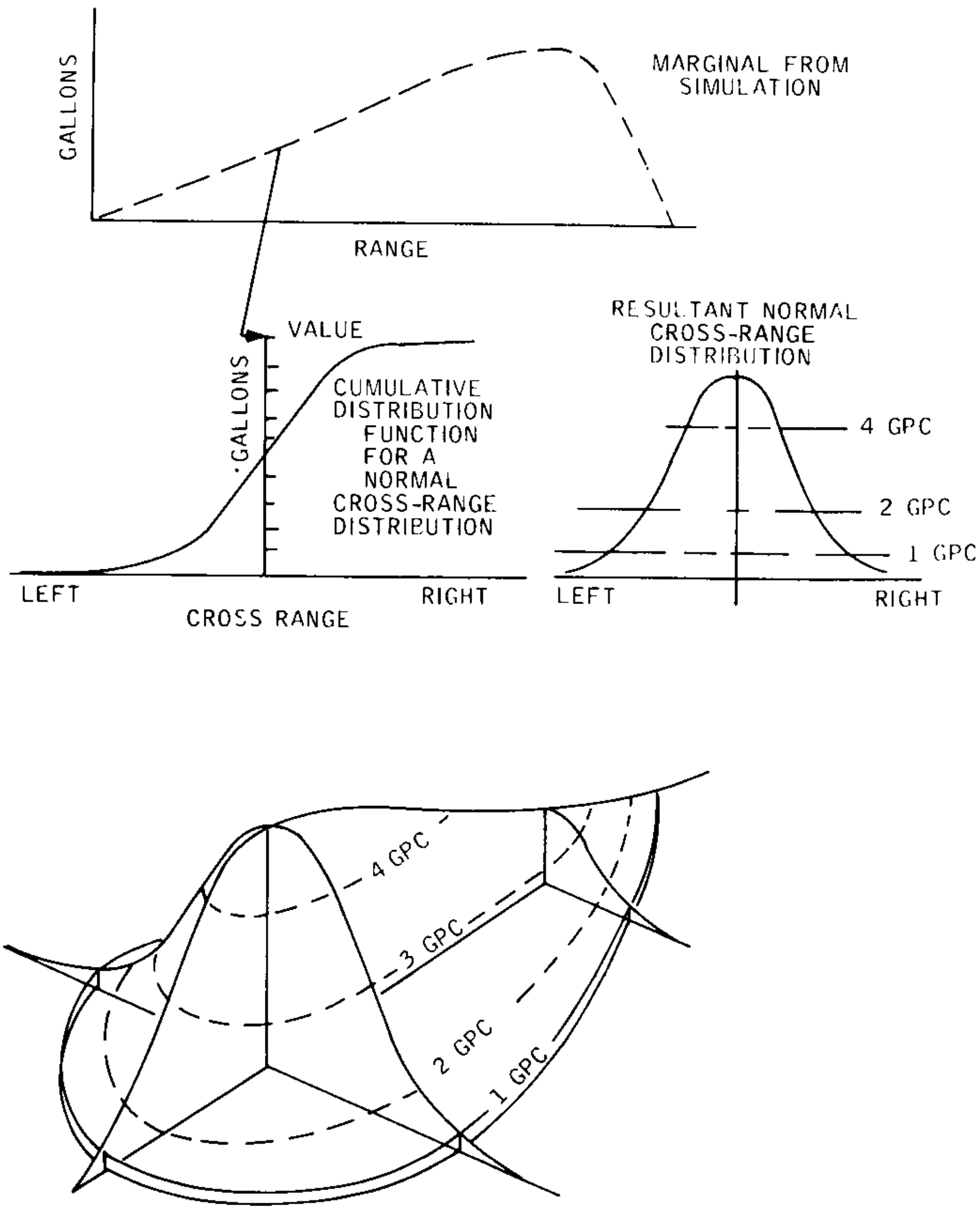


Figure 72. Reconstruction of Pattern from Marginal Distribution Assuming Normal Distribution in Cross Range

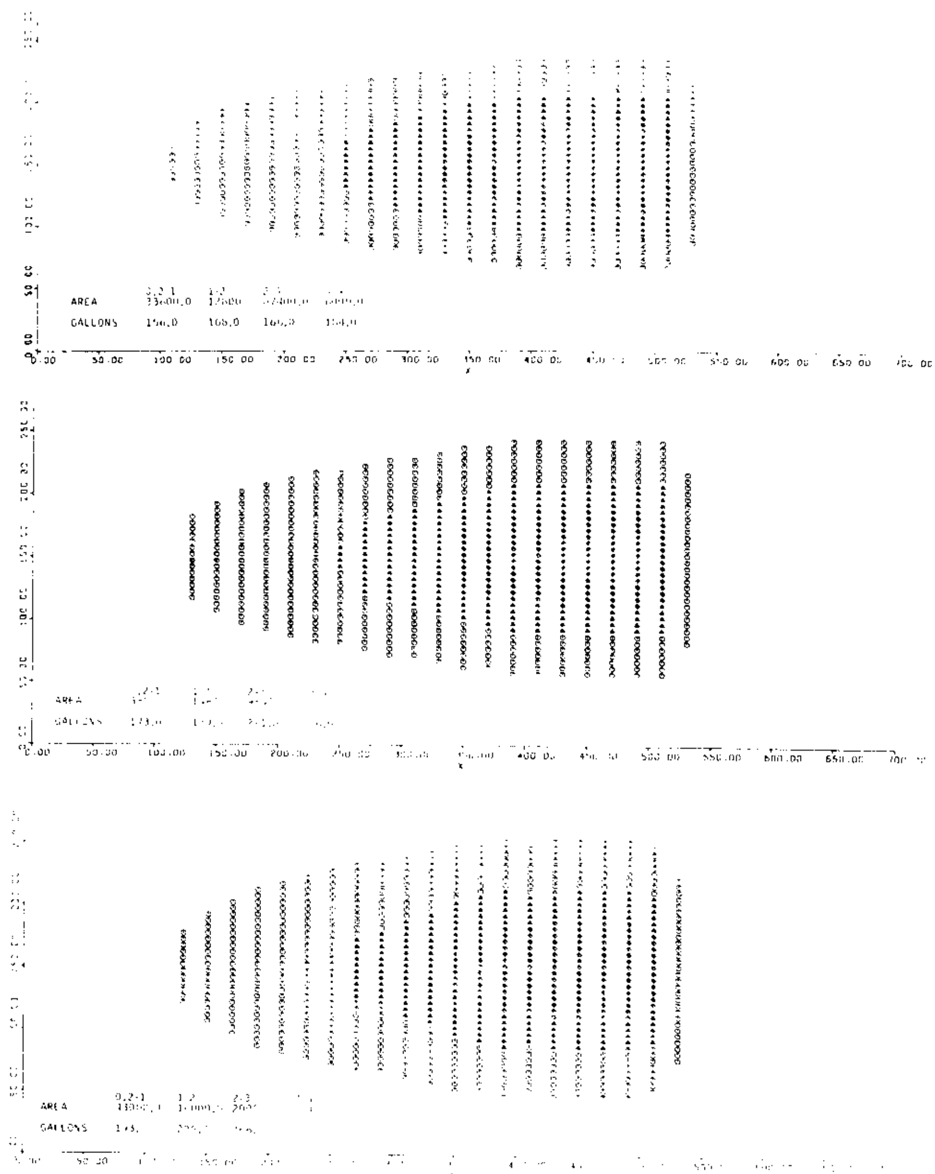


Figure 73. Computer Representations of Predicted Patterns, CL-215

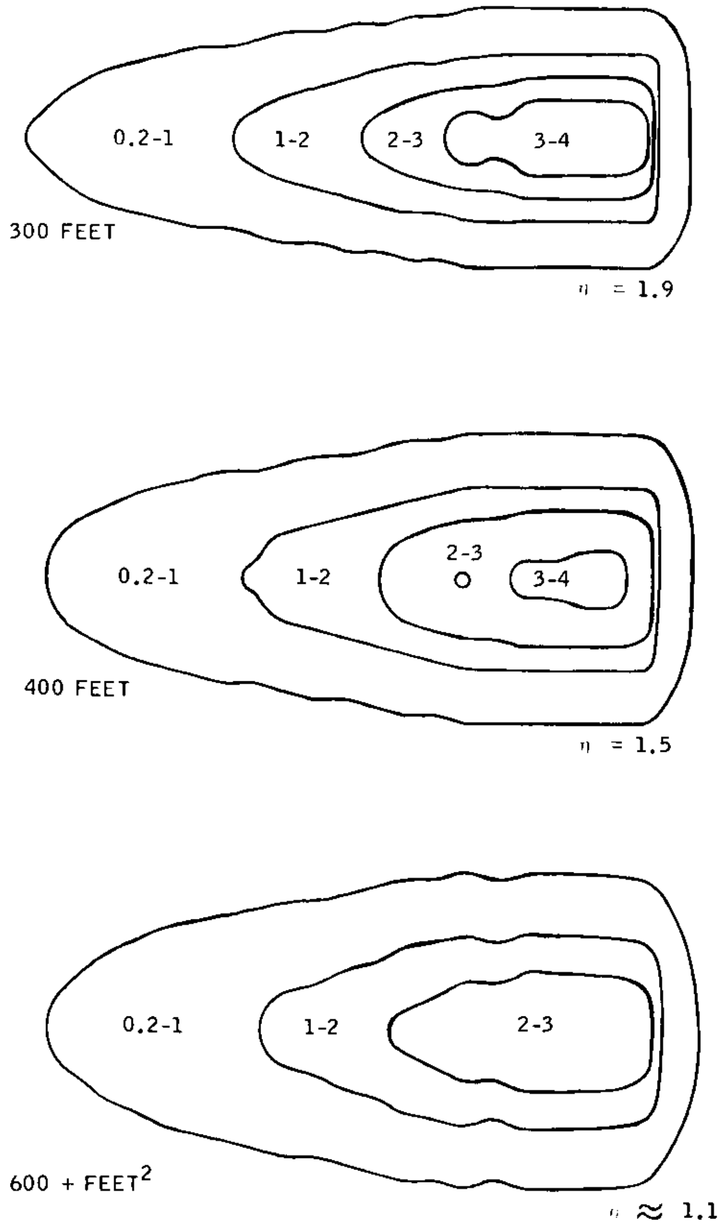


Figure 74. Pattern Isopleths Traced from Computer Printout

Although it was not intended to calibrate the model formally in a cross-range sense, the top two patterns exhibit reasonable characteristics that can be related to approximate altitudes. These altitudes correspond to 300, 400, and something around 600 feet. It is believed that these patterns represent a reasonable, but not rigorous, estimation of pattern performance preserving traceability to tanking values until further data are available to refine the total simulation.

C. WEIBULL CHARACTERIZATION

The marginal distribution alone does not account for certain differences in pattern, particularly those that occur over an altitude range. This is due in part to cross-range development, lateral separation of tanks used in the release, release geometry, and the completeness of breakup at the termination of the simulation. For this reason, the Weibull analysis (discussed in this subsection) has been developed in parallel with the basic simulation to account for altitude-related changes in the pattern following primary breakup.

One of the first problems encountered in evaluation of test site data is to determine a quantitative technique of viewing the pattern. A Weibull distribution was selected as a statistical method of nominating a pattern; i.e., it allows us to say that it is a 2-gpc pattern with a Beta value (form of the distribution) of 1, etc. Specifically, it is a statistical technique of viewing three variables simultaneously.

This analysis serves two purposes: 1) to obtain a quantitative relationship of factors contributing to pattern formation (or decay) not related to those now incorporated in the MacPhearson simulation and 2) to determine in a general sense the sensitivity of the Weibull parameter, Eta, in resolving experimental questions.

1. Method of Determining the Weibull Characterization

The Weibull technique has been shown in most cases to provide a good fit to actual pattern statistics. The technique of assigning a pattern value, Eta, is outlined in Figure 75.

Mathematically, the Weibull distribution[25] is the cumulative probability distribution

$$F\ (x^{j}\ \beta,\ \eta)\ =\ 1 - \exp\left[-\frac{X\beta}{\eta}\right]$$

where β is the shape parameter and η is the scale parameter.

The shape parameter of interest lies in the range of $0.8 \leq \beta \leq 2$, which changes the form of the probability density function. Figure 76 shows two examples of this distribution.

Appendix B presents a discussion of the detailed data analysis of Maranna test patterns using the Weibull characteristics. The following subsections summarize the generalized conclusion resulting from this analysis.

2. General Conclusions from the Weibull Analyses

Using the data in Appendix B it can be shown that the major effects of flight delivery on pattern value, Eta, are the volume in the drop and the altitude. Lesser differences are caused by aircraft velocity and viscosity (of a retardant of otherwise fixed rheology). There are also differences between aircraft that appear to be related to (1) release geometry and (2) multiple-tank releases. (Note: that aircraft velocity, flow rate, and quantity appear to dominate in the MacPhearson matches.)

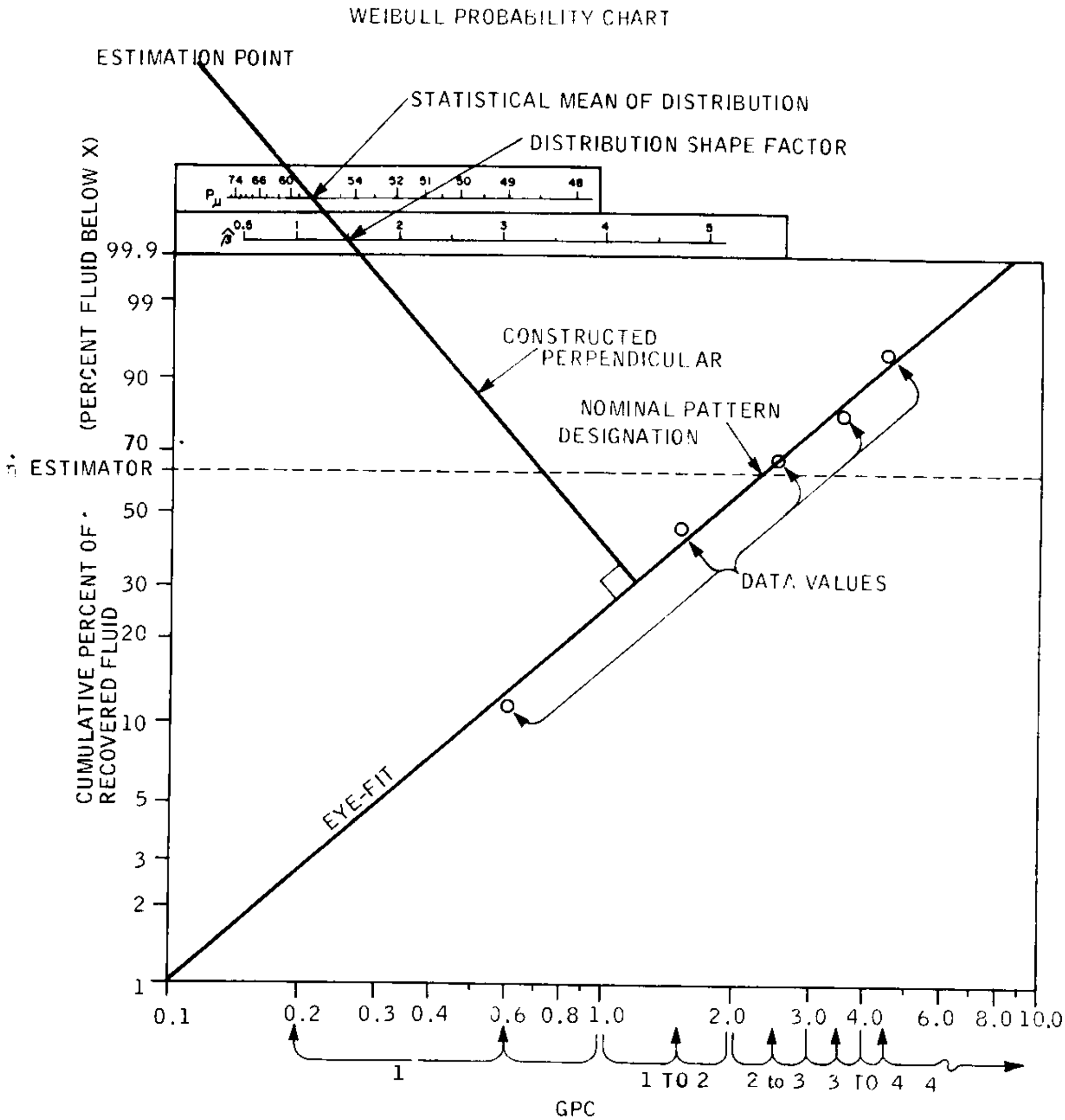


Figure 75. Use of the Weibull to Compare Patterns

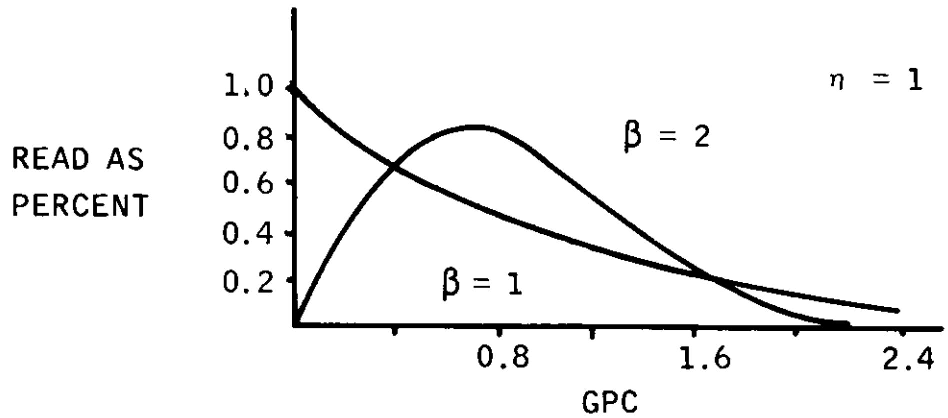


Figure 76. Weibull Distribution

The altitude variation in pattern was of primary interest because the basic MacPhearson model assumes the pattern to be steady state after the termination of the breakup phase. Figure 77 shows the altitude-related change in β as a function of altitude for the CL-215 drops. Figure 78 shows the change in η as a function of altitude for three quantities. There is also evidence that different η decline curves also result from trajectory values.

Most significantly, however, the conclusions of the Weibull study show the following:

1. A large number of patterns have been subject to this analysis, and with few exceptions the data show a good linear fit relationship.

2. The η value is sufficiently sensitive to parametric variations to be a high resolution technique of measuring performance differences between tanks.

3. An appropriate η altitude curve can be applied to approximate the cross-range development of patterns as a function of altitude. (This technique was applied in patterns of Figure 76.)

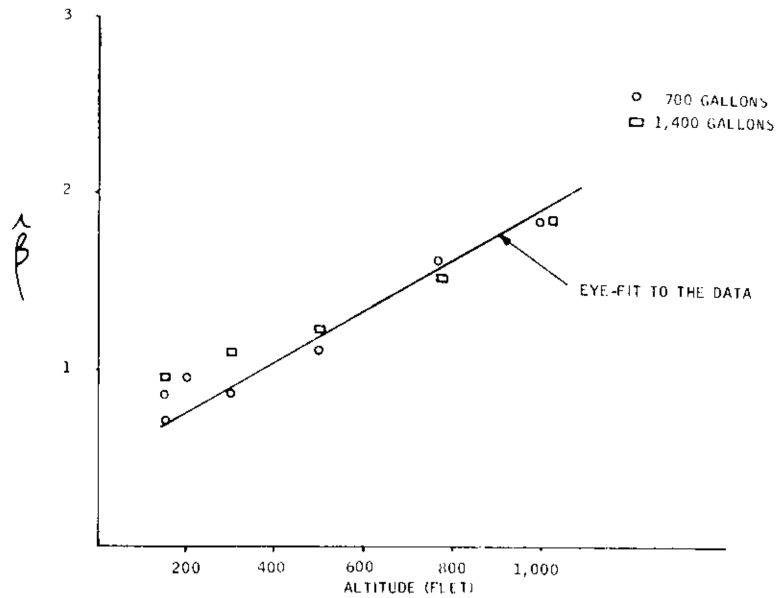


Figure 77. Beta Estimate Versus Altitude

Items 1 and 3, when taken together, show that there are certain limitations to the current model in the development of cross range. Specifically, it was originally assumed that, using a normal cross-range distribution, a set of sigma values (critical values related to gpc) could be selected such that the Weibull distribution characteristics of the pattern would be preserved. (These Weibull representations have been shown repeatedly to provide a good fit to actual pattern representations.) However, it was found that the surface generated by applying the normal assumption cannot be sectioned by constant sigma values in a manner that yields a fit to the Weibull distribution, except in a very limited range. This discovery is significant in that it casts doubt on the normal cross-range distribution heretofore assumed.

Although the difficulty cannot be solved until refinement of the basic model through experimentation is accomplished, this consideration leads to the basic proposition of an extended model.

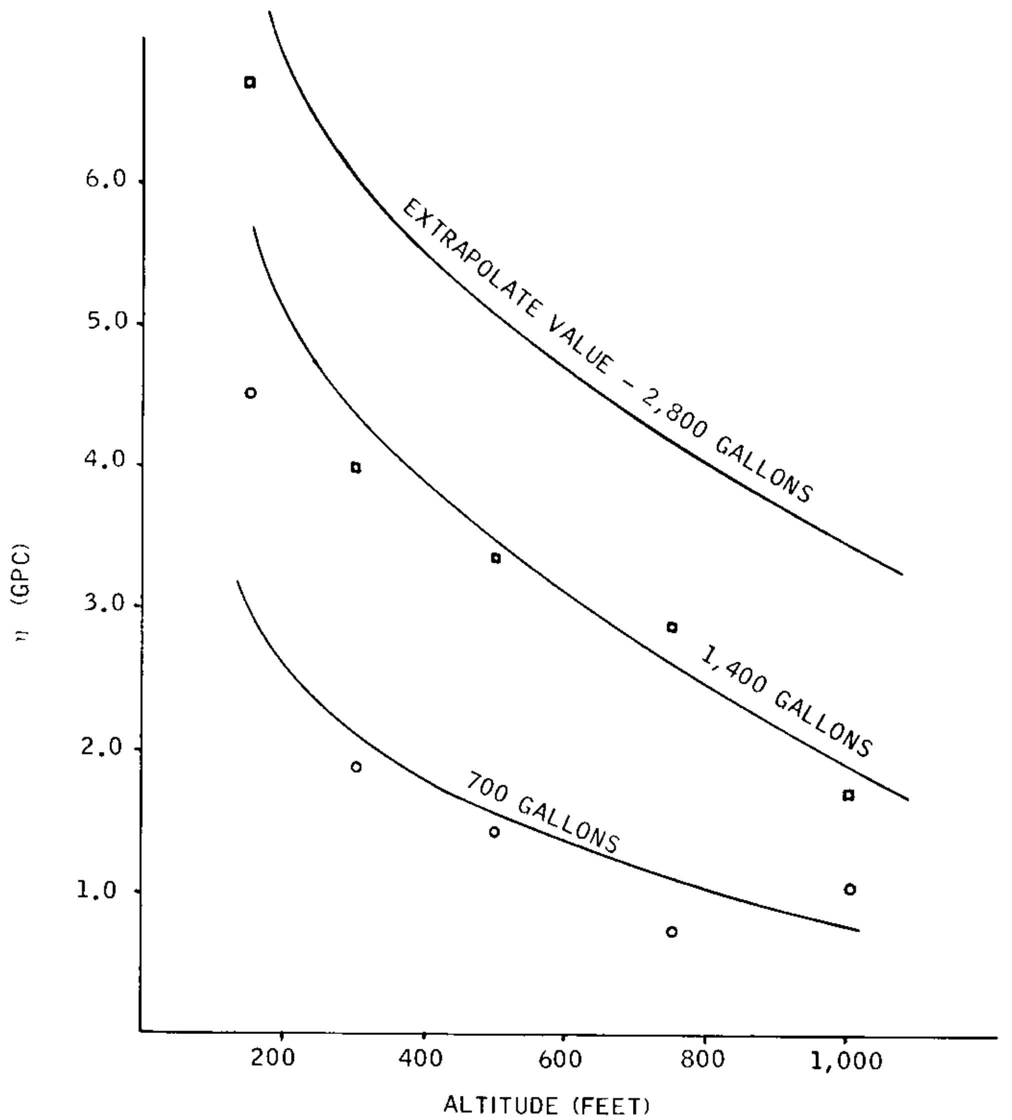


Figure 78. Eta GPC Versus Altitude

D. EXTENDED DROP DISPERSION MODEL

In the extended model, the cross-range pattern development is viewed as two independently changing distributions. Specifically, this approach starts with the spatial distribution of mass from the MacPhearson simulation (Figure 79). Cell zones are identified that separate the mass field into steady-state products and products subject to continued change. Figure 80 shows the generalized operation of this model in developing pattern plots. The large volume cells are identified. The terminal product distribution is characterized by a moderately expanding normal distribution in cross range. Large-mass particles are characterized by a more radically changing parabolic distribution. The sum of these distributions taken over the range distribution yield a surface with enough variability to be constrained to Weibull distribution parameters. The model is now operable; however, its calibration was beyond the scope of the current contract and of limited value until experimental checkout of other model aspects.

TABULATED MASS FROM MAC PHEARSON

25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500	525	550
0.455	0.459	0.292	0.259	0.198	0.045																
0.001	0.094	0.170	0.274	0.441	0.711	0.600	0.617	0.205													
	0.004	0.063	0.109	0.171	0.278	0.449	0.752	1.202	1.245	0.757	0.126										
		0.007	0.050	0.086	0.135	0.217	0.354	0.575	0.934	1.544	1.804	0.908									
			0.010	0.045	0.076	0.118	0.191	0.305	0.503	0.804	1.343	2.171	2.628	0.234							
				0.013	0.043	0.069	0.110	0.176	[illegible]	[illegible]	0.755	1.244	2.029	3.317	1.640						
					0.020	0.045	0.074	0.116	[illegible]	[illegible]	0.499	0.797	1.329	2.128	2.908	1.986					
						0.025	0.045	0.072	[illegible]	[illegible]	0.306	0.495	0.796	1.350	2.154	3.534	2.735				
						0.001	0.029	0.046	0.076	0.121	0.197	0.315	0.512	0.834	1.376	2.237	3.648				
							0.003	0.034	0.051	0.011	0.131	0.212	0.334	0.550	0.896	1.464	2.482		2.315		
								0.007	0.038	0.057	0.089	0.144	0.231	0.375	0.606	0.995	1.622	[illegible]	3.153	2.601	
									0.012	0.044	0.067	0.104	0.167	0.268	0.435	0.695	1.142	1.893	3.835	2.801	
										0.026	0.069	0.102	0.158	0.256	0.410	0.660	1.878	1.714	2.579	0.814	

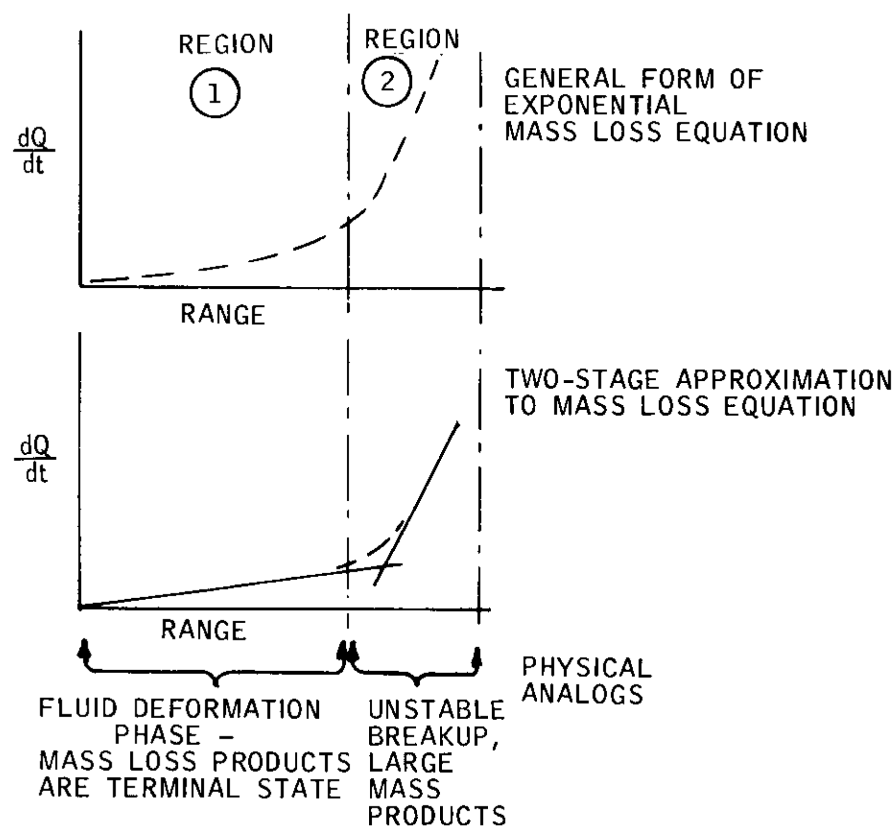


Figure 79. Theoretical Basis for the Modified Pattern Development Program

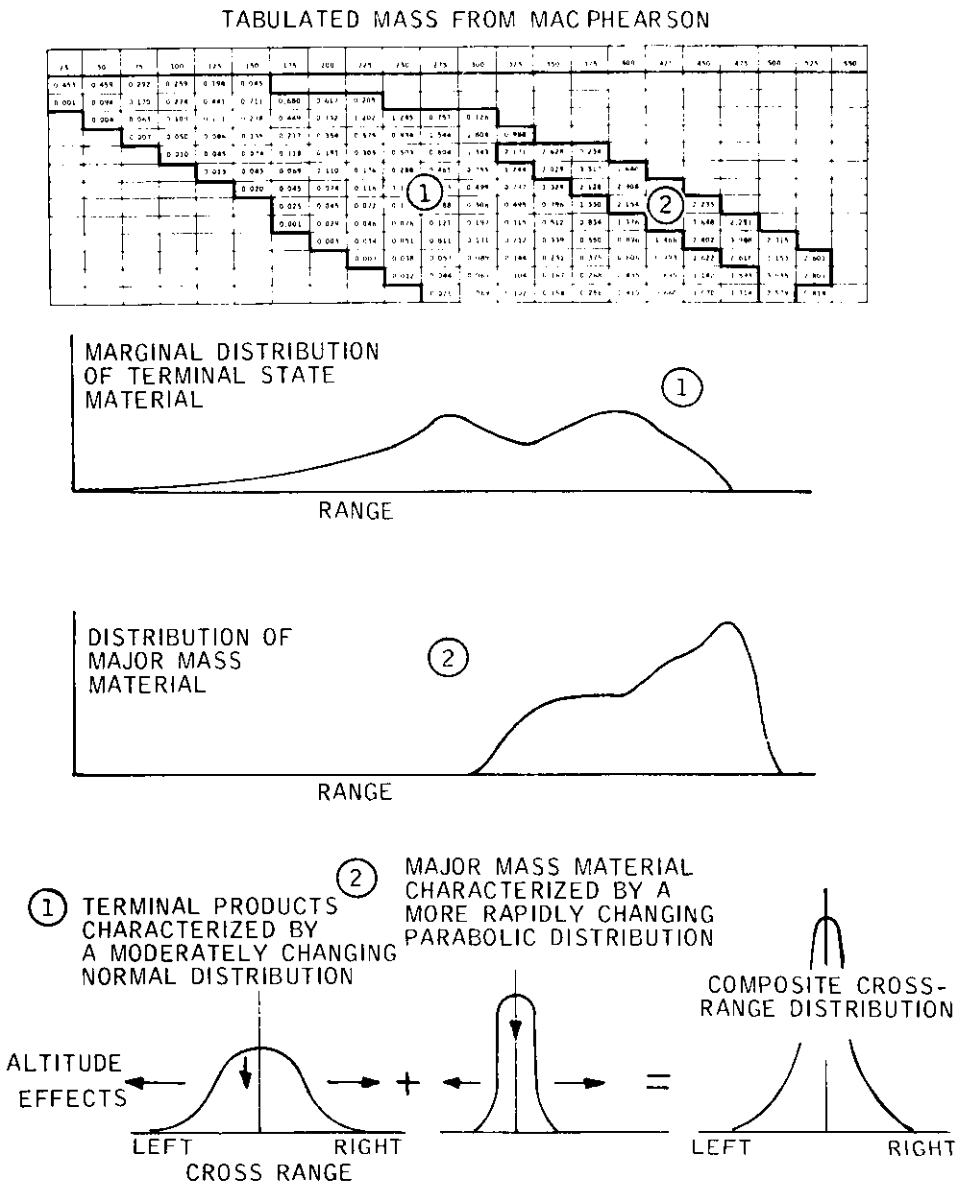


Figure 80. Schematic Outline of Method of Generating Cross-Range Distributions Constrainable to Weibull Values

V. RECOMMENDATION FOR A TEST BED TANKING SYSTEM

Current capabilities of retardant delivery modeling account for certain dominant characteristics of the tank and gating system and enable tracing the effect of these tanking parameters to the ground patterns. There remain differences in performance that are not accountable directly through parameters of interest; these include the effect of release geometry on trajectory and pattern formation as well as the effect of multiple tank arrangements.

To incorporate these values into the model, two steps are necessary. First, the actual input data to the model must be ascertained. Specifically, flow-rate histograms and door-opening rates must be measured. This results because within the current limits of certainty on these measureable values there is little resolution of the effects of subordinate variables. Firm values on these inputs can be expected to resolve differences in tank performance resulting from factors other than flow rate and door rates that are expected to exert an influence on performance. Secondly, the model should be refined and validated using a relatively noise-free, calibrated tank to increase the resolution and yield a generalized design model.

Such a model can be used to: (1) prepare usage guidelines for current tankers, (2) assist in evaluating practical design modifications that would improve performance, and (3) generate guidelines and specific requirements to assure that optimum performance is achieved in any new tanking systems built. It is a design aid that will work in conjunction with systems analysis studies on tactical mission effectiveness to assure maximum tanker performance against a wide spectrum of fires.

For this reason it was recommended that a definitive experiment be planned in support of model development. It was further recommended than an experimental tank be developed. Such a tank can also serve as a reference standard for testing of retardants as improvements are advanced. The substance of this recommendation was approved by the Forest Service and became, with additional data analysis incorporated in previous discussions, the basis for final stages of effort under the contract.

In addition to the recommended experiment, it was also recommended that tank and gating performance be recovered if possible from one or more of the aircraft used in the Maranna test series as an immediate aid in refining the models.

The following subsection presents the recommended test plan and a general specification for a tank and gating system to carry out the tests.

A. RECOMMENDED TEST PLAN

1. Purpose

The purpose of this test is to generate data for use in refining and extending the simulation capability for a computer prediction of pattern performance as a function of tank and gating system parameters. Ultimately, this program will prepare usage guidelines for current tankers, assist in evaluating practical design modifications that might improve performance, and generate guidelines and requirements to assure optimum performance is achieved in any new tanking systems built. It is a design aid that will work in conjunction with projected mission effectiveness determinations to assure maximum tanker effectiveness against a wide spectrum of fires.

2. Basic Approach

The approach used in this test is to establish a reference standard performance curve for a fixed tank of known release characteristics over a range of altitudes. This standard is then perturbed systematically to determine the quantitative effect on performance of tank variables as shown in Figure 81.

Figure 82 shows the conceptual tank in the test data matrix, as an aid to understanding the interrelationship of varying parameters in the test discussion to follow.

The basic data requirements from each test are as follows, although other relevant data similar to that now recorded should be collected as a matter of record.

a. Preflight Flow-Rate Tests: These tests measure tank flow dynamics required for calibrating the initial part of the simulation prograns and for establishing fixed known characteristics for the tanking combinations used in the drop.

b. Trajectory Data: These data are required for adjustment of control constants in the early trajectory portion of the similation leading to the completion of the breakup phase. They are also required in cross range to assess the lateral development of patterns during the breakup phase. A third value of the trajectory information is a suspected correlation between pattern values in terms of the Weibull η parameter and the characteristic change in trajectory. If established, this correlation could reduce the number of tests in the later portions of the perturbation study.

c. Pattern Coverage Data: These data are required to relate performance to prior test tank results, to confirm marginal distribution predictions, and to aid in developing rigorous cross-range subroutines for the predictive program.

TANKING VARIABLES	AIRCRAFT/RETARDANT VARIABLES
EXIT CONFIGURATION	ALTITUDE
FLOW RATE • DOOR OPENING RATE • DOOR AREA • HYDRAULIC HEAD • REGULATED PRESSURE	VELOCITY VISCOSITY
QUANTITY	
TANK-TO-TANK COMBINATION	

INDEPENDENT VARIABLES
• RETARDANT TRAJECTORY • PATTERN SAMPLE VALUES

Figure 81. Quantative Effect on Performance of Tank Variables

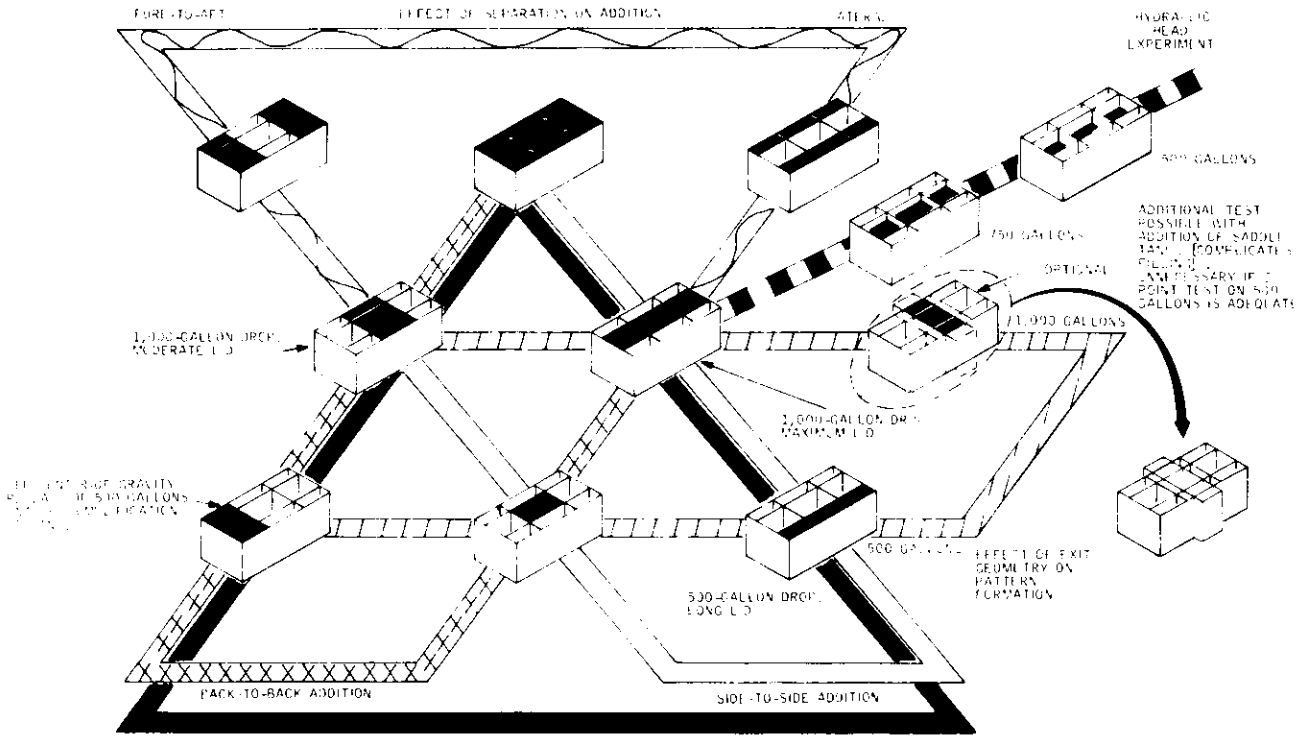


Figure 82. Conceptual Tank in the Test Data Matrix

3. Preflight Tank Tests

Prior to flight tests the experimental tank and gating system shall be subject to ground tests to determine flow rate characteristics for each possible test condition. These tests require:

- Histograms of the actual flow rate in cubic feet per second at 0.1 second (or continuous) increments from the door-opening command to tank evacuation.
- Door-opening rate histories from door-opening command to full open.
- Lateral impetus to the fluid caused by partially open doors should also be recorded on film as a matter of interest. This is particularly significant when it contributes to the intermingling of fluid released from adjacent tanks.

4. Tests to Establish Reference Standard Performance

The reference standard will be established using a 1,000-gallon nominal tank in a sequence of tests to determine pattern change as a function of altitude as measured in the η and β parameters of the Weilbull statistics. The following altitudes are recommended: 150, 300, 500, 700 and 1,000 feet.

Tolerances on altitude are not critical in these tests provided actual values are obtainable. Precision depends to some extent on the ability to control aircraft retardant variables, specifically viscosity and release velocity.

NOTE: Examination of Maranna Test data suggests that viscosity can be controlled within $\pm$ 2 poise. The error in η introduced by these tolerances is on the order of $\pm$ 0.06 and is not thought to be significant. Aircraft velocity appears to be controllable within ± 5 knots of the planned value yielding an error of about ± 0.05 in η that is again of minor significance.

5. Perturbation Study on Aircraft/Retardant Variables

Although aircraft velocity and retardant viscosity are not specifically related to tanking parameters, it is desirable to conduct a perturbation study regarding their effects on pattern performance and to provide additional information on these effects for use in modeling.

a. Aircraft Velocity -- The variability achievable in aircraft velocity is on the order of 30 knots, or ± 15 knots from the reference standard. This does not afford a major perturbation in η values; however, for trajectory purposes and to assist in compensating velocity variables it is recommended that two tests be conducted at approximately fixed altitude (300 feet).

Maximum delivery speed

Minimum delivery speed.

b. Retardant Viscosity -- Considerable variation can be provided in retardant viscosity. The following tests are recommended:

	Viscosity Variation	
Altitude (feet)	(poise above standard)	(poise below standard)
300	10	10
500	10	10

An additional two tests at approximately 5 poise below the reference standard at each 300 and 500 feet is desirable, but not mandatory.

6. Perturbation Tests on Gravity Feed Tank Parameters

NOTE: These tests are separated from tests requiring pressure to establish a hierarchy of potential equipment requirements.

a. Tests to Determine the Effects of Quantity on Pattern and Trajectory -- These tests are used in conjunction with data on release configurations and methods of tank addition to determine performance parameters so that no scaling as such is necessary in terms of configuration. It is recommended, however, that the 500-gallon drop be achieved by releasing the central half of the reference 1,000-gallon load (i.e., using the same doors and hydraulic head). It is also recommended that the 2,000-gallon drop use the reference 1,000 gallons plus an additional 1,000 gallons from an adjacent tank(s).

	Altitude (feet)		
	150	300	500
500 gallons	X	X	X
2,000 gallons	X	X	X

NOTE: The 1,000-gallon reference standard will also be the result of adding two separate 500-gallon tanks back-to-back. The 2,000-gallon drop will be the result of adding two 500-gallon tanks, one on either side of the reference 1,000-gallon drop.

b. Tests to Determine the Effect of Hydraulic Head on Reference Standard Performance -- These tests are optional in terms of asserting modeling variables, but they represent real world constraints where altitude density or runway limits may require partial loading of the aircraft. The tests use the reference standard tank operating at three-quarter and one-half volume. In this way the one-half volume drop shows in relation to the reference standard the effect of adding 500 gallons as head rather than door area. The three-quarter drop is simply an intermediate value to allow extrapolation.

	Altitude (feet)	
	150	300
Head Three-quarters of Reference Standard	X	X
Head One-Half of Reference Standard	X	X

c. <u>Tests to Establish Effect of Exit Geometry on Pattern Formation and Trajectory</u> -- These tests are believed critical to the resolution of performance differences, particularly in the relatively unquantified area of shape effects on breakup and cross-range developments. They have been defined in conjunction with test tank design studies to yield a maximum of information without cluttering the tank. They provide one length-to-diameter variation on the 1,000-gallon standard and two length-to-diameter variations on the previous 500-gallon drop. The data are also used in conjunction with the test matrix to assess techniques of addition.

	Altitude (feet)		
	150	300	500
1,000-gallon; Moderate L:D		X	X
500-gallon; Long L:D	X	X	
500-gallon; Short L:D	X	X	

d. <u>Tests to Determine the Effect of Tank Separation on Pattern and Trajectory</u> -- To preserve aircraft center-of-gravity requirements, it is often necessary to add tanks from fundamentally separated locations. These four tests are used to determine the relative significance of lateral and horizontal separation.

	Altitude (feet)	
	150	300
Two laterally separated 500-gallon tanks	X	X
Two longitudinally separated 500-gallon tanks	X	X

e. Tests to Confirm Door Rate and Area on Flow Rate Parameters Contributing to Pattern -- Simulation work to date indicates that door-opening rate and area are the most significant tank parameters contributing to pattern results. These tests are designed to provide data on these parameters rather than to assert a specific requirement. The reference 1,000-gallon tank is used in these experiments with the door arrangement shown in Figure 83.

(1) Door Area -- The two-part door on the central tank allows three tank release areas from unrestricted flow (full open) to one-third restricted and two-thirds restricted. (These values are roughly equivalent to the restrictions provided in the PB4Y2 tank and the Aero Untion trail doors. The total matrix, then, represents three different flow rates. Additional tests are:

	Altitude (feet)		
	150	300	*500 feet
One-third open	X	X	X
Two-thirds open	X	X	X

* Optional: necessity determined after basic data set.

(2) Door Rate -- The door rate on the standard 1000-gallon should be reasonably fast (full open in about 1 second). In this test the door rate must be changed.

	Altitude (feet)	
	150	300
Increased Door Rate ~ 0.5 seconds	X	X
Decreased Door Rate ~ 1.5 seconds	X	X

(3) Dual Rate Door -- Simulation studies have indicated that flow rate can be prolonged by modulation afforded by a dual-rate door (see Section VI, D). This door opens fast to a preset distance at which point it encounters a hydraulic (or mechanical) stop that resists and slows opening of the door to its fully open position. The experiment will be conducted using the one-third door on

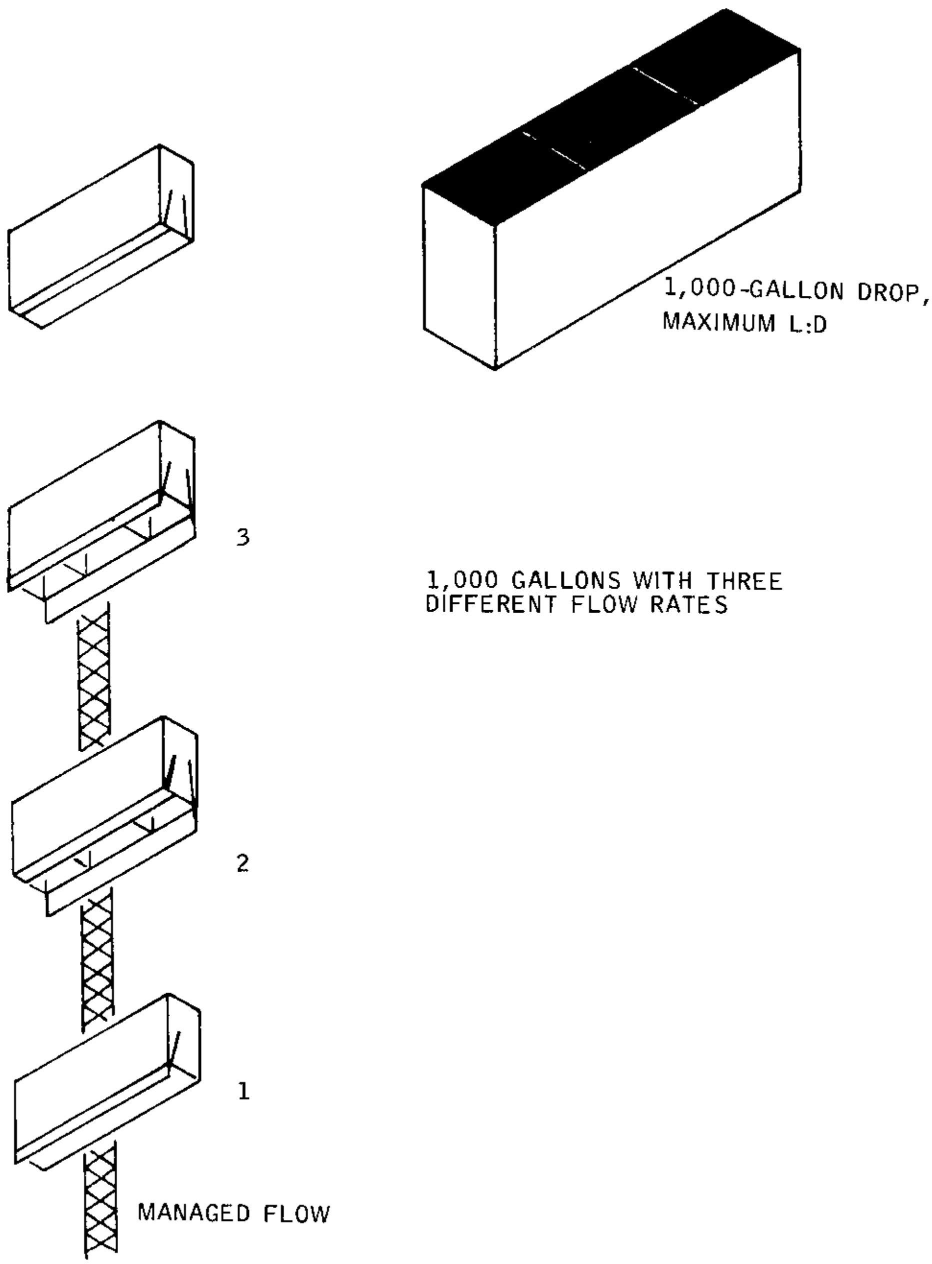


Figure 83. Managed Flow Experiment

the reference 1, 000-gallon tank. Opening rate shall be the reference rate through the first 50 degrees of travel, at which point the rate will reduced such that the average opening rate for the final 40 degrees of travel shall be one-half the reference rate.

This demonstration will require two tests, one at the altitude yielding the best 2-gpc line from the one-third door constant rate test and one at a planned altitude expected to yield the most line at 2-gpc from examination of the door area test data.

f. Tests Requiring Regulated Pressure -- A potentially significant improvement in the flexibility of line building has been shown in simulations. This improvement is the result of using four door areas and two low pressures. The regulated pressure is the single variable under examination here because the rules of door combination have been separately considered. Pressure levels required are to replace head lost during release, thus achieving a relatively constant flow rate, and to increase the ejection velocity approximately 25 fps. Pressures required must be regulated to provide a continuously increasing pressure up to about 6 psi. These tests shall be conducted with the reference 1, 000-gallon tank and the one-third door opening (constant rate door).

Two tests will be run at the altitudes selected for (1) above for each pressure condition.

Application of regulated pressure demands more in terms of hardware development and could potentially require additional tests simply to establish hardware performance. It is nonetheless recommended that the test tank be designed to accommodate the requisite pressures, on the order of 10 psi maximum, to enable subsequent modification even if pressure is not included in the initial tests.

B. GENERAL SPECIFICATION: EXPERIMENTAL TANK AND GATING SYSTEM

1. Purpose

This specification establishes requirements for an Experimental Tank and Gating System (ETGS) for use in a definitive experiment to perfect and extend computer models of tank performance.

2. Intent

The ETGS is applicable in principle to any suitable aircraft (i. e., any aircraft capable of carrying the tank specified herein with sufficient performance capability and avionic instrumentation to hold delivery conditions within tolerances specified in the test plan). The nominal 2, 000-gallon maximum capacity does not necessarily attempt to maximize the load of any particular aircraft. Adaptation of the tank to a specific aircraft can be accomplished by a modular tank, modification to an existing tank, or a new integral tank design. Dimensional adjustments or departures from nominal values are not critical as long as the basic interrelationships of the configuration are maintained. In case of conflict, the requirements and intent of the test plan will supersede requirements expressed herein.

3. Tank Capacity

Minimum total capacity shall be 1, 600 gallons (2, 000 gallons desired). Subordinate capacities shall enable the release of one-half the total capacity and one-quarter the total capacity as specified in the configuration portion of this specification and the test plan.

(Nominal values of 2, 000, 1, 000, and 500 gallons are used in this specification.)

Compartment volumes including internal structure shall be within 5 percent of the selected design values.

4. Compartment Configuration

The tank shall be divided into nine separately fillable compartments with the dimensional relationships shown in Figure 84. This will enable the delivery of (1) the total volume, (2) one-half the total volume, and (3) one-quarter the total volume in the release configurations shown.

NOTE: Although most of the release configurations are symmetrical about the tank center of gravity, two of the tests require release of one-quarter capacity from off-center positions. If this release cannot be achieved within center-of-gravity limits of the tank/aircraft, an alternative solution must be applied. A suitable alternative is shown as an example in Figure 85. This preserves the three-point experiment on length-to-width ratio with a 1,000-gallon drop (in lieu of the 500-gallon drop), at the expense of additional doors and filling complexity.

The long central tank with a nominal capacity of 1,000 gallons shall be designated the Standard Tank. It is this release configuration against which all other perturbations are measured. This configuration will be used as the datum reference for all related compartmental volumes.

Configuration of the tanking system shall provide for release of a fixed volume, with three variations in the release configuration expressed as a length-to-width ratio (measured with the length on the flight path). Although experimental intent can be preserved with considerable variations in the actual values, the following guidelines can be established.

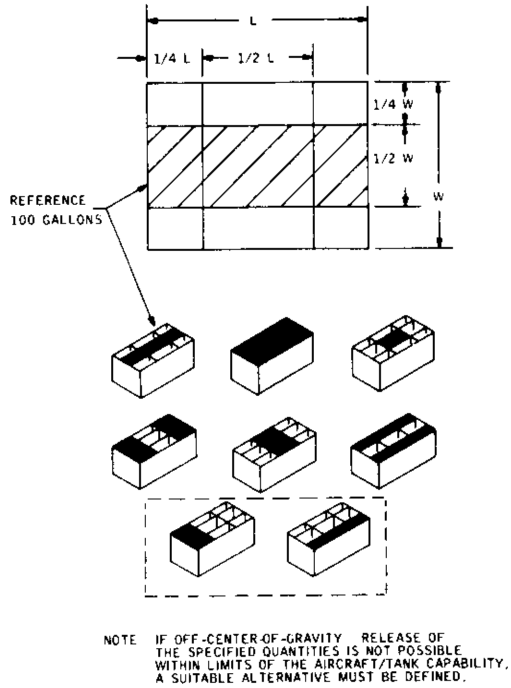


Figure 84. General Compartment Configuration

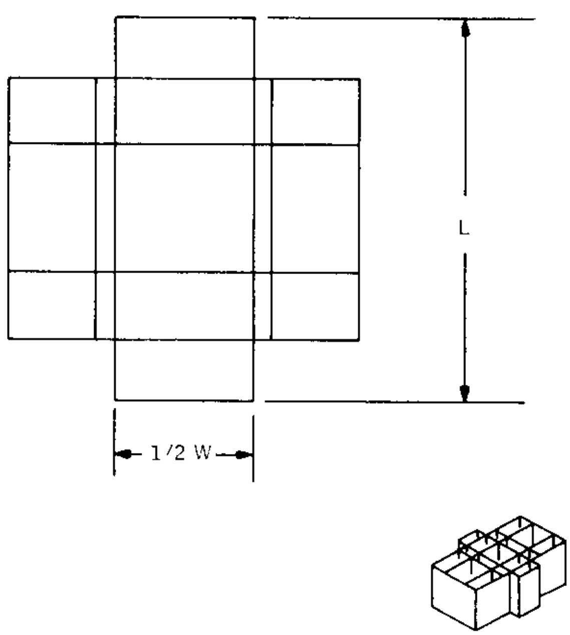


Figure 85. Example of Alternative Configuration to Preserve Test Data with all Releases Symmetrical with Respect to Tank Center of Gravity

Minimum Length of Lowest L:W release	–	2 feet
Nominal Length of Intermediate L:W	–	4 to 5 feet
Nominal Maximum Length of Highest L:W	–	10 feet.

5. Hydraulic Head

The minimum nominal value for hydraulic head for the filled tank shall be 4 feet.

Provisions must be incorporated for assuring that the required hydraulic head is constant within each of the separately fillable compartments. This may be accomplished by (1) inherent tanking characteristics, (2) direct measurement techniques, or (3) intercompartment valving.

Provisions must be incorporated to allow the downloading (partial filling) of the Standard Tank compartments to three-quarter and one-half of the filled tank head, with the same constant value within each of the compartments equaling that volume.

Head tolerances shall be maintained such that the volumes involved are within 5 percent of nominal.

6. Door Characteristics

NOTE: The door arrangement (Figure 86) shall provide for release of the individually fillable tank compartments. In most of the experiments, all doors will be opened simultaneously, with the quantity regulation provided by the filled increments. In a subsidiary set of experiments on door area and opening rate, the doors on the Standard Tank are required to open independently and with rate variations.

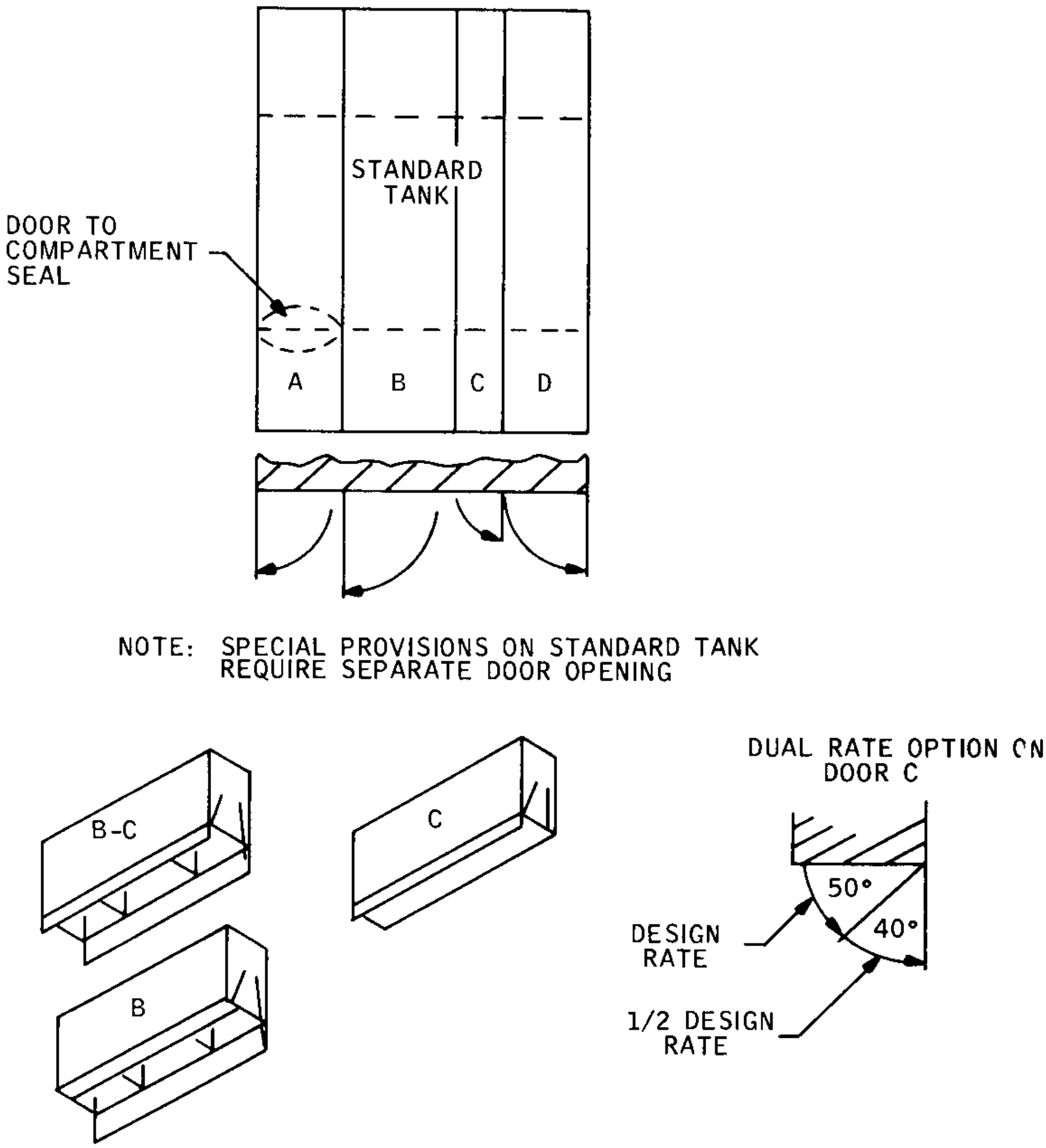


Figure 86. Door System for Test Tank and Gating System

a. General Door-Opening Requirements --

(1) Door-Opening Rate -- Nominal door-opening rate shall be 1.4 seconds (or less) from first opening to the fully open condition under load. The rate should be repeatable within ± 0.2 seconds, with greater repeatability desired.

(2) Door Area -- Open door areas for each release configuration shall be in the same ratios as the volume (within about 5 percent on area basis).

(3) Sealing -- Door-to-compartment seals shall prevent leakage from full to empty compartments prior to release.

(4) General Construction -- The internal clutter resulting from door-supporting structure and actuators shall be minimized.

b. Special Provisions on the Door System for the Standard Tank -- The Standard Tank shall be provided with two doors, one opening one-third of the tank width and the other opening two-thirds of the tank width, to evaluate the effects of restricted (or managed) flow on pattern formation. Both doors must be capable of independent opening at the established nominal rate.

A fast-opening rate shall be provided for the doors of the Standard Tank to provide opening at approximately twice the basic rate, i.e., to fully open in 0.5 to 0.7 seconds. This rate shall be repeatable within 0.1 second.

The two-thirds width of the Standard Tank must withstand pressure during evacuation,(with the smaller door open)equivalent to at least twice the width of the hydraulic head with a moderate additional margin (10 percent).

The one-third width door of the Standard Volume shall also provide the capability to open the door 50 degrees at the nominal rate and complete opening through the use of a mechanical or hydraulic stop at an average rate of one-half the nominal for the remaining 40 degrees of travel to allow the effect of door modulation on managing flow rate to be tested.

7. Venting

Venting for all release configurations shall be sufficient to preclude development of negative pressures (less than ambient static) for all release conditions.

Venting on the Standard Tank shall be closable when pressurization options are under test.

8. Regulated Pressure

The Standard Tank shall be able to be pressurized on door opening to the extent necessary to achieve the following performance:

1. Regulate pressure sufficiently to offset gravity head loss in achieving near constant flow rate from the one-third door exit.

2. Regulate pressure to achieve near constant flow at an evacuation rate equivalent to that achieveable with approximately 30 percent greater ejection velocity.

Since the pressurization will be initiated only on door opening, the doors are not required to retain the load under pressure conditions. (For a 4-foot tank, peak pressures will be on the order of 6 psi.)

Regulated pressure shall be provided to two levels from the time of door opening to tank evacuation as expressed above and explained in the following paragraph. Because the intent of this experiment is to generate an approximately constant volume flow rate, regulation shall be provided such that

Pressure X Volume increases constantly with time.

The constant flow rate to be approximated shall be selected as the peak value of flow rate achieved from the one-third door of the Standard Tank.

NOTE: Pressures required are low, 0 to 1.7 psi (4-foot head) in the head replacement case and 0 to 6.5 psi in the increased rate case. Flow rate is high, on the order of 2,600 cubic feet per minute. Regulation may be provided either by a time-calibrated valving arrangement or through a closed-loop system operating off head measurement. Because intent of this experiment is to assess the regulation as it affects flow, an approximate technique is acceptable and Bernoulli equations may be used:

$$P + 1/2\, \rho V^2 + \rho g Z = K$$

where

P is the pressure (pound/feet^2)

ρ is the fluid density (slug/feet^3)

V is the velocity (fps) calculated from simulation or obtained from test on an unpressurized tank.

Z is the head height (feet).

Initial ejection velocity from the MacPhearson simulation is 18.5 fps for a 4-foot initial head. Sloving for K under this

$$P + \rho g Z = 250 \text{ (pound/feet}^2)$$

Under these conditions, the range of regulated pressure is 0 to 1.7 psi.

For an ejection velocity of 30 percent greater (25 fps),

$$P + \rho g Z = 930 \text{ (pound/feet}^2\text{)}$$

Under these conditions, the range of regulated pressure is 0 to 6.5 psi.

Design provisions for including the pressurization option will include a suitable pressure generator or accumulator, plumbing, and valving which shall be considered part of the total weight for purposes of aircraft loading.

9. Instrumentation

The ETGS shall provide a flash indication of sufficient intensity, duration, and location to be visible from ground cameras upon (1) receipt of the command to open the doors and (2) the completion of door opening.

It is desirable that the tank include instrumentation to measure door-opening time histories and to record flow rate histories of tank evacuation and pressure during release. This will be possible both in flight and during ground tests. These records should be referenced in time to the command signal for release as shown in Figure 87.

It is desirable (but not mandatory) that appropriate aircraft flight data immediately prior to and during release be collected on the same time base. Such data may include airspeed, groundspeed, altitude, and acceleration.

10. General Construction

The ETGS will provide for regulated loading of the separately fillable compartments that facilitates quick turnaround and adequate control.

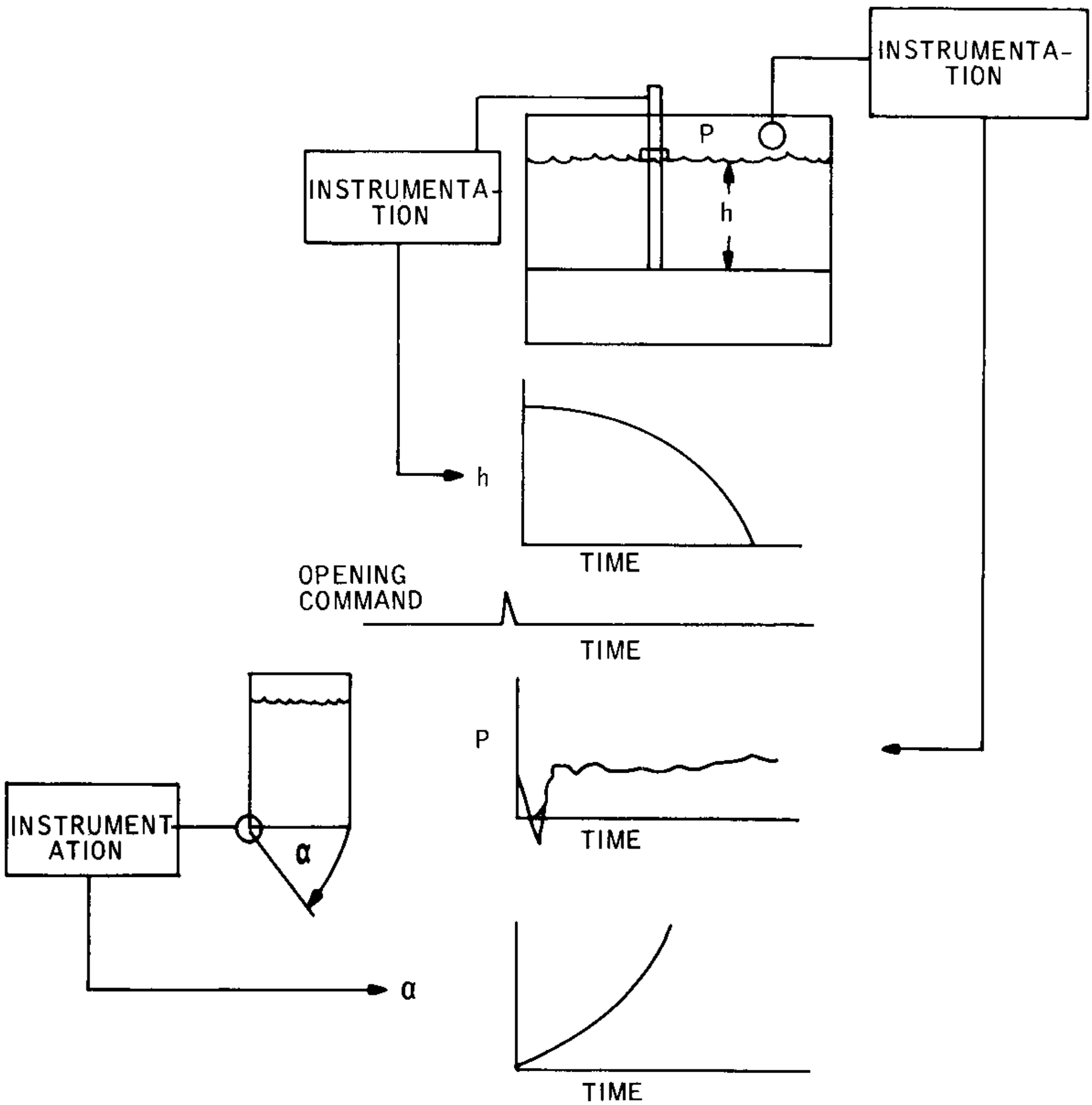


Figure 87. Schematic of Desired Tank Instrumentation

The ETGS will be designed so as to be structurally and functionally safe for use with the selected aircraft.

The tank will preserve center-of-gravity shift limits within those compatible with the safety of the aircraft.

VI. CONCEPT STUDY

A. BASELINE AIRCRAFT

A requirement of the contract was evaluation of three distinct types of aircraft: Bomb Bay Release, Tail Release, and Helicopter. For purpose of the original study, the C-130, P2V, and CH-47 helicopter were chosen; the S2 and C-119 were also considered during the course of the study. Payload quantities to be considered were obtained from operator's manuals, flight handbooks, and other publications. Actual capacities vary with the specific model because of considerations for fuel load, maneuvering load factor, and structural modifications for conversion to a tanker. For study purposes, nominal payload weights were established for each of the candidate aircraft.

Other factors that should be considered in choosing a tanker are:

- Aircraft Capacity Versus Maneuverability -- The altitude breakpoint between unaided and aided accuracy is in some respects a tradeoff between aircraft capacity and maneuverability. The maneuverability index is relatively complex and beyond the scope of the current study. The effects of some of those factors are indicated in the accuracy study.

- Aircraft Visibility -- The other factor determining the altitude accuracy breakpoint is aircraft visibility. The effect of visibility is further discussed in the accuracy study.

- Aircraft Capacity -- Another factor in aircraft selection is the relative ease of tank inclusion at or near the center of gravity. In general, to achieve the levels of volumetric controls desired, the area should be free of volumetric restrictions. This suggests that high-wing aircraft are preferable to low midwing aircraft in terms of the permissibility of the design within structural restraints.

Although many of the factors in aircraft selection relate to decisions on availability, airport and runway limits, and tactical considerations beyond the scope of this study, they do influence the nature of the tank design. There is a legitimate distinction between small-capacity aircraft and large-capacity aircraft in terms of tank design characteristics. This distinction is believed to be more fundamental to the tank design problem than the distinction between tail release and bomb-bay release of the retardant loads. It further appears that the mixed-fleet concept currently in use provides a valid aircraft complement; both accurate low-level and high-capacity, high-level aircraft are available, and each would appear to be effective in different roles. Although with targeting aids and volumetric controls, high-capacity aircraft could potentially replace the small dive bomber in functional capability, there still may be tactical advantages associated with smaller aircraft in first attack and followup missions against spotting that should be preserved and improved using the techniques under development in this program. For this reason, the S2 was added to the baseline aircraft as one of the few small bomb-bay aircraft available.

B. RELEASE METHODS

Fundamentally there appears to be little difference in the pattern formed by tail or bomb-bay release. The physical principle associated with rearward ejection of the retardant mass is the relative reduction of the retardant velocity with respect to the free airstream, which in classical stripping theory suggests the formation of larger and consequently more stable drops. Our initial attempts at simulation approached the problem from this standpoint, but as shown in Section IV, this form of stripping is not a significant factor for three reasons:

1. Classical stripping off the surface of the retardant mass does not account for a significant volume loss.

2. To achieve drop size increases, the velocity must be reduced to about 60 fps requiring a considerable ejection velocity.

3. If breakup has not been induced at this point, the low-velocity retardant mass will accelerate substantially without breakup to velocities comparable to the initial release condition.

Because the survival principle is not valid, the only advantage of rear ejection is that it permits a modular tank approach. However, pressurization is required since gravity alone is inadequate to assure adequate flow from the center of gravity to the aft release point. For this reason, bomb-bay release is generally preferable to the tail-release mode.

From an engineering standpoint there are some complicating factors in tail release. Release at or near the center of gravity is easier to handle than at some other location, and it is somewhat easier to work in the direction of the gravity vector than at angles to it.

From a tactical standpoint, bomb bay aircraft are more naturally used in a dive bombing mode than their tail release relatives. These values are to a certain extent offset by the potential capacity of tail-loading cargo craft, their availability, and their potential for use (without modification) as a reserve fleet. For dedicated operation, it seems practical to consider conversion to bomb bay release in a manner similar to the current C-119 modifications.

In general, then the fundamental relationships of aircraft types can be described as follows:

First Attack Capability:	Bomb bay -- fast to the target, superior accuracy. Capable of delivering high, decisive mass in toss or dive bombing mode. Can be designed for good line building.
Sustained Attack:	Large helicopter -- can deliver a cooling flux. Superior accuracy. High-volume turnaround.
Reserve Capacity:	Unmodified (modular) tail-release aircraft -- Potentially high-volume capacity with good short-runway capability and ability to operate off relatively unimproved air strips.

C. DIRECT-ATTACK SYSTEMS

As a first concept study, let us isolate the direct-attack system. It is relatively straightforward, simple, and serves as a departure point for evaluating other systems as we proceed from the simple to the more complex. In addition, the direct-attack capability places greater restrictions on tank geometry and is therefore mcre sensitive to aircraft configuration than line-building operation.

The requirements for a deep penetration or direct-attack tank system are shown in Figure 88. Most of the characteristics have already been discussed. The significance of tank cleanliness and fast-opening doors requires some elaboration. Tank clutter produces a reduction in flow rate, but it also introduces turbulences and instabilities that contribute to early breakup of the liquid mass. Inadequate venting creates the same effect.

DESIRED CHARACTERISTICS

- LONG DOORS
- LENGTH-TO-DIAMETER RATIO OF 3 OR LESS
- MAXIMUM DOOR AREA (FLOW RATE)
- FAST-OPENING DOORS
- CLEAN TANKS

PERFORMANCE

- SMALL AIRCRAFT: 2-PASS CAPABILITY
- LARGE AIRCRAFT: 4-PASS CAPABILITY

GENERAL

- MUST FIT WITHIN ALLOWABLE AIRCRAFT GEOMETRIES
- MUST ALLOW 20 PERCENT DOWNLOADING WITHOUT MAJOR CHANGE IN PERFORMANCE
- SHOULD YIELD COMPARABLE TRAJECTORIES FOR ALL COMBINATIONS OF DROPS

Figure 88. Requirements for Deep Penetration

The significance of door-opening rate in the direct-attack mode is shown in the MacPhearson simulations in Figure 89. The door affects both the flow rate, as shown, and the geometrical shape of the emerging liquid. Trailoff is actually an insignificant portion of the losses in the salvo mode.

Figure 90 compares the effect of two door-opening rates on end performance. It shows that doubling the door speed reduces inadequate flow volumes by significant amounts.

The effect of door opening on the geometry of the early release increments is shown in Figure 91 for doors opening with a constant length to the flight path and a constant width to the flight path. In either case, the early increments are subject to degrees of premature breakup, but through different breakup principles. Neither approach eliminates the fundamental problem, but the amount of premature breakup can be minimized by increasing the door-opening rate.

The possibility of using pressure to encourage deep penetration and increase momentum was also evaluated by applying the MacPhearson simulation to a salvo drop with 7 psi and 14 psi constant pressure. Figure 92 shows that little change is caused by the pressure itself, and the effects ultimately are little different from what might be achieved if flow rate were held constant. There is also little difference in the downrange marginal distributions as shown in the figures.

The issue resolves, therefore, to the value of additional penetration (depth below the aircraft) of the high-momentum portions of the trajectory.

The trajectory comparison of Figure 93 shows that pressure on the deep-penetration tank results in about 50 feet of additional penetration. This minimal improvement (substantially less than that achieved in a dive mode), in association with the mechanical difficulties of implementing such a system,

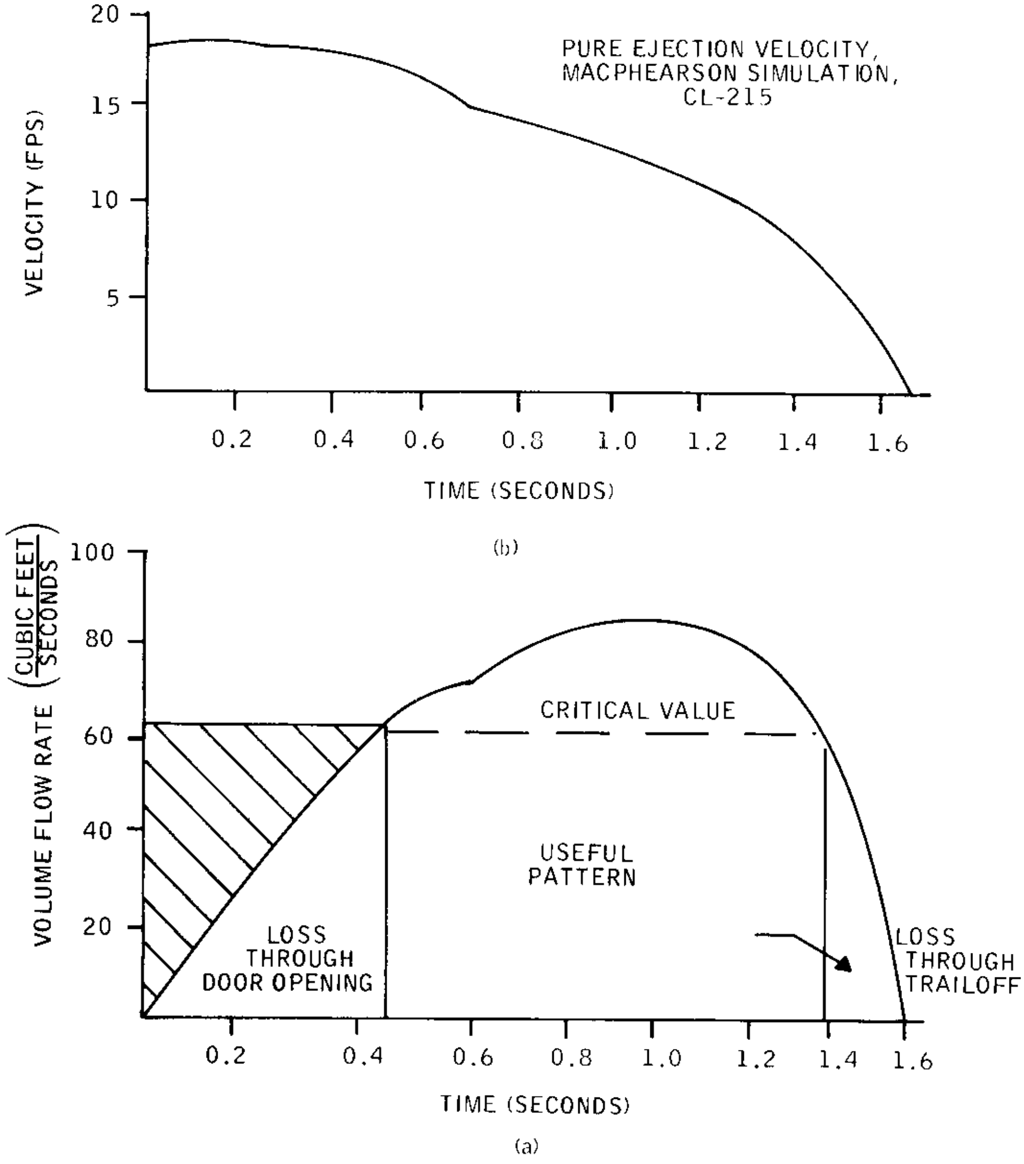


Figure 89. Influence of Door Opening on Pattern

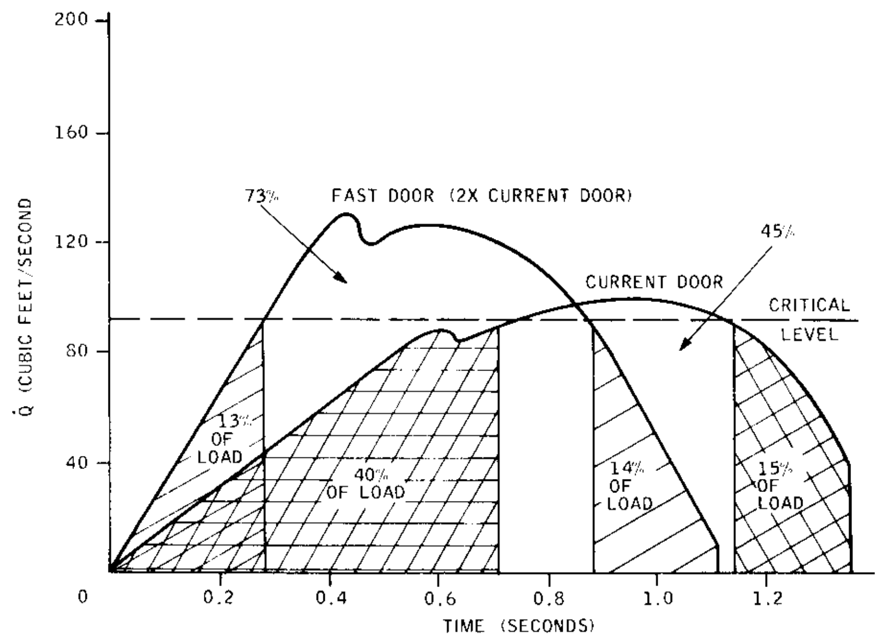


Figure 90. Effect of Fast Door Opening on Volume Flow Rates and Losses from Meaningful Pattern

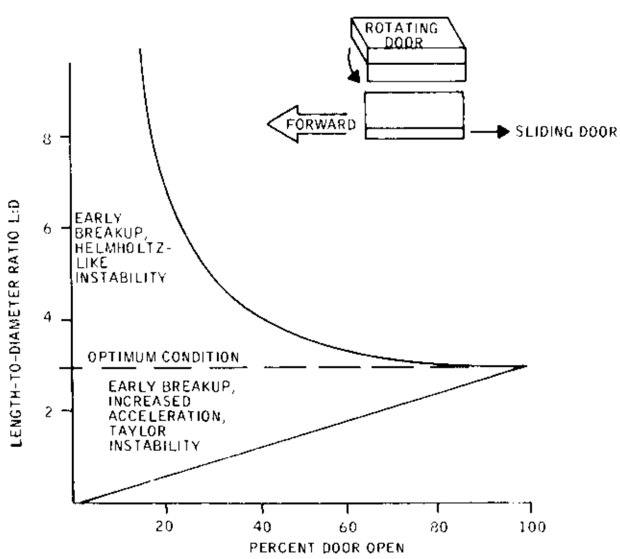


Figure 91. Changes in Geometry for Various Door Types

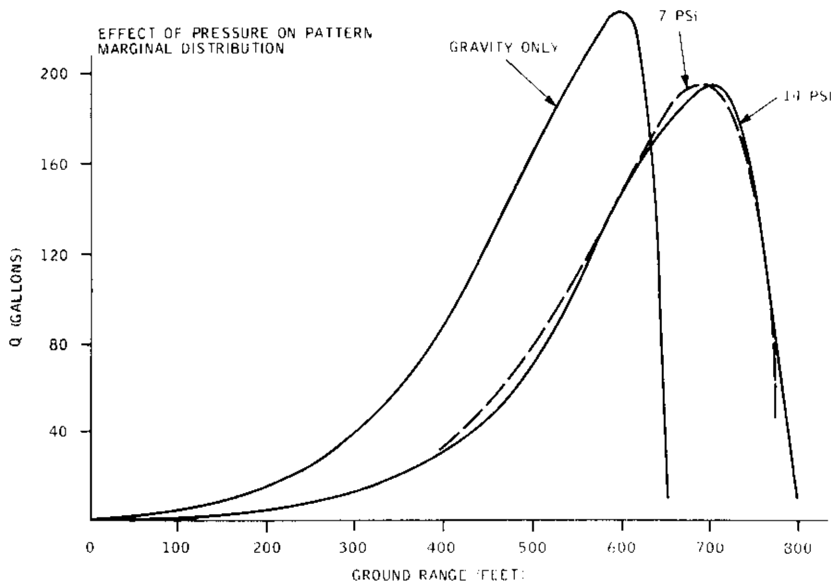
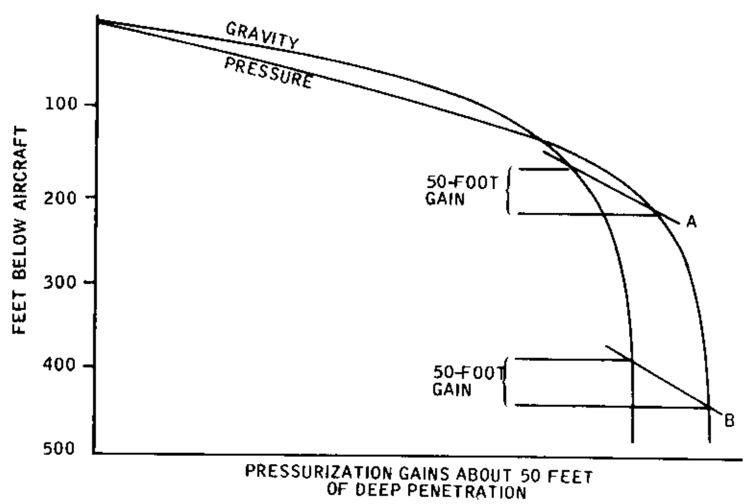


Figure 92. Effect of Pressure on Pattern Marginal Distribution



- PRESSURIZATION OF SALVO RELEASE OFFERS LITTLE IMPROVEMENT IN PERFORMANCE.
- IN ADDITION, HIGH PRESSURIZING FLUID FLOW RATES, ON THE ORDER OF 260 CUBIC FPS, MAKE THE ACHIEVEMENT OF EVEN LOW PRESSURES DIFFICULT, AND REGULATION VIRTUALLY IMPOSSIBLE.

Figure 93. Pressure Effects on Trajectory

suggests gravity release as the best technique for achieving salvo release for direct-attack missions.

One of the concepts selected for evaluation was a large aircraft designed specifically for the direct-attack mission. By definition, the large capacity value was specified to be on the order of 2,500 to 3,000 gallons. In addition, the ability to deliver effectively in four passes from a single load is desired. Typical aircraft selected were the P2V, C-119, and C-130.

The effect of release geometry on trajectory and pattern formation requires further refinement in terms of the experimental design. To explore the direct-attack concept, it was necessary to assert some dimensional characteristics. Evidence (Section IV) indicates that the length of the tank determines the initial value of acceleration on the liquid drop and, therefore, that if repeatable trajectories are desired increments should have, insofar as possible, similar length characteristics. Other evidence suggests that a tank can be too long (or concomitantly to thin), resulting in stringing out of the material. Since the critical value of this length-to-diameter value is not known, an arbitrary limit of 3:1 was assumed. A similar limit was placed on hydraulic head (length-to-head ratio).

Intent of these limits is to assure that the frontal instabilities dominate, with as little mass lost to separation due to the development of horizontal instabilities as possible. In any case, these assumptions will suffice in the preliminary generation of tanking designs for the direct-attack system until more quantitative techniques of assessing release geometry tradeoffs are developed.

Applying dimensional limits to the liquid volumes of interest, the graph of Figure 94 was developed. It allows us to select the idealized optimum tank for various values of cargo gallonage in the direct-attack mode.

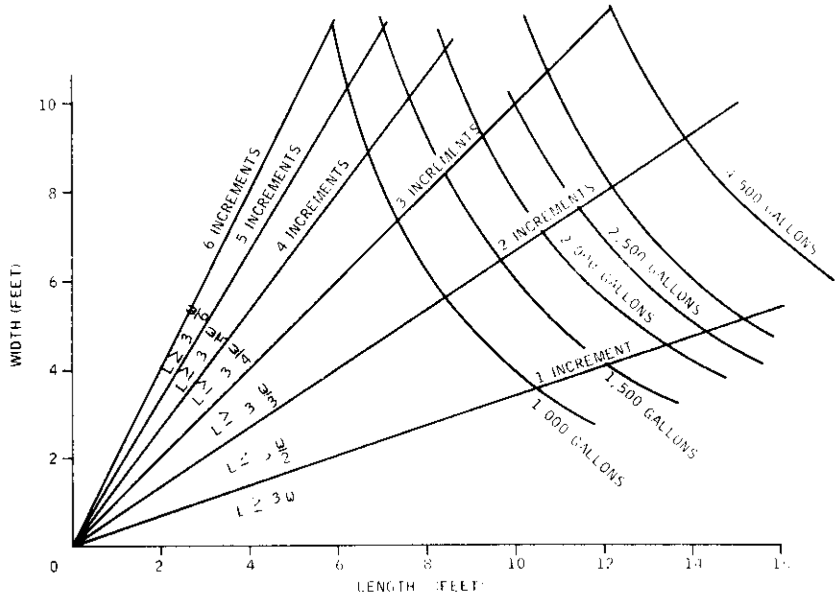
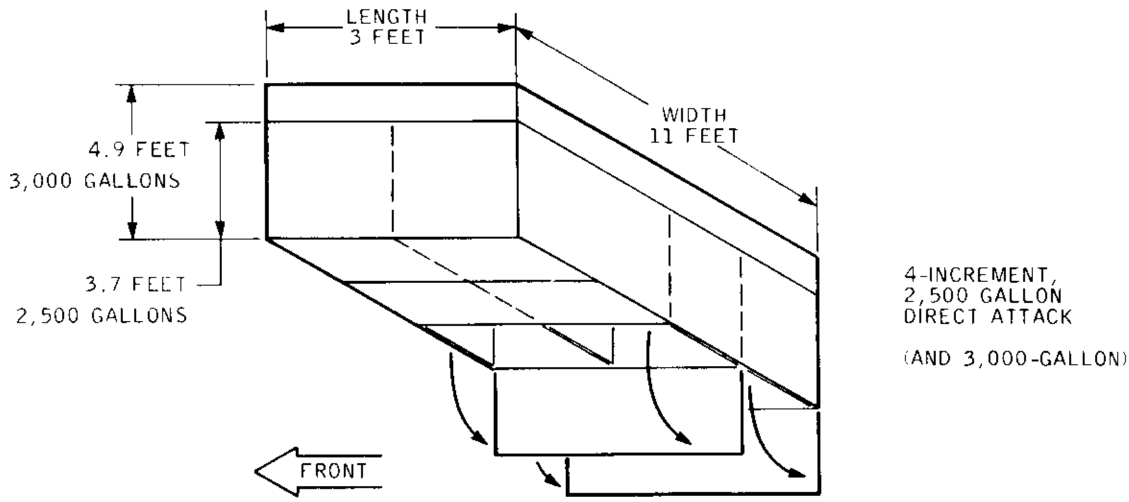


Figure 94. Door Dimension Relationships for Fixed Trajectory Systems

Figure 95 represents the abstract ideal tank for deep penetration with four increments of delivery capability, all essentially traveling in the same trajectory. The concept was generated on the basis that, if such an idealized system could be maintained, it would perform in a near optimum manner. Unfortunately, it cannot be contained in most of the aircraft of interest.

To permit ease of aircraft evaluation, dimensional analyses were run on the C-119 and P2V to determine appropriate options. These are shown in Figures 96 and 97.

In the curves of these figures, the overall limits are determined by the aircraft dimensions, but within these limits there is a maximum weight of retardant that can be carried and desirable ratios of length to width and of height to width as discussed earlier. Thus the tank must fit above the desired increment line and to the left of the head-limit line.



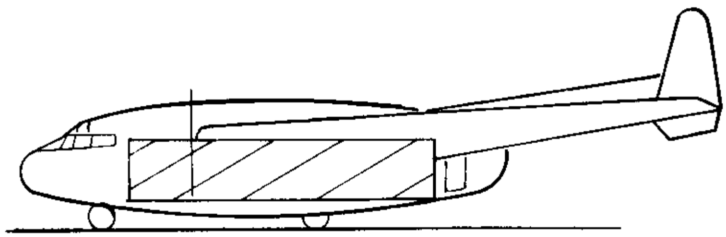
NOTE: WILL FIT ONLY IN MODIFIED C-130.

Figure 95. Abstract Tank to Optimize Deep Penetration from Large-Capacity Aircraft, Four-Pass Capability

The inability of the ideal tank to fit aircraft of major interest led to the consideration of alternatives. Relaxing the requirement for four-pass capability to allow three delivery increments provides a tank that will fit the geometrical limits of the C-119 as shown in Figure 98. This is a valid position, since the 800-gallon increments are reasonably well suited to higher altitude delivery. The tank will still not fit the P2V volume envelope.

Fitting the tank to the P2V requires some compromise over the fixed-trajectory approach, either tandem tanks or four longitudinally separated tanks exceeding the length-to-diameter limit. The tanks are shown in Figure 99.

In conference with the Forest Service, it was agreed that a small aircraft with capacity under 1,000 gallons should be designed primarily to preserve the direct-attack capability. This results because altitude survival and the decreasing accuracy that results as altitudes increase place a premium on



BASELINE AIRCRAFT - C-119

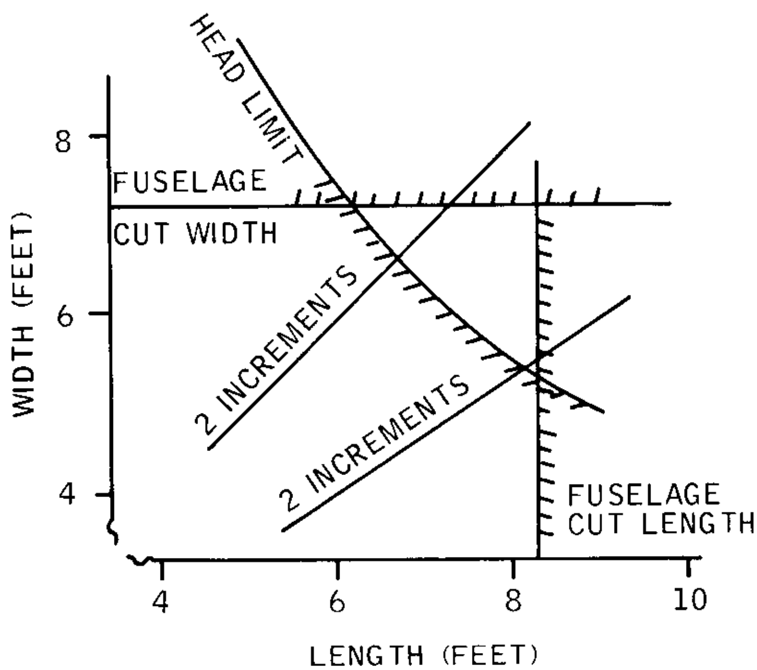
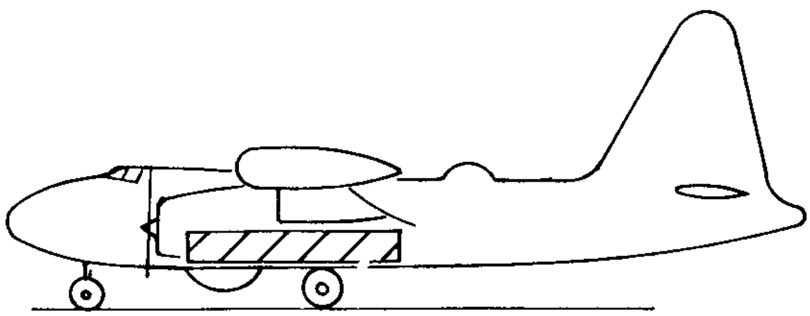


Figure 96. C-119 Dimension Analysis



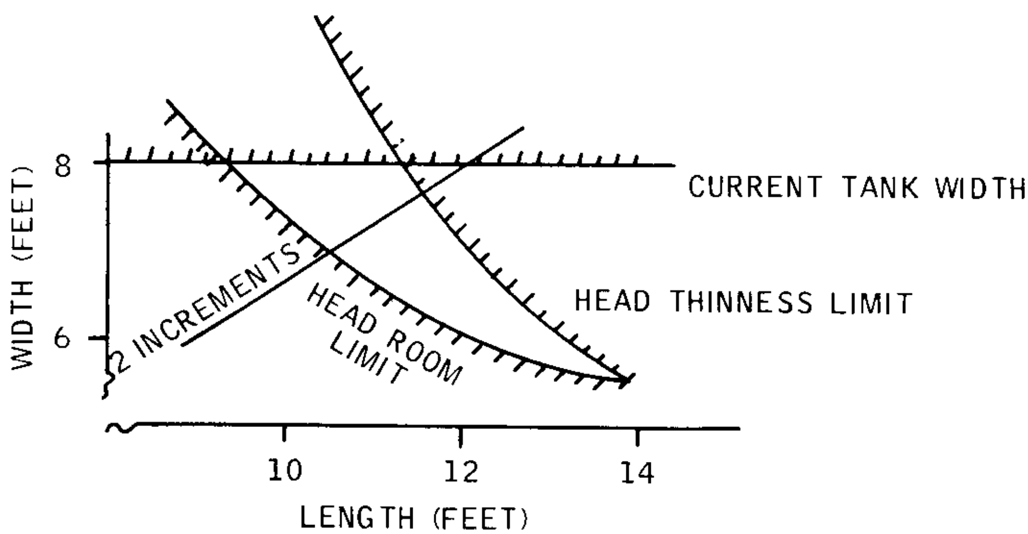


Figure 97. P2V Dimensional Analysis

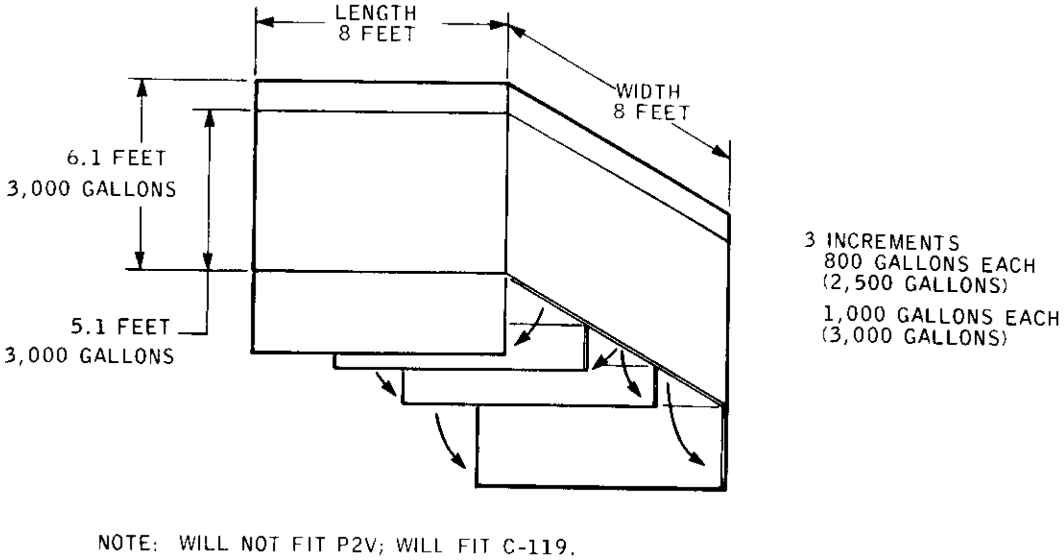


Figure 98. Abstract Direct Attack Tank for Three-Pass Capability

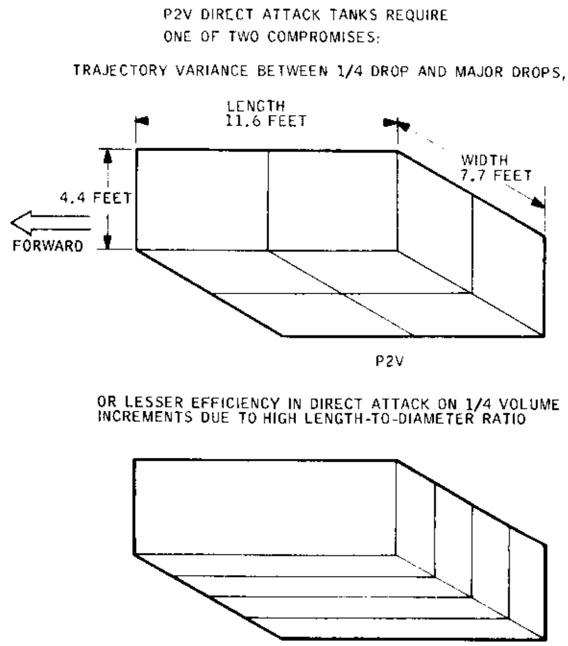


Figure 99. Tandem Tank (P2V)

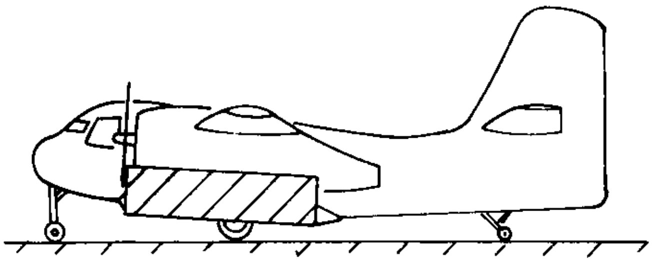
quantity. Thus, the desire is to improve performance in the direct-attack mode by increasing the effective altitude rather than by extending the altitude to an arbitrarily high level.

The S2 was selected for the baseline aircraft, one of the few bomb bay aircraft available for such applications. It is shown schematically in Figure 100.

Figure 101 shows three conceptual S2 tanks in steps of increasing complexity and capability. Each retains the capability of the one above, with an additional feature added. The middle concept is recommended as the basis for an operational system, performing the deep-penetration mission with a low-to-moderate altitude line-building capability. The third design provides a high-altitude line capability, but clutters the tank (potentially reducing performance in the deep-penetration mode) and roughly doubles the number of operational tank parts. The additional complexity is not offset by improved capability because the 450-gallon increment is marginal at best for higher altitude line building.

The recommended tank concept uses external actuators and an interlocking two-door arrangement on each half tank. The hydraulic system and accumulator used with the military version of the aircraft is believed to be a good system for fast door opening, with torpedo doors opening in 0.5 seconds. The tank is similar in performance characteristics (both trail and salvo) to the current Aero Union B-17 in respects other than total volume.

The longitudinally oriented trail door drains each tank increment equally, requiring no cross flow through the baffles. This trail door is a two-stage door described later in the discussion of line building.



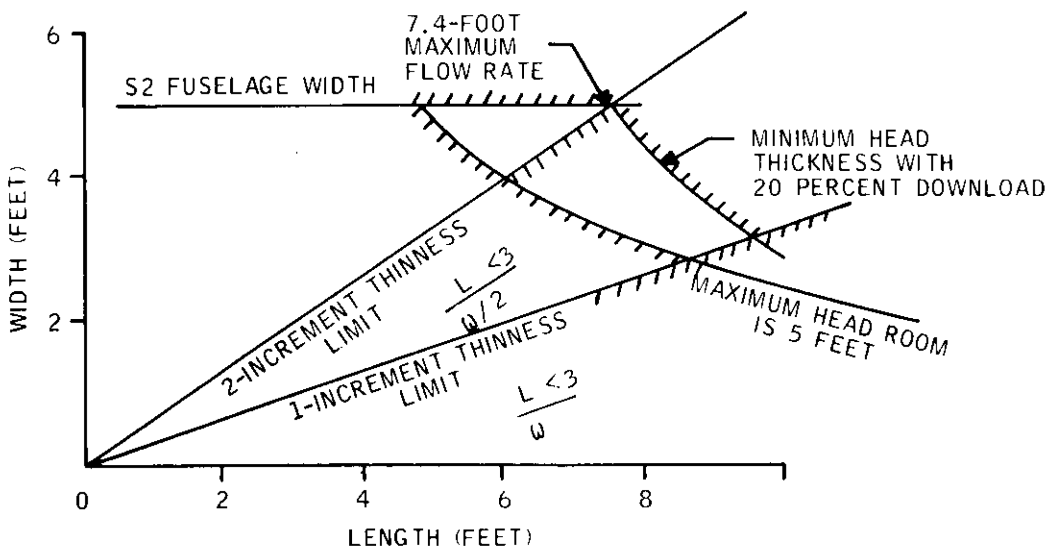


Figure 100. Concept No. 1, Small Aircraft - Direct Attack

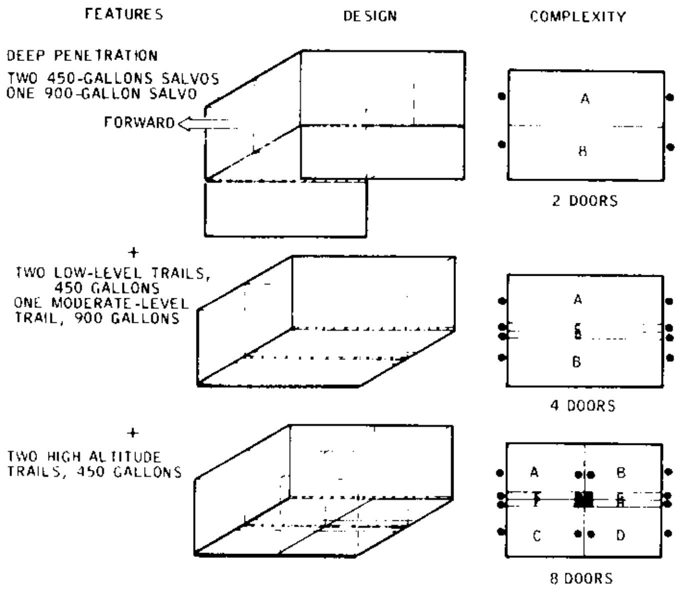


Figure 101. S2 Deep Penetration Tanks

D. LINE BUILDING SYSTEMS

Line building is limited to large-capacity aircraft because they are the only aircraft that can carry sufficient retardant to produce a significant line from high altitudes. The requirements for line building differ substantially from those applied in direct attack. Substantially, it is a matter of controlling flow rate and breakup to match the pattern desired with altitude.

The five basic techniques of rate control are shown in the matrix of Figure 102. Basically, there are two options that bear comparative evaluation: the strictly gravity feed door system and a moderate-to-low pressure combination system.

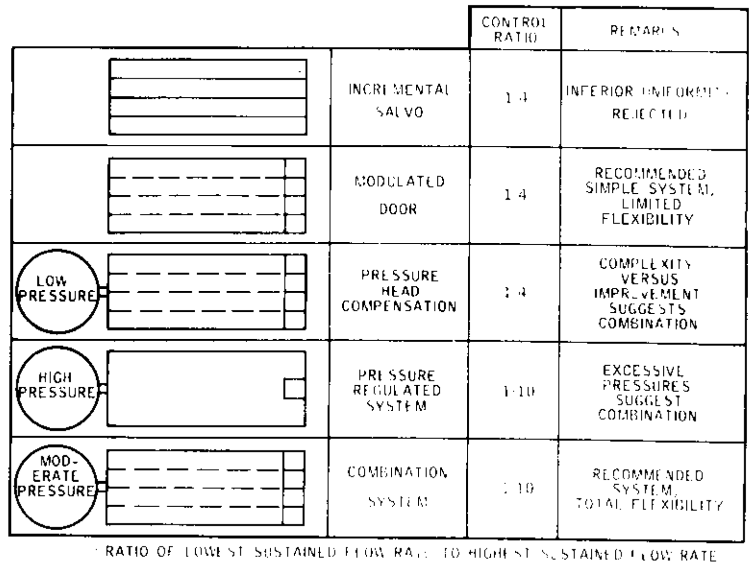


Figure 102. Five Techniques of Flow Rate Control

There are two basic types of line-building systems:

- Those that develop line from a series of incremental salvo drops, relying on airstream breakup to encourage pattern length.

- Those that meter flow from the tank, allowing the aircraft to accomplish the linear spread of the pattern.

Let us look first at the salvo mode. In general the long thin tank (length-to-diameter ratio greater than 4) is preferable in that the mechanism of breakup encourages elongation of the pattern.

Following this approach, the design of Figure 103 looks roughly like the current P2V tank, whose six tank increments represent high length-to-diameter values. It is also similar in characteristics to the TBM.

Problems with this type of system are in its total reliance on aerodynamic breakup, the lack of uniformity, and the lack of controlability through tanking parameters. It is concluded that metered systems offer a better chance of improvement.

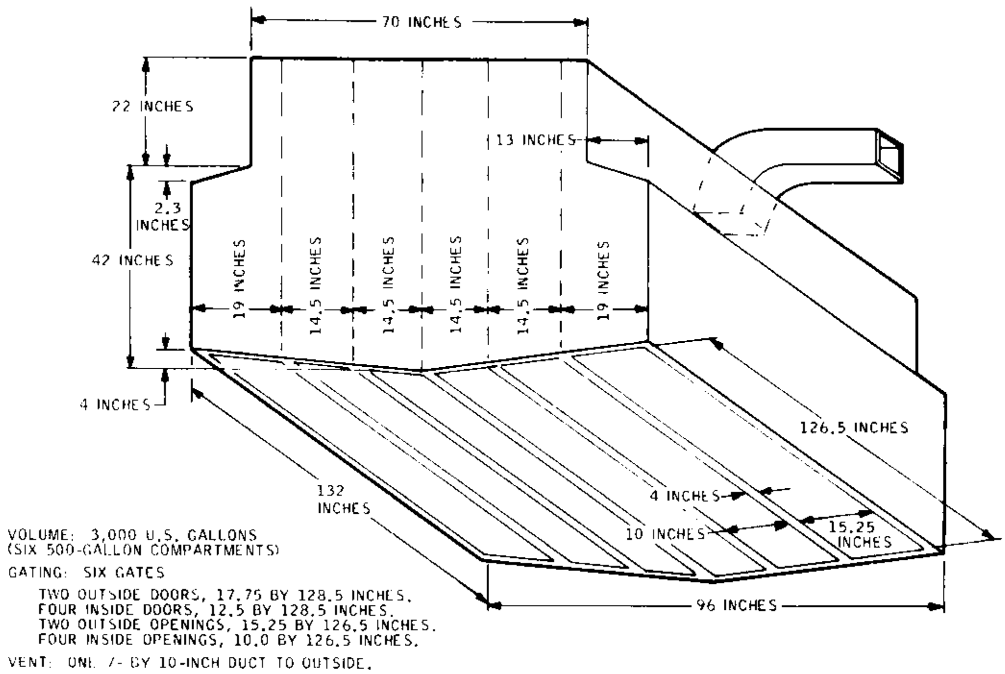


Figure 103. P2V Retardant Tank

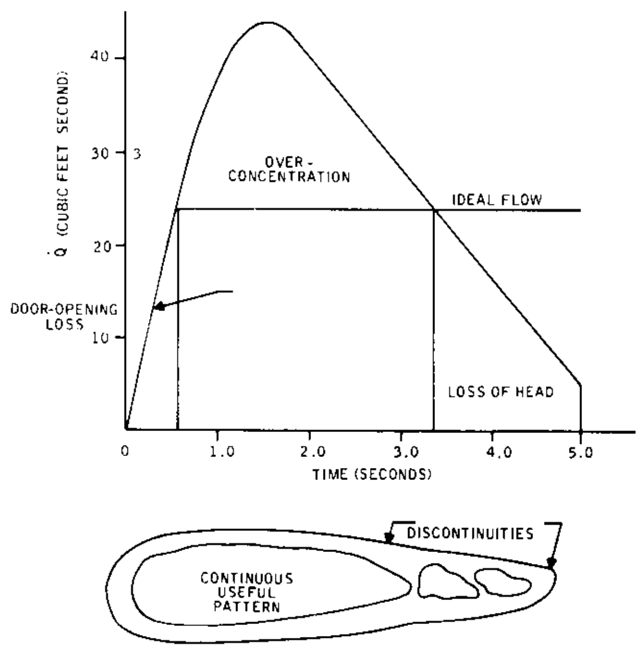


Figure 104. Effects of Flow Rate Variance on Line Building In the Trail Mode

Metered-flow or trail-type systems offer more flexibility, greater control, and improved uniformity of line patterns.

The effect of various tank parameters on line-building efficiency with a gravity flow system is shown in Figure 104. Unlike the salvo mode, it is little affected by door-opening rate, but is considerably reduced by loss of head in the terminal stages of operation. The door in any such system must be sized to provide an average flow rate compatible with line-building requirements. This average is a compromise between overconcentration and underconcentration.

One method of moderating the average flow rate is the use of a two-stage door as shown in Figure 105. The door opens fast to the level established for the desired line. It then engages a stop that reduces the opening rate during the remainder of travel. The net effect is a relatively simple method of increasing the useful line in gravity feed systems. This type of operation is recommended for line building in a gravity feed mode, but it is not useful if pressurization is available.

Even small pressures help considerably in line building if they are regulated. Under these conditions a minimum pressure, simply to compensate for the loss of head, can be used with a selected door area to appreciably lengthen the continuous line as shown in Figure 106. The value of this approach weighs heavily in favor of the use of pressure.

With metered flow, flow rate becomes the dominant control parameter in association with release geometry. Figure 107 shows the range of variation that may be required. This estimate allows us to judge the flexibility of various options in terms of providing a full range of altitude coverage.

Tank release pressure achievable with typical aircraft power applied over a 10-minute pumping time into a suitable accumulator were estimated as a

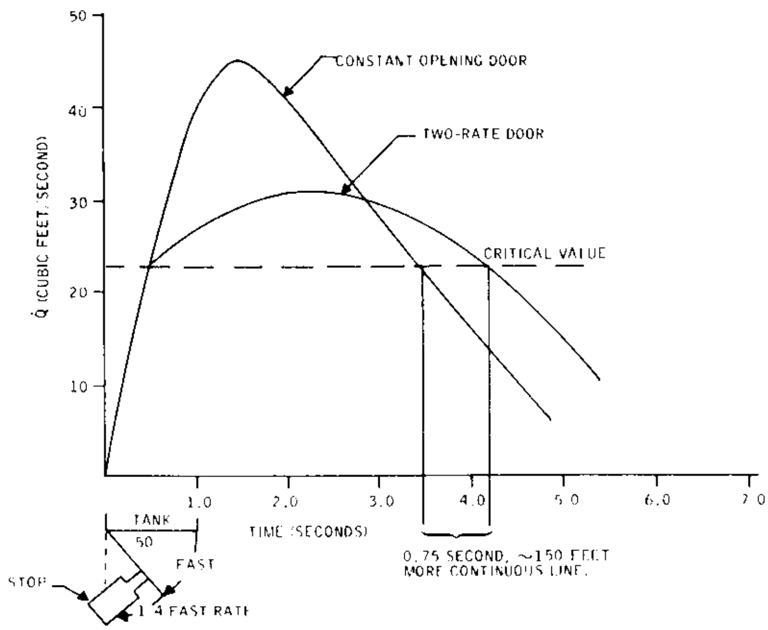


Figure 105. Two-Stage Door Improves Line Building at Low Cost

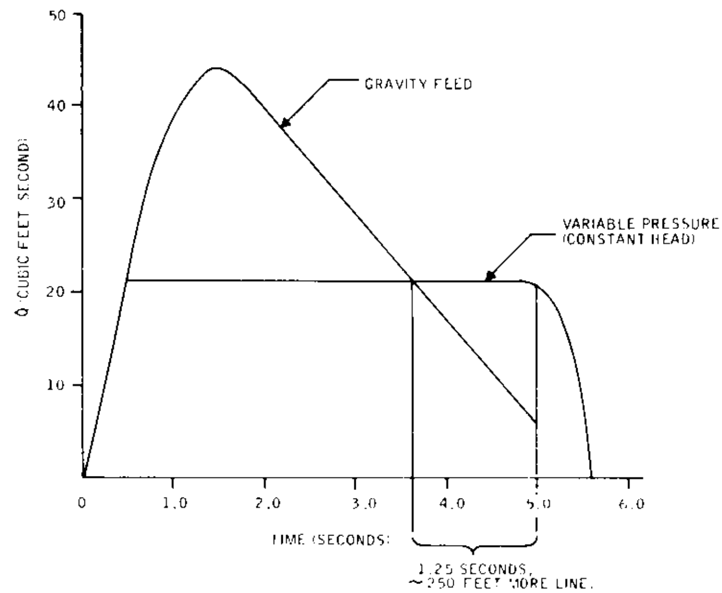


Figure 106. Effect of Pressure to Achieve Constant Head Condition

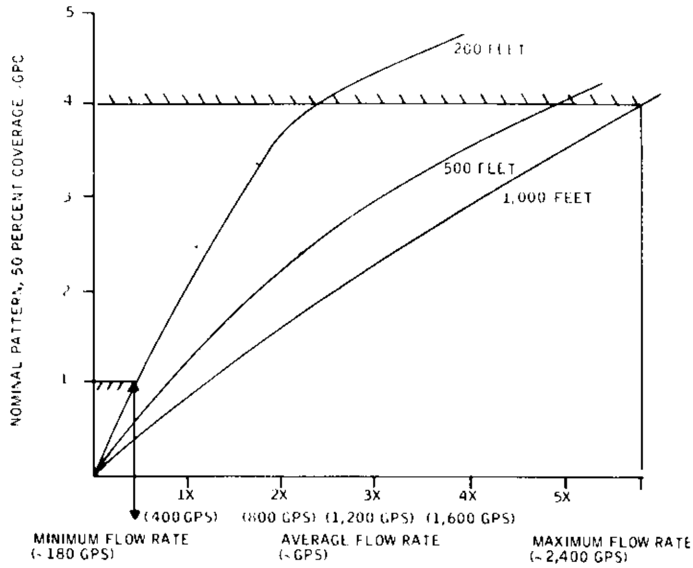


Figure 107. Flow Rate Variation to Accommodate Full Altitude Range

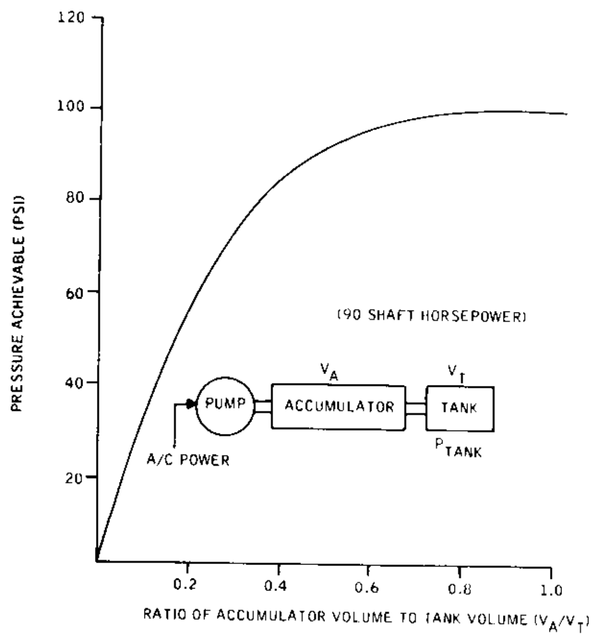


Figure 108. Tank Release Pressures Achievable with Typical Aircraft Power Over a 10-Minute Pumping Time (3,000-Gallon Tank)

function of accumulator size to tank volume ratios. These values, shown in Figure 108, may also be considered typical of those for stored or bottled pressure systems rechargeable in the field for purposes of this evaluation.

The volume pressure restraints were then compared with the basic flow established by the door-opening area. From Figure 109 it is apparent that a one-door system requires substantial pressures to achieve a full range of variation. The more door areas available, the less pressure is required.

The matrix of Figure 110 evaluates the pressure, accumulator volume, and door options for a 3,000-gallon tank. It shows that, with three or four increments, relatively low pressures can be used to achieve the required flow rate variations, with little penalty in volume or structure.

The pressure assist technique yields twice the number of rate options offered by the door system alone. This becomes increasingly significant as altitude increases.

As shown in Figure 111, a schematic concept for a pressurized system using the P2V tank as a basis was generated to assess the practicality of the pressure system. Essentially, it requires a programmable pressure value, but the system appears well within state-of-the-art considerations.

Estimates of the relative line lengths, considering 10 percent better regulation for the pressure system in offsetting head, show a significant increase in capability. It is therefore recommended for the line-building option.

Applying either the door or pressure technique implies similar options for the tanking system. Although the selection of door size and application technique is properly the subject of detailed design, the options shown in Figure 112 are available, with more or less equivalence.

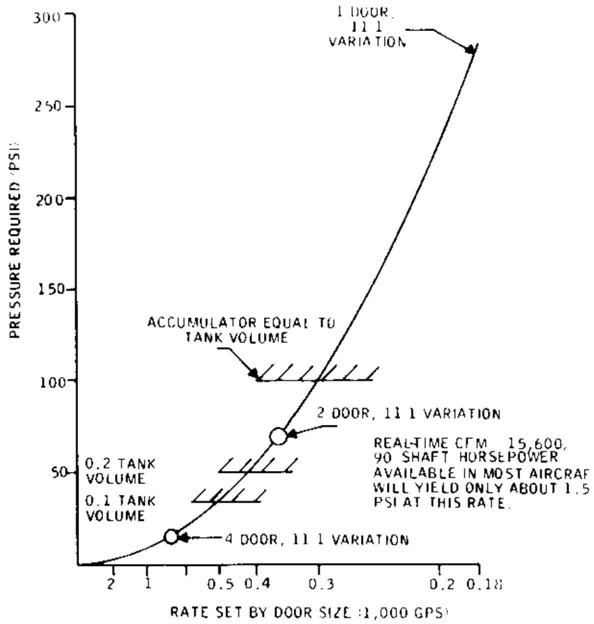


Figure 109. Pressures Required to Achieve 2,000-Gallon-per-Second Flow Rate as a Function of Door Area Ratios

BASIC DOOR YIELD	NUMBER OF DOORS	PRESSURE TO ACHIEVE 3 GPC AT 1,000 FEET (PSI)	H [illegible]	PRESSURE WHEN H [illegible] 0.1[illegible]
1 GPC AT 200 FEET	1	280	--	3,080
	2	75	0.3	825
	3	35	0.1	385
	4	20	0.05	220
2 GPC AT 200 FEET	1	75	0.3	825
	2	20	0.05	220
	3	10	MINOR	110
	4	-	MINOR	---

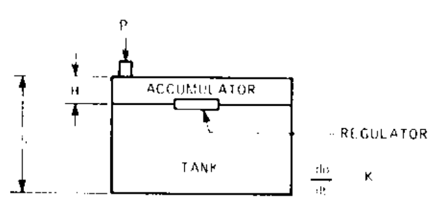
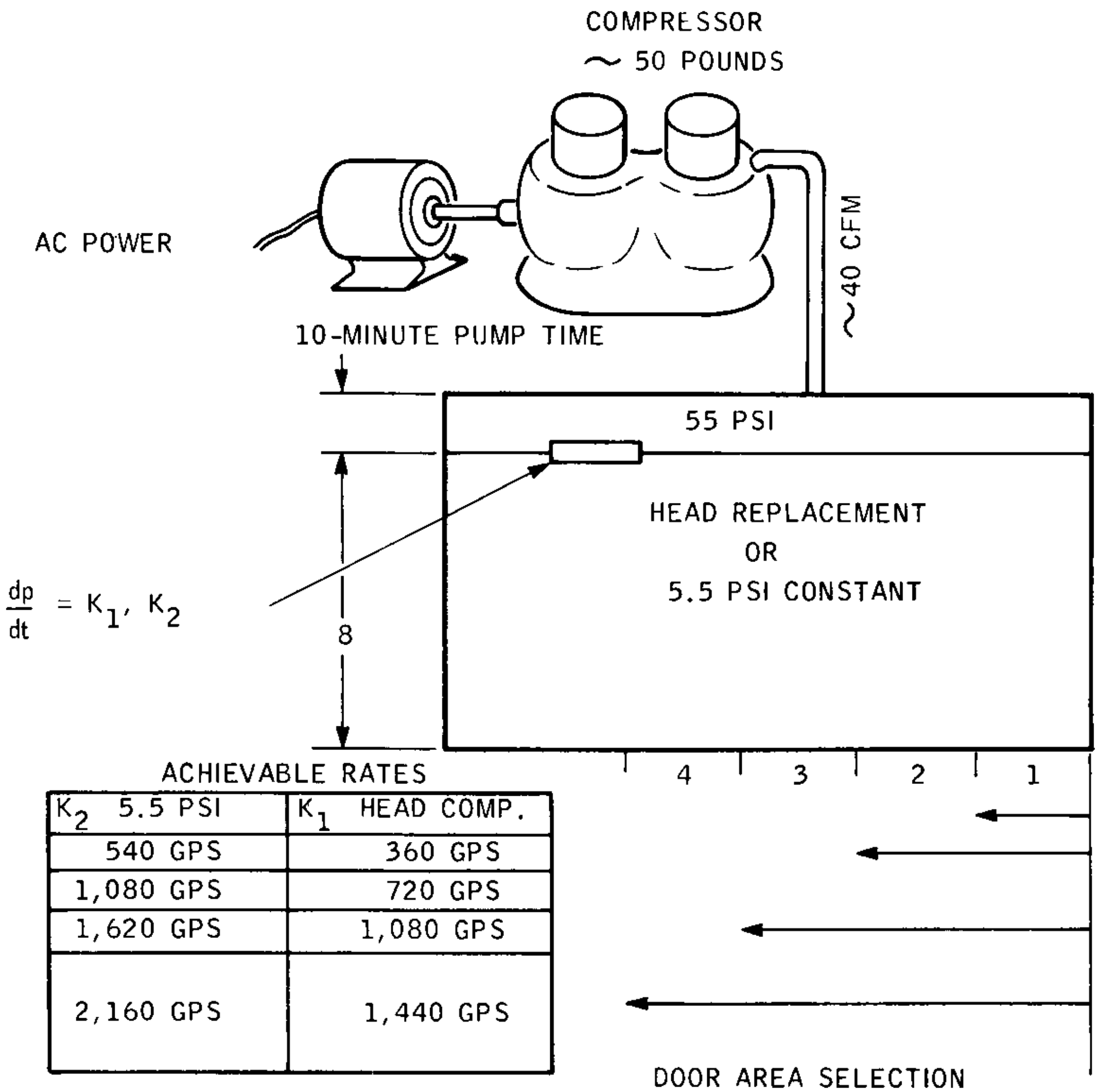


Figure 110. Combination Options for Doors and Pressures



ACHIEVABLE RATES

K_2 5.5 PSI	K_1 HEAD COMP.
540 GPS	360 GPS
1,080 GPS	720 GPS
1,620 GPS	1,080 GPS
2,160 GPS	1,440 GPS

Figure 111. Schematic Concept for Pressure Door System

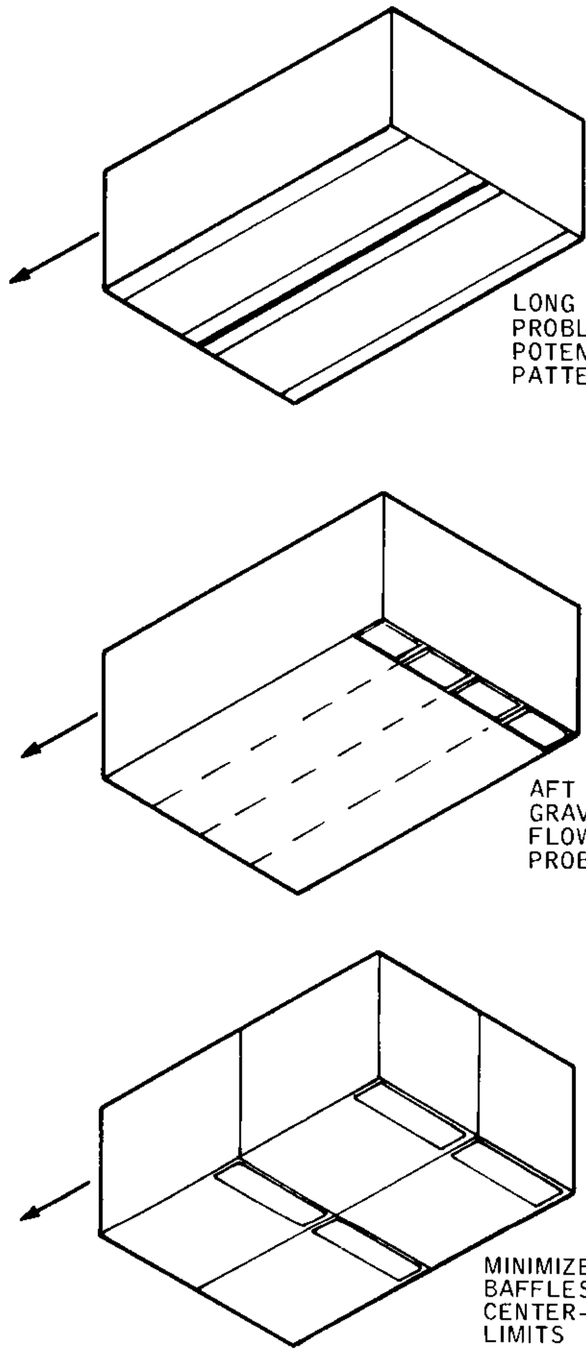


Figure 112. Alternative Line-Building Systems, Pressure-Augmented of Modulated Door

There appears to be little penalty in achieving a combination system. These are shown schematically herein for the C-119 and P2V tanks.

To confirm the results of these studies, a test bed tank system is needed for use in conjunction with the C-119, an available vehicle with adequate size, door area, and volume to carry the test bed.

E. HELICOPTER SYSTEMS

The helicopter design study matrix of Figure 113 shows a legitimate emphasis on quick-turnaround systems capable of delivering tremendous quantities of retardant from remote bases. Volumes up to 10,000 gallons per hour were shown by Aerospace Studies.

RETARDANT	HELICOPTER TEST BED AND SPECIAL APPLICATIONS
ADVANCED CASCADE (WITH VARYING RHEOLOGICAL PROPERTIES)	CONSIDER QUICK TURNAROUND SYSTEMS SUCH AS: ● SLING-LOADED ● RIGIDLY ATTACHED
CONTAINS PREFILLED CAPSULES OR BAGGIES, SELF-FILLING CONTAINERS, FROZEN, HYBRID OR COMBINATIONS OF ABOVE; OTHER AS PROPOSED BY CONTRACTOR	CONSIDER QUICK TURNAROUND SYSTEMS SUCH AS: ● SLING-LOADED ● RIGIDLY ATTACHED ● OTHER

Figure 113. Helicopter Concept Matrix

Containerized delivery is only marginally practical for the helicopter. In addition to problems previously discussed in achieving good ground coverage, the logistics problem of container resupply is potentially great. The permissibility of the helicopter in selecting delivery velocities and a relatively lower altitude requirement also suggest that the potential advantages of containerized delivery in improving survivability will be minimal. Containerized delivery is therefore not recommended as an option for helicopter use. This does not apply to large reusable containers such as those used in sling carriage.

Retardant selection for helicopter operations is less critical in achieving performance than for fixed-wing aircraft. Indeed the advantage of remote base operation may in some cases be achieved with unmodified available water, at least in the early stages of remote operation before true retardant bases can be established.

We have therefore specified the following baseline retardants for differing application:

- Where high-speed delivery is retained as an option, the same retardants used for fixed-wing aircraft will be employed.
- Where high-speed delivery and low-speed capability are included, some mechanism to supplant airstream induced breakup will be included.
- Where moderate- or low-speed delivery is the only option, water, and water-like retardants, will be used as the baseline.

Three general approach may be defined for helicopter conceptualization as shown in Figure 114.

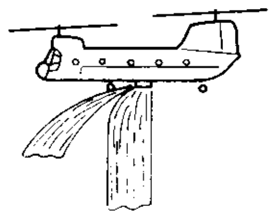
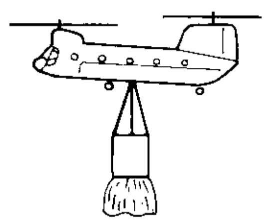
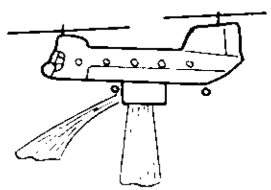
METHOD OF CARRIAGE		CAPACITY (POUNDS)	RELOAD RATE	THRUST RESISTANCE	VELOCITY LIMITS	REMARKS	LINE BUILDING	DIRECT ATTACK
INTERNAL		20,000	SLOWEST	BEST	NONE	• BEST FOR HIGH-SPEED DELIVERY • OPERATIONS FROM FIXED BASE • STANDOFF CAPABILITY • HIGH PARASITIC WEIGHT IN LOW-VELOCITY OPERATION REQUIRING DOWNLOADING		STANDOFF
SLING		15,000	FAST	WORST	SOME	• BEST FOR REMOTE OPERATION • BEST IN LOW-VELOCITY REGIME • NO STANDOFF CAPABILITY • HIGH TURNAROUND CAPACITY	COMPARABLE	NO STANDOFF
CONFORMAL		12,000	SLOW	BETTER	MINOR	• CAPABLE OF LOADING IN HOVER • STANDOFF CAPABILITY • LIMITED CAPACITY WITH CURRENT HOIST CAPABILITY • RELATIVELY DIFFICULT HOOKUP PROCEDURE		STANDOFF

Figure 114. Three General Approaches for Helicopter Conceptualization

- Internal carriage, in which helicopters perform substantially as airtankers, but with a remote base operating capability and with the freedom to select their delivery velocity to modify pattern density.

- Sling Carriage, a lesser capacity system with potentially high turnaround rates, a limited high-speed delivery, and a potential limitation on the way the retardant is released to avoid introducing a destructive oscillation or pendulum motion.

- Conformal Carriage, a sling-like system that avoids the limitations on retardant release by pulling the tank into swaybrace contact with the fuselage.

The relative merits of these options are clarified by viewing the relationship of the aircraft to the fire and its local turbulence conditions. Flyover systems require the aircraft to pass through the fire-induced turbulence with altitude alone as a safety factor. They are thus low-momentum systems of limited use in direct attack, but good in line building. Any system imparting significant velocity to the retardant mass allows the helicopter to avoid the fire turbulence while directly attacking the fire.

The cargo weight capacity of a helicopter varies with altitude density and on the method of loading and delivering the retardant as shown in Figure 115. The top curve shows the payload capacity for airbase operation. The middle curve shows the capacity for hovering reload, and the bottom curve shows the capacity for a system in true remote operations where takeoff must be vertical or where the retardants must be released while hovering.

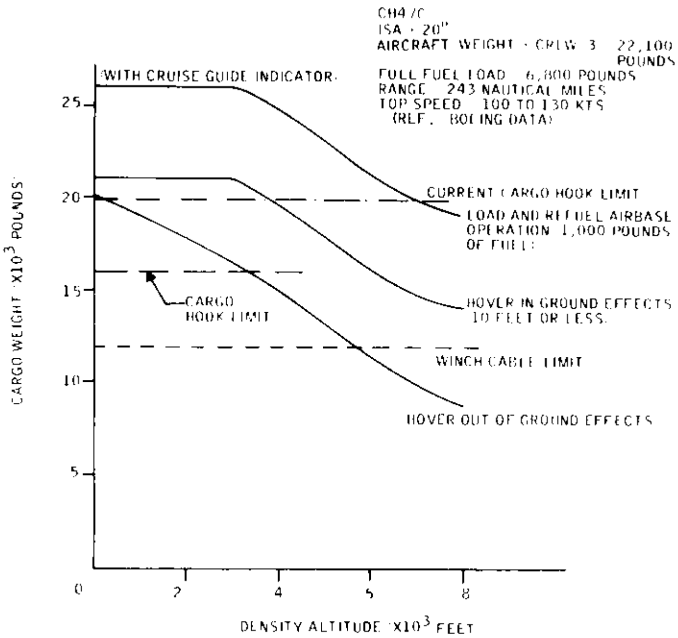


Figure 115. Cargo Weight Analysis for CH47 Class Helicopters

Using parasitic weight estimates for various tanks, the loss in efficiency resulting from the weight of unused tankage was evaluated in several situations as shown in Figure 116. This shows that the greatest efficiencies are achieved when the tank is designed not to a maximum capacity but to a capacity typical of its real mission.

The significance of overcapacity for a given mission is amplified by the turn-around times achieved in various modes of operation as shown in Figure 117.

It was concluded that:

- The airbase type of internal tank should not be required to deliver in a true hover.

- The nominal carriage capacity for a remote operation tank should be about 17,500 pounds, a compromise between Improved Remote and Restricted Remote operation.

TANK SIZED FOR \ TANK CAPACITY IN	AIRBASE OPERATION (GALLONS)	IMPROVED REMOTE OPERATION (GALLONS)	RESTRICTED REMOTE OPERATION (GALLONS)	6,000-FOOT HOVER DELIVERY (GALLONS)
AIRBASE OPERATION	2,200	1,600	1,100	800
IMPROVED REMOTE OPERATIONS	1,700	1,700	1,200	900
RESTRICTED REMOTE DELIVERY	1,400	1,400	1,400	950

Figure 116. Loss in Efficiency Resulting from Weight of Unused Tankage

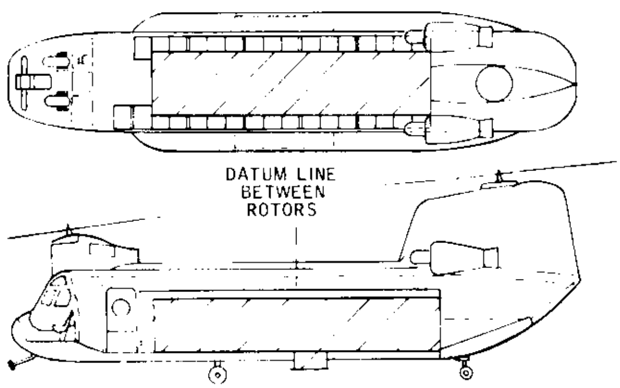
	CAPACITY IN	AIRBASE OPERATION	IMPROVED REMOTE OPERATION	RESTRICTED REMOTE OPERATION
		FOUR-HOUR TURNAROUND VOLUMES		
	TANK SIZED FOR	ONE LOAD/ HOUR (GALLONS)	THREE LOADS/ HOUR (GALLONS)	FOUR LOADS/ HOUR (GALLONS)
INTERNAL TANK	AIRBASE TANK	8,800	19,200	17,600
INTERNAL TANK	IMPROVED REMOTE TANK	6,800	20,400	19,200
INTERNAL TANK	RESTRICTED REMOTE TANK	5,600	16,800	22,400
EXTERNAL TANK	NOMINAL 17,500 POUNDS STORE	6,600	19,800	19,680

Figure 117. Selection of Nominal Payloads

The internal tank selected for the CH-47 was a modular tank that is ramp-loaded into the aircraft without modification at the time of need. It operates through the 40-inch square hoist door as shown in Figure 118.

Figure 119 shows the two basic tanks chosen for evaluation. They differ primarily in methods of managing the internal volume, with the more precise tank requiring more head room and consequently a slightly more complex method of inserting the tank into the aircraft.

The significance of such precise measurement is minimal; at low flow rates (low-velocity delivery mode) it is possible to terminate flow by gradually closing the doors. Consequently, the less complex tank is recommended for internal carriage.



REQUIREMENTS

NOMINAL PAYLOAD: 2,200 GALLONS

TYPES OF DELIVERY:
HIGH-SPEED ~200 fps (100 TO 140 KNOTS)
LOW-SPEED ~60 TO 150 fps
TYPE OF TANK: MODULAR (NO AIRCRAFT MODIFICATION)

Figure 118. Internal Carriage for the CH47

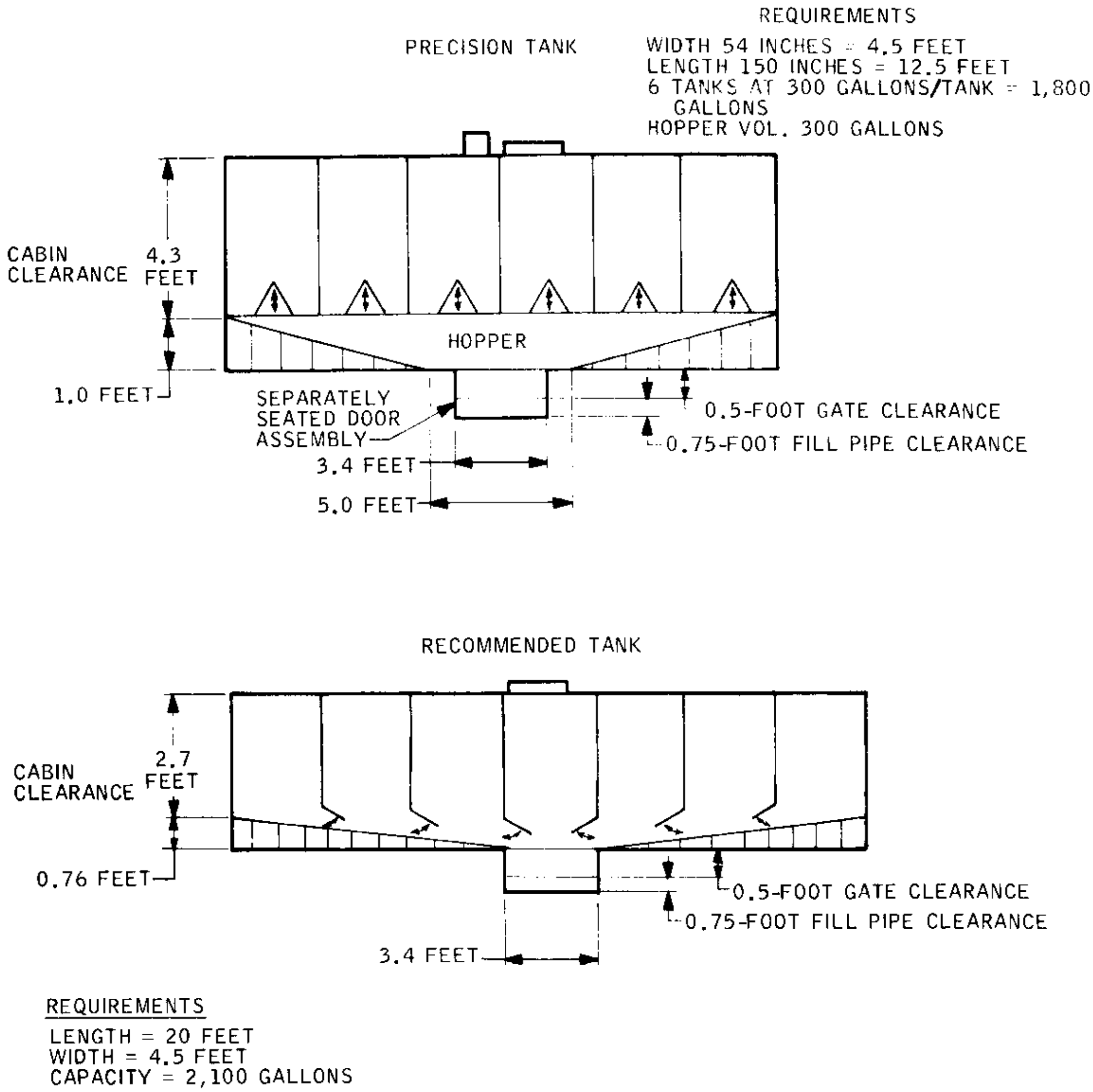


Figure 119. Two Basic Tanks Chosen for Evaluation

The recommended design shown in detail in Figure 120 contains 2,200 gallons in seven 300-gallon (nominal) compartments. Each compartment is individually opened or closed by a pneumatic or hydraulic door to preclude excessive center-of-gravity shifts during flight and to allow unrestricted flow to the door. It also allows downloading without loss of head by closing off the extreme compartments. A louvered door provides for two types of opening, one for high flow rates (high-speed mode) and one providing a lateral impetus to the retardant to encourage a wide pattern and retardant breakup. Retractable wheels allow the tank to be ramp loaded and lowered into position over the hoist door.

Although the louvered door does not satisfy the desire for a clean door opening; this is not considered significant for a fast breakup system, and it does require limited clearance for door opening, allowing the aircraft to land if the doors should fail open.

The possibility of using a similar tank on the S64 was also evaluated. It appears, however, from Figure 121 that the tank should be foreshortened and increased in height to facilitate loading on the cargo pads of the helicopter.

1. External Carriage

Figure 122 shows a high-density load suspended at the center of gravity. This imposes no fundamental limits on aircraft performance beyond normal gross weight limitations, although there are some minor limits on banking. The evacuated container does impose a velocity limit on the return flight because of aerodynamic trailing.

However, evacuation of the cargo may be critical because the container will react to any thrust resulting from unbalanced fluid flow. The resulting

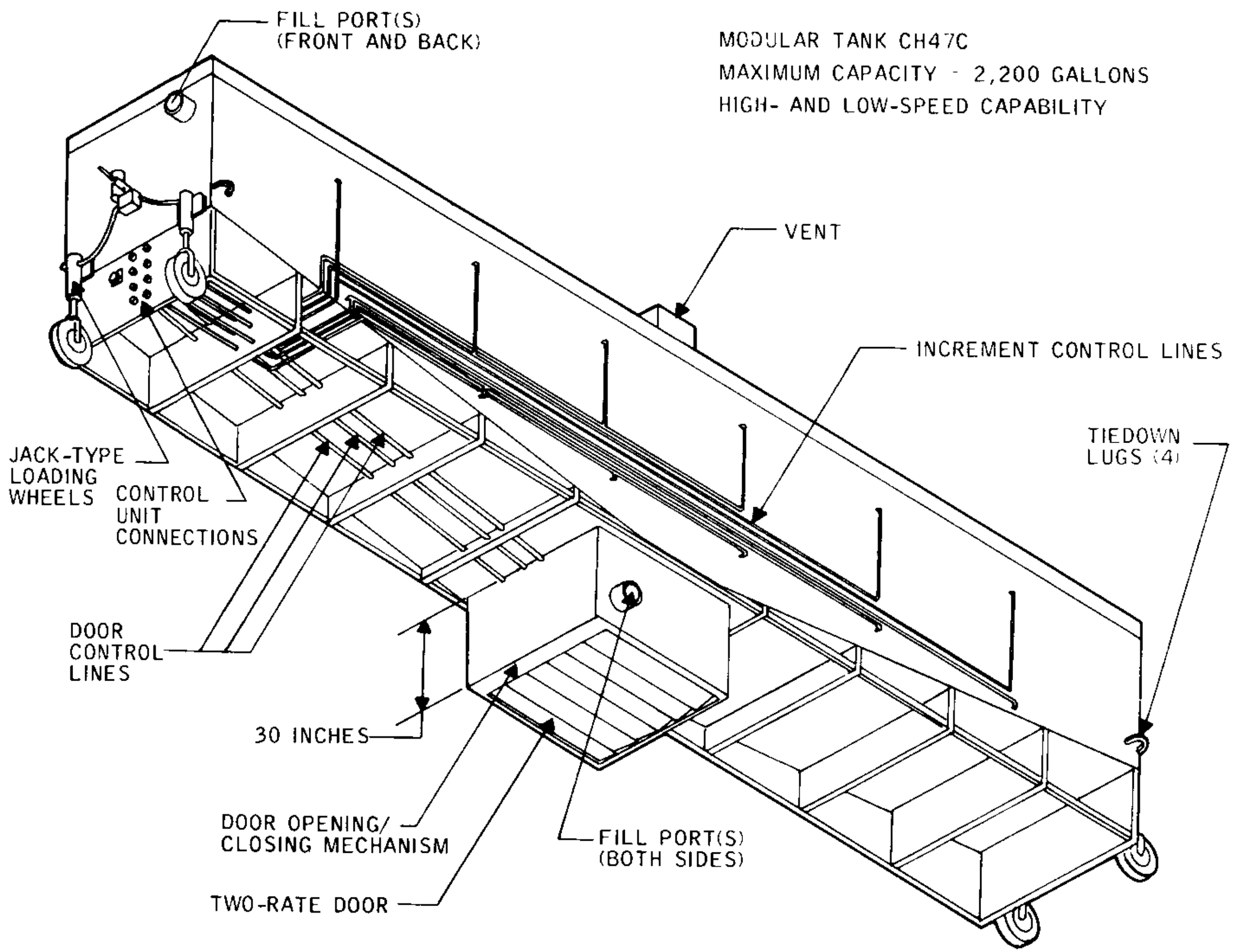


Figure 120. Modular Tank, CH47

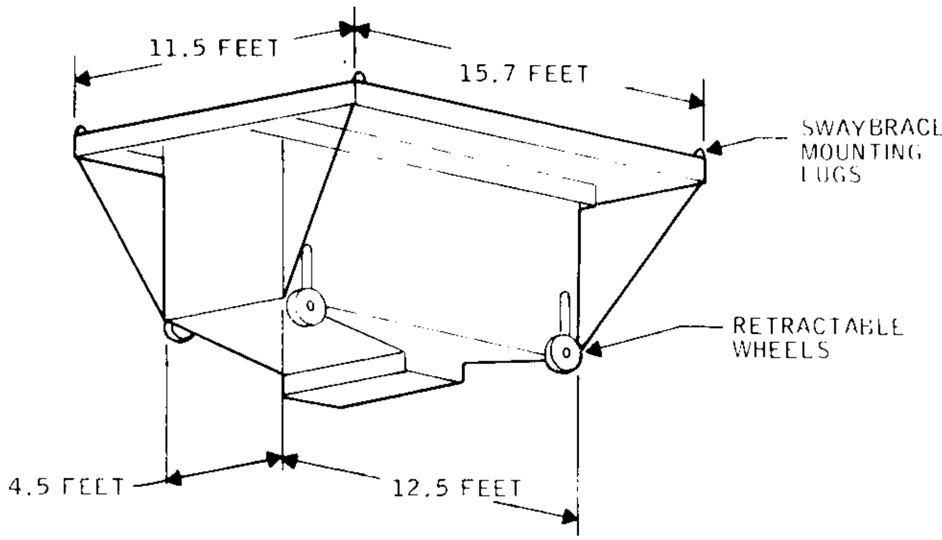


Figure 121. Skycrane Class Tank

oscillations can potentially build up to a destructive level. The currently used cable and winch system is limited by the cable strength to a capacity of 12,000 pounds. Systems developed to carry more weight would require aircraft modification.

2. Conformal Carriage

If the retardant container is hoisted into firm swaybrace contact with the helicopter fuselage, sensitivity of the external container to load-generated thrust is minimized and full high-speed evacuation of an external load can be achieved.

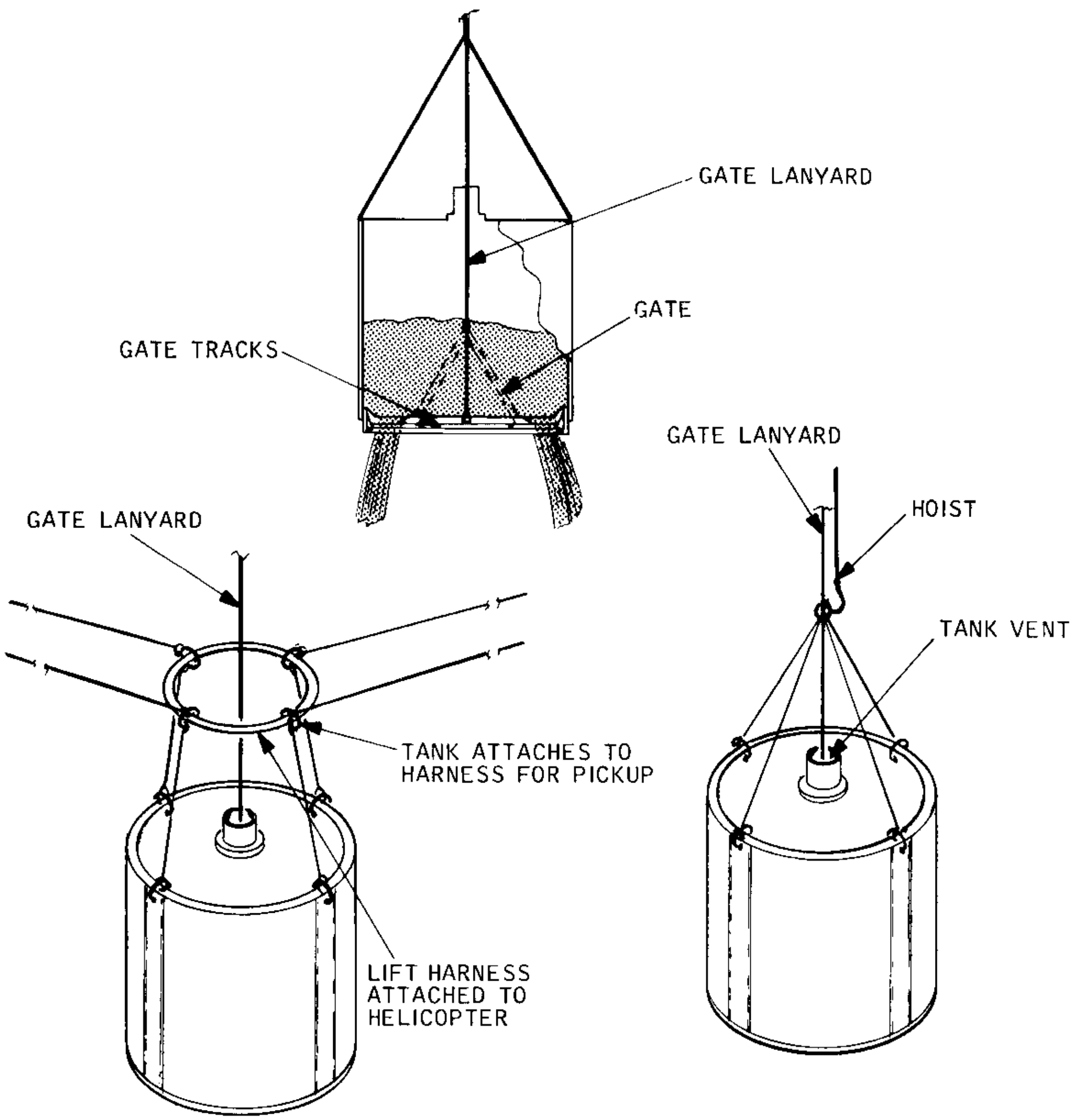


Figure 122. High-Density Load Suspended at Center of Gravity

Figure 123 shows a possible system using an auxiliary pulley system with lift controllable by a crewman stationed at the hoist. This system can drop the cargo hook and empty container about 25 feet in one minute, but hoisting requires 5 minutes. Therefore, for minimum turnaround time with this arrangement, lifting must be done en route to the target, with the crewman operating through the 40-inch-square door to maneuver the load into adequate contact with the fuselage. Special crew training would be required even if this system is practical from an engineering viewpoint.

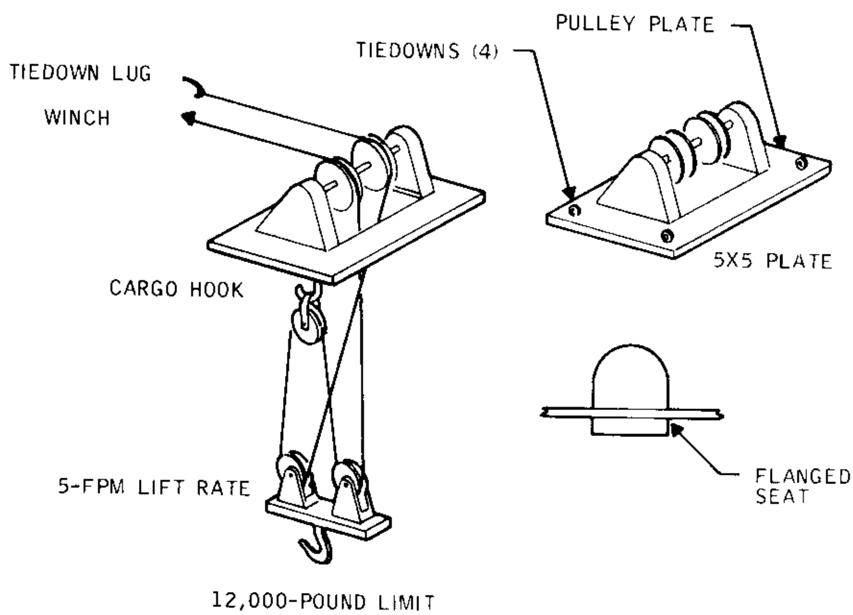


Figure 123. Scheme for Hoisting Load to Swaybrace Contact Using Existing Winch

Conformal carriage has some potential advantages that might be considered for Sky Crane helicopters as shown in Figure 124. The advantages of this specialized system can only be determined by a cost-effective analysis beyond the scope of the present study.

3. Sling Reservoir

Another method of reducing the sensitivity of external storage to load-generated thrust is to carry the retardant in a replaceable pressure vessel, with a pumping and delivery system carried in the helicopter as shown in Figure 125. There is ample power for pumping the retardant at rates required, but the weight of the pumping and delivery system will reduce the possible load-carrying capacity. Fundamentally, the issue resolves into the tradeoffs between using gravity as the releasing force and adding the weight and complexity necessary to operate against this force. Standoff or fire hose delivery might be achieved, but this potential advantage in some situations is difficult to justify because in the primary mission gravity drop is superior.

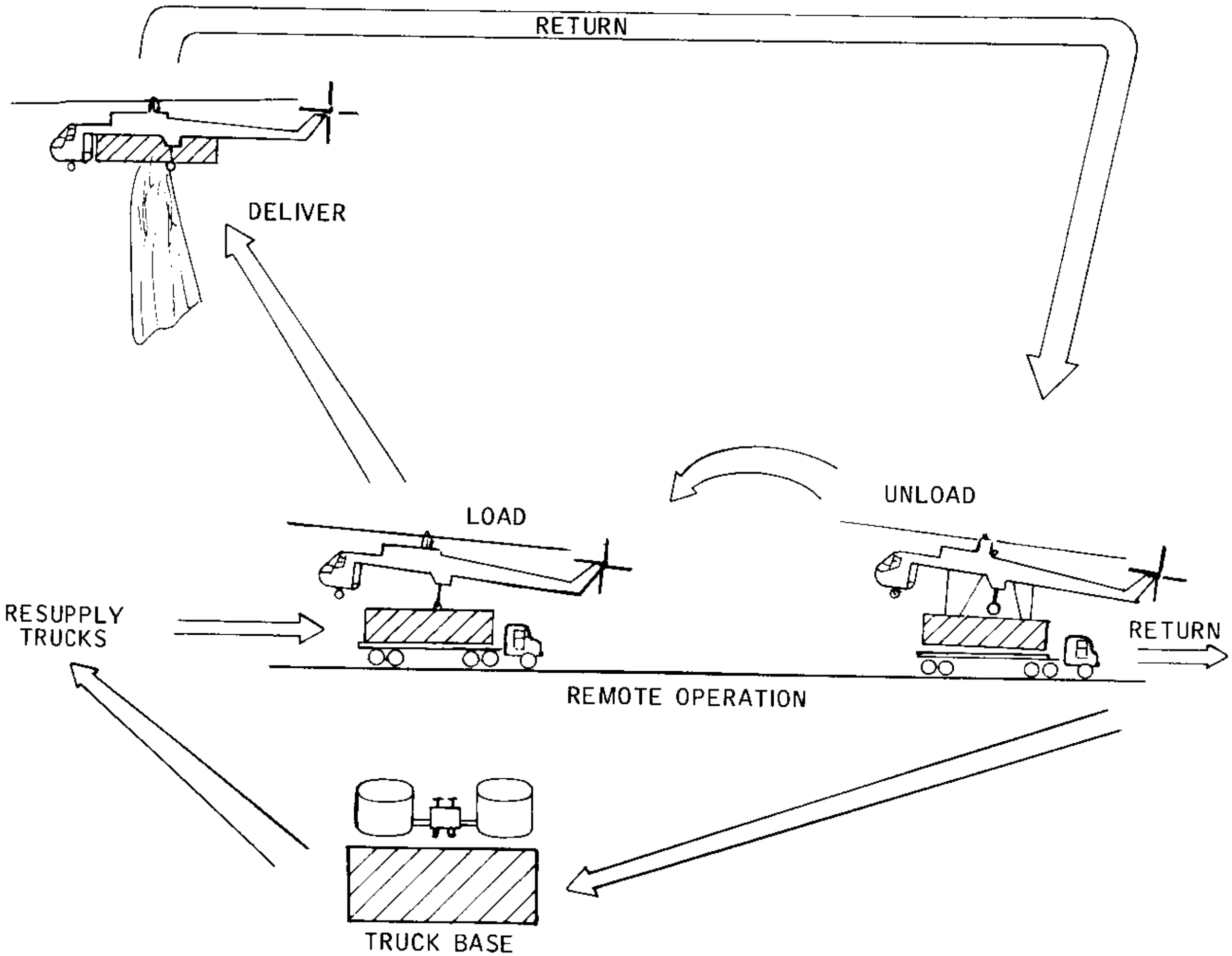


Figure 124. Possible Concept for Remote Operations

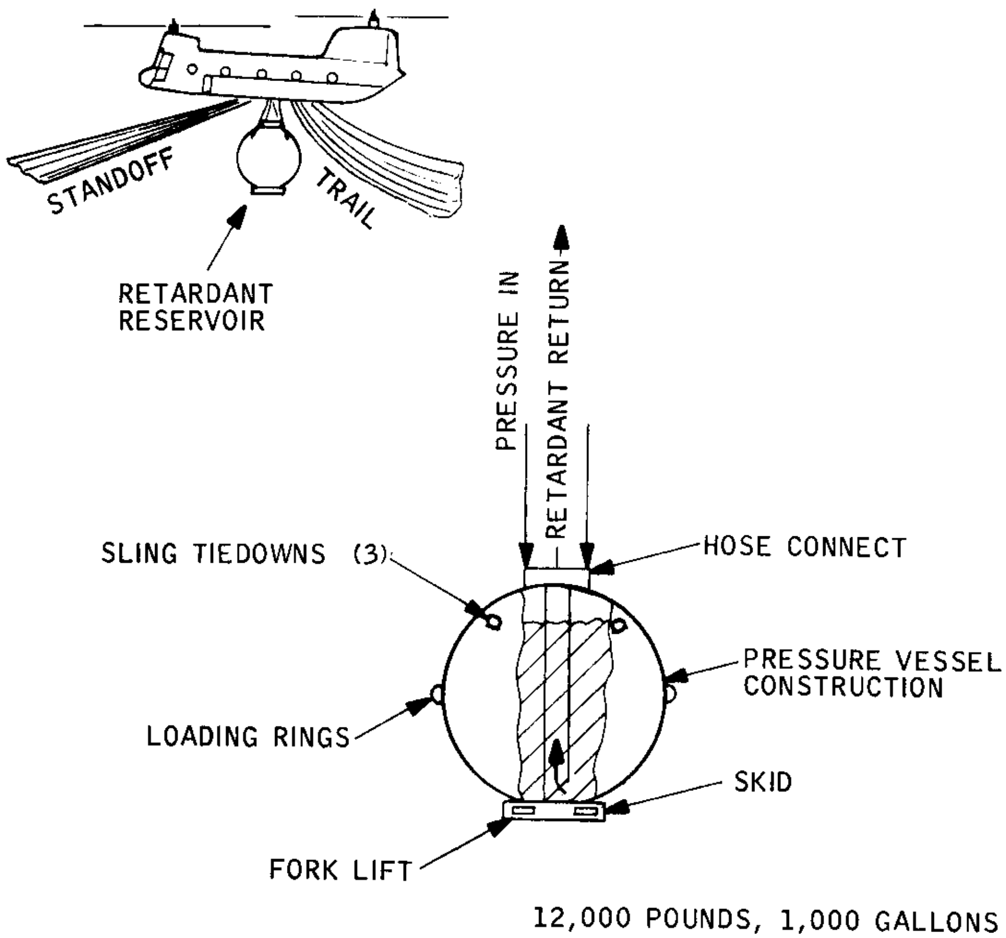


Figure 125. Retardant Reservoir Concept

APPENDIX A

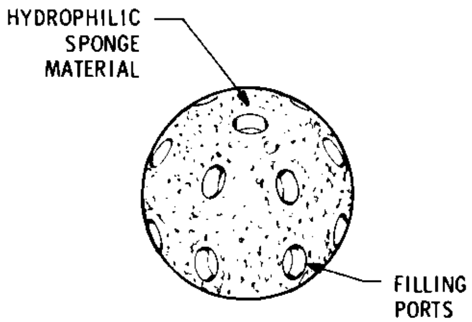
OTHER DELIVERY CONCEPTS

1. CONTAINER CONCEPTS

To assure as wide a range as possible for conceptual evaluation, a number of containerized delivery concepts were generated (Figures A1 through A9). This range of possible approaches extended from relatively simple dunnage to structurally organize the retardant load to complex containers participating actively in the release and dispersion of the retardants at or near the ground. Although all of the containerized concepts involve logistics, handling, and cost implications, these factors do not necessarily cause rejection. Instead, studies presented in the basic text showed that they did not, as a class, offer potential improvements in delivery effectiveness sufficient to offset their attendant disadvantages.

This results partly because the high-altitude capabilities of a well designed retardant system operating in a cascade mode were underestimated prior to the Maranna tests. However, the relative value of containers could increase considerably if water were the only available retardant, or if they were used to deliver suppressants performing in a substantially different way than those associated with current retardant mixtures.

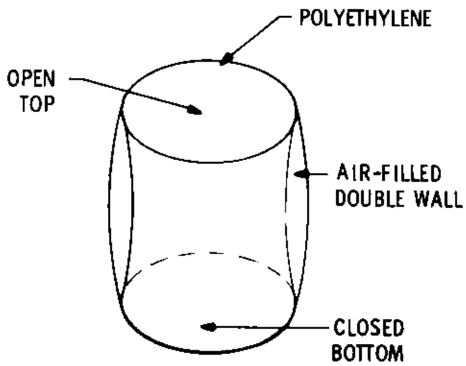
Although all were rejected in favor of improved cascade systems, they are presented here as a historical record and as possible enabling candidates to deliver special suppression systems that might evolve under some future study.



DESCRIPTION

- UP TO 1/2-GALLON, HOLLOW, SELF-FILLING SPONGE SPHERE
- CARRIED WITHIN RETARDANT TANK(S)
- CONVENTIONAL CASCADE RELEASE
- SPLASH-DISPERSION UPON IMPACT

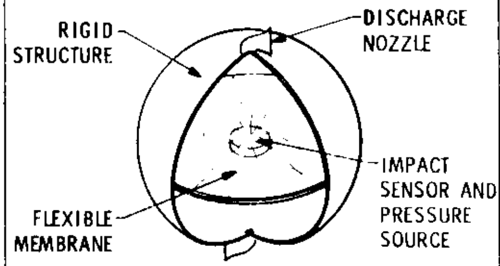
Figure A1. Impact Burst, Sponge Sphere



DESCRIPTION

- UP TO 1/2-GALLON, SELF-FILLING CAPSULE
- CARRIED WITHIN RETARDANT TANK(S)
- CONVENTIONAL CASCADE RELEASE
- SPLASH-DISPERSION UPON IMPACT

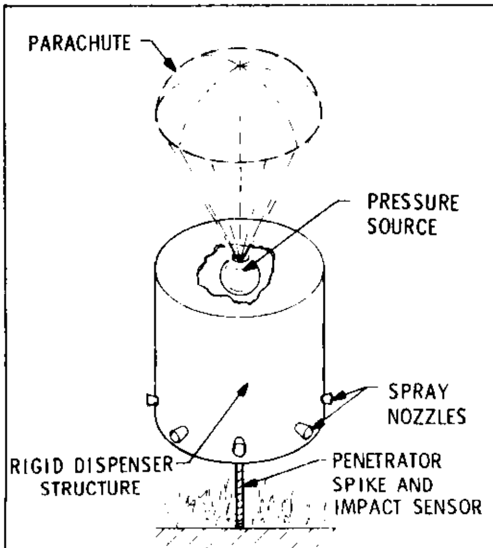
Figure A2. Impact Burst, Thin-Wall Capsule



DESCRIPTION

- UP TO 1/2-GALLON, PREFILLED, SPHERICAL DISPENSER
- CARRIED WITHIN BOMB BAY OR CARGO SECTION OF AIRCRAFT
- IMPACT-SENSOR-ACTIVATED PRESSURE SOURCE
- IMPACT SENSOR ARMED UPON RELEASE
- PRESSURE SOURCE ACTIVATED UPON IMPACT
- RETARDANT DISPERSION FROM NOZZLE SPRAY AND DISPENSER SKITTER

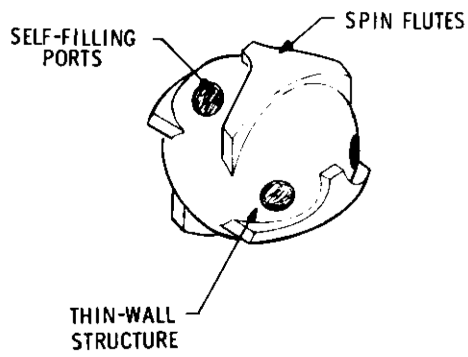
Figure A3. Impact Burst, Skittering Dispenser



DESCRIPTION

- 5- TO 25-GALLON, PREFILLED SPRAY DISPENSER
- CARRIED WITHIN BOMB BAY OR CARGO SECTION OF AIRCRAFT
- IMPACT SENSOR AND DISPENSER PRESSURE SOURCE
- PARACHUTE FOR DESCENT VELOCITY CONTROL
- UPON RELEASE LANYARD DEPLOYS PARACHUTE AND ACTIVATES IMPACT SENSOR
- SPIKE CONTACT WITH RELATIVELY RIGID SURFACE ACTIVATES PRESSURE SOURCE
- RETARDANT DISPERSED UNDER PRESSURE THROUGH NOZZLES

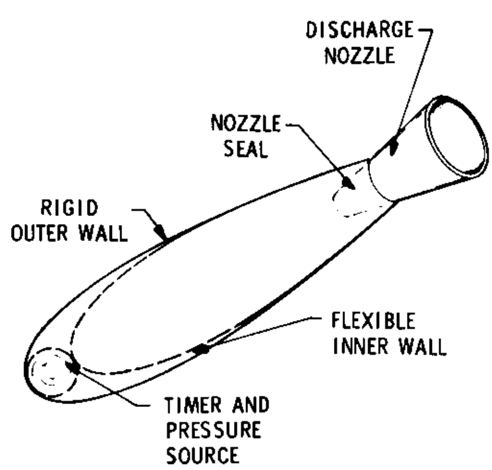
Figure A4. Impact Burst, Spray Generator



DESCRIPTION

- UP TO 1/2-GALLON, SELF-FILLING THIN-WALL SPHERE
- CARRIED WITHIN RETARDANT TANK(S)
- CONVENTIONAL CASCADE RELEASE
- BALLISTIC FLIGHT UNTIL SPINUP
- MAGNUS DISPERSION OF SPHERES
- RETARDANT PORTING AFTER SPINUP.

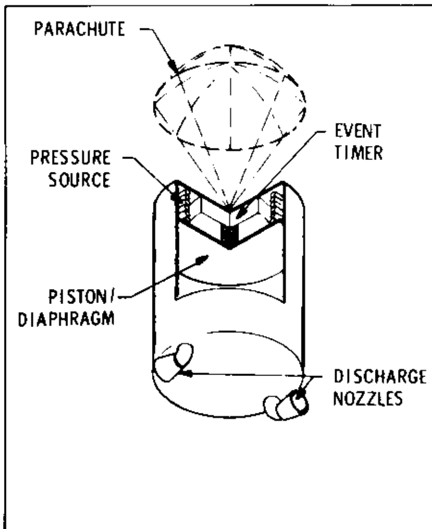
Figure A5. Airburst, Spinning Sphere



DESCRIPTION

- UP TO 1/2-GALLON, PREFILLED, DOUBLE-WALL DISPENSER
- CARRIED WITHIN BOMB BAY OR CARGO SECTION OF AIRCRAFT
- TIMER-ACTIVATED PRESSURE SOURCE
- ALTERNATIVE: PRESSURE-FILLED, ELASTIC SINGLE-WALL DISPENSER
- UPON RELEASE, LANYARD ACTIVATES TIMER
- AT TIMER RUNOUT, PRESSURE SOURCE INITIATED
- RETARDANT DISPERSION FROM NOZZLE SPRAY AND RANDOM DISPENSER FLIGHT PATH.

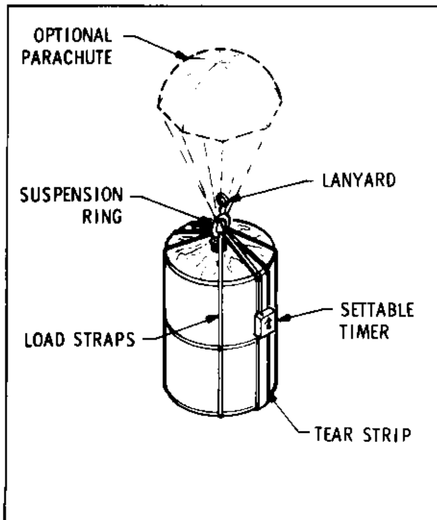
Figure A6. Airburst, Skittering Dispenser



DESCRIPTION

- 10- TO 100-GALLON PREFILLED DISPENSER
- CARRIED WITHIN BOMB BAY OR CARGO SECTION OF AIRCRAFT
- MECHANICAL TIMER FOR PRESSURE SOURCE INITIATION
- PARACHUTE FOR DESCENT VELOCITY CONTROL
- UPON RELEASE, LANYARD ACTIVATES PRESET TIMER AND DEPLOYS PARACHUTE
- AT TIMER RUNOUT, PRESSURE SOURCE ACTIVATED AND NOZZLES OPENED
- RETARDANT DISPERSION FROM NOZZLE SPRAY AND DISPENSER SPIN.

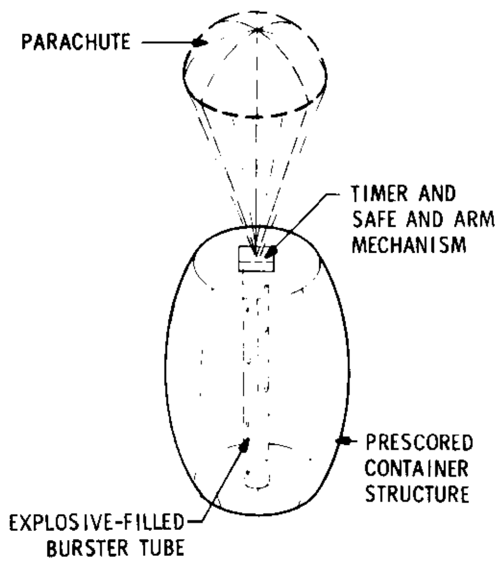
Figure A7. Airburst, Pressure/Nozzle Dispenser



DESCRIPTION

- 1- TO 100-GALLON PREFILLED DISPENSER
- CARRIED WITHIN BOMB BAY OR CARGO SECTION OF AIRCRAFT
- MECHANICAL TIMER FOR DISPENSER OPENING
- OPTIONAL PARACHUTE TO DECELERATE DISPENSER
- UPON RELEASE, LANYARD ACTIVATES PRESET TIMER [$\Delta = f(h, V, \rho)$] AND DEPLOYS OPTIONAL PARACHUTE
- AT TIMER RUNOUT, TEAR STRIP IS ACTIVATED AND AERO/HYDRO FORCES CAUSE BULK RELEASE
- RETARDANT DISPERSION CAUSED BY IN-FLIGHT EROSION.

Figure A8. Airburst, Bulk Dispenser



DESCRIPTION

- 5- TO 50-GALLON PREFILLED DISPENSER
- CARRIED WITHIN BOMB BAY OR CARGO SECTION OF AIRCRAFT
- TIMER AND S&A FOR BURSTER INITIATION
- PARACHUTE FOR DESCENT VELOCITY CONTROL
- UPON RELEASE, LANYARD ACTIVATES TIMER AND DEPLOYS PARACHUTE
- PARACHUTE DEPLOYMENT ARMS BURSTER CHARGE
- AT TIMER RUNOUT, BURSTER CHARGE INITIATED
- RETARDANT DISPERSION FROM EXPLOSIVE BLAST.

Figure A9. Airburst, Explosive-Activated Dispenser

2. OTHER CONCEPTS OF FIRE SUPPRESSION

Several radical methods of fire suppression were considered early in the study to establish a broad base for the investigations and a general catalogue of possible techniques for future reference and investigation. All were rejected for one or more of the following reasons: because all investigation was considered beyond the scope of this study, because they were considered beyond the current state of the art, or because they were determined to be impractical on close examination.

a. Use of Drones

Drone aircraft guided to the drop zone by the bird dog could be controlled in the drop run by terrain-following radar, allowing achievement of low-altitude delivery without risk to pilots. The expense of such a system is relatively high, with considerably higher R&D costs. Critical issues are the safety of ground forces and the reliability of the system, which is exceedingly complex to implement. It is believed that such a system is not practical within the current state of the art.

b. Guided Containers

Like drones, these containers are guided to location by the delivery pilot. Wire or infrared heat seeking guidance can be considered. The device would burst either within or above the treatment zone. It is potentially capable of applying heavy retardant or suppressant dosages on small fires from very high altitudes by providing pinpoint accuracy. It is, therefore, potentially useful as an armament on high-altitude fire detection planes to provide an initial attack capability with essentially zero response time. The device represents a high expenditure that can be justified only in terms of the damage preventable from such an attack capability. It also requires a high certainty of determining the nature of the fire and of asserting a real-time decision to suppress it. Volumetric coverage can be selected by establishing a fuzing altitude with respect to the fire situation and size.

This type of system is envisioned as a highly effective device in the future, but it is currently not compatible with the decision/information processes that could ensure ground personnel safety. It would not in any case represent the only capability used by retardant aircraft, and was excluded from further consideration in the current study.

c. Towed Containers

The possibility of achieving faster retardant delivery turnaround times by aerial pickup of ground-loaded containers appears worthy of further consideration. The towed containers could be controlled by wire guidance techniques to maneuver below the aircraft, providing release from a considerably lower altitude than that flown safely by the pilot. The critical issue is the inflight pickup capability of the aircraft. Such a device could take the form of a fluid and air-inflated parawing with control surfaces. It could be loaded on the ground and in any convenient location near the fire where a pickup run could be negotiated. The extensive investigation required to determine whether or not this system is economically practical or even usable from the types of airfields available to the Forest Service was considered beyond the scope of this study.

d. Use of Explosives

Numerous uses of explosives can be suggested to attack fires or build lines. These range from the use of conventional bombs to clear fire breaks or throw dirt on the fuels through cratering effects to devices less damaging to the environment. Airburst bombs provide blast overpressures that can strip foliage, knock down trees, and potentially, extinguish fires. These techniques are limited by ground safety and indeed by the special handling and training requirements for ground personnel. They are thus rejected for purposes of the current study. (It should be noted that the delivery of fuel-air explosive devices to clear helicopter landing zones in brush or forest areas has been successful under military applications. The resultant cleared area is reported to be ecologically viable in that recovery is exceedingly rapid.)

e. Incendiary

Two approaches that involve the use of air-delivered incendiaries have been used to create prescribed burns in Australia. The process is to drop carefully spaced incendiaries that burn into each other, creating a low-intensity fire with substantial fuel thinning. Such a technique could be used for backfiring or fuel thinning in advance of a major fire front, i.e., to provide controlled spotting under reverse wind conditions. The second hypothesis projects the overfueling of the fire front by adding a flammable fuel. This overburning effect creates high updrafts (similar to a prescribed slash burn) and encourages a reverse wind suitable for backfiring. The practicality of using incendiary approaches is restricted by the necessity for a predictive knowledge of fire behavior, the ability to deliver the incendiaries only where they will tend to suppress (not expand) the fire problem, and ground safety. Although there is some theoretical basis for this application, it is rejected for purposes of the current effort.

f. Foams

Direct application of foams is used substantially in fighting processed fuel fires. In an early evaluation of foams, the Canadians suggested that the foams at that time did not retain moisture, but drained over short time periods and made footing excessively slippery for ground personnel. An examination of current foams appears warranted to determine the relative change in foam consistency and the fragility of foams in air drop. The potential advance effects of retardant coating thicknesses suggested by vertical fuel coverage studies suggest that a more reasonable technique for using foams is to generate them after impact, as it is very probably that air-dropped foams will not penetrate the forest canopy. However, if dropped in containers, considerable parasitic weight for the containers is involved. In general, it appears that, while foams may have a place in fighting wild fires, they should be used by ground personnel and are therefore not a proper part of this study.

g. Intumescents

Certain retardants exhibit some intumescent qualities, i.e., the formation under heat of a porous flame-resistant cinder, not necessarily a product of retardant reaction with the fuels. Such an additive effect might produce a change in the fire spread rate under certain conditions. Delivery of such devices is not different from traditional retardants and consequently does not affect the nature of this study.

h. Chemical Inhibitors

Flame inhibitors act in the flame reaction zone to interfere with the formation of radical chains. They are substantially more effective extinguishers than carbon dioxide, for example, although their subsequent cooling capability is marginal. They therefore contribute to knockdown, but do not prevent rekindling unless a considerable concentration is maintained for some time. They are typically a gas (bromotrifluoromethane) liquified by compression that could be used as the sole content of a container or simply as the pressurizing agent for a conventional contained retardant. As it is impossible to maintain an adequate concentration of a gas under any wind conditions, this technique is not suitable for aerial delivery.

j. Stable Liquid Vortex

The possibility of ejecting the retardant as a series of stable liquid vortices, like smoke rings, could potentially delivery retardant over relatively long ranges intact. Such vortices appear to exist when the density of the vortex material is on the order of 1.5 times the density of the supporting medium. For retardants in air, this would imply a considerable aeration. It potentially could be used to apply small droplets or dry salt, although such a system is deemed impractical under the current state of the art.

APPENDIX B

WEIBULL PATTERN ANALYSIS

One evaluation of the Maranna data used the Weibull technique of characterizing pattern distributions. This technique has been shown in most cases to provide a good fit to actual pattern statistics. A large number of patterns have been subject to this form of analysis, and with few exceptions the linear fit relationship appears to apply.

The main purpose for this analysis was (1) to obtain a qualitative indication of factors contributing to pattern formation not related to those modeled in the MacPhearson simulation and (2) to determine in a general sense the sensitivity of η in resolving experimental questions.

The technique was applied to the evaluation of the Maranna test data of the matrix in Figures B1 and B2. Primary emphasis, particularly early in the study, was placed on the CL-215 and Aero Union B-17 to develop confidence in the technique. Figures B3 and B4 present η values in terms of the data matrix. In some cases the data appear orderly. In others, there is considerable scatter. In only a few cases were there enough sample points to assess the effect of variables in a true statistical fashion.

1. CL-215

The CL-215 was one of the most thoroughly characterized aircraft and results appear to be relatively well organized as shown in Figure B5. These data are based on actual pattern values in the Maranna Test Series[26] as tabulated in Table B-1. Figures B6 through B10 show the relative fit of these

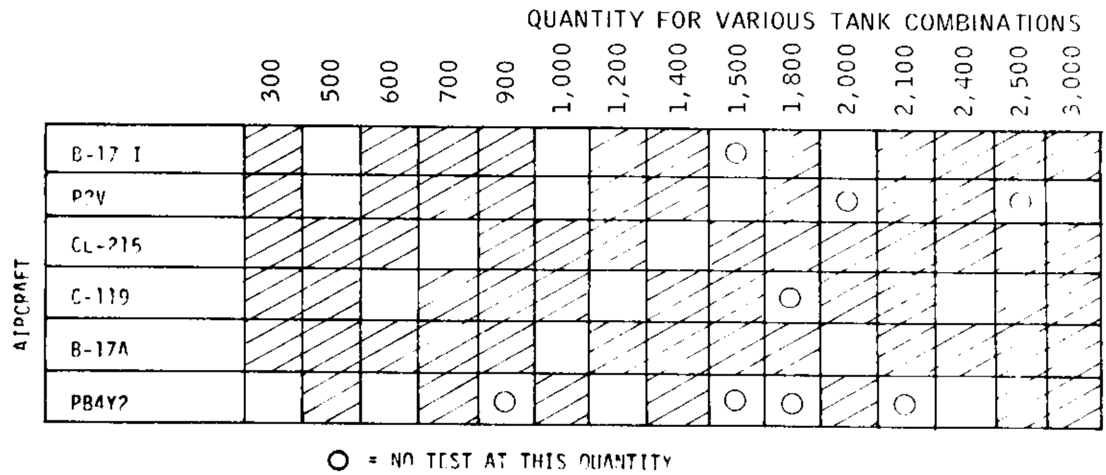


Figure B1. Potential Dataset

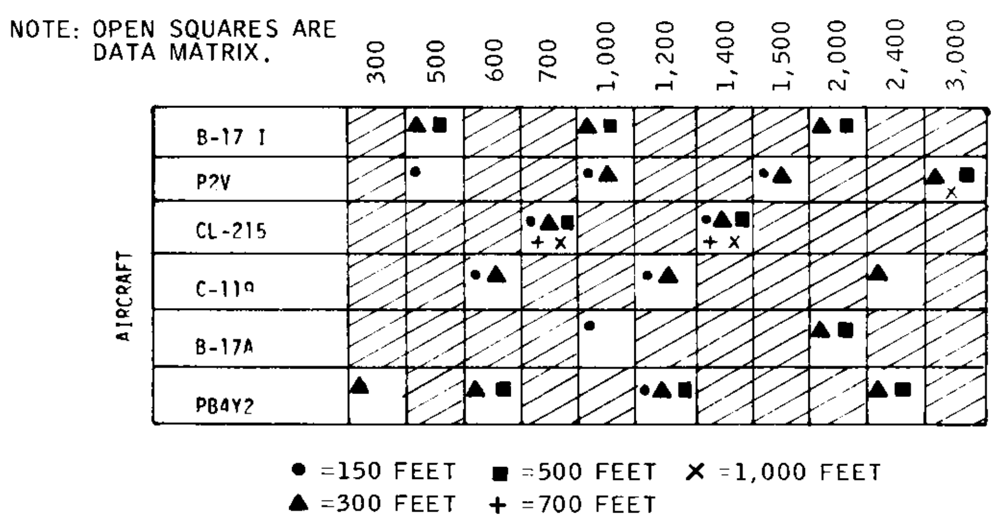


Figure B2. Actual Dataset

150 FEET

AIRCRAFT	500	600	700	1,000	1,200	1,400	1,500
B-17 I							
P2V	2.3			3.8 2.3			3.2
CL-215			4.5 30,30 29			7.1	
C-119		2.4			2.4		
B-17A				1.1			
PB4Y2					6.4		

300 FEET

AIRCRAFT	300	500	600	700	1,000	1,200	1,400	1,500	2,000	2,400	3,000
B-17 I		0.9			1.25				3.1		
P2V					0.86 2.0 2.3			2.4			5.2
CL-215				1.6 1.9			4.3				
C-119			1.1			1.5				5.7	
B-17A					3.3				4.7		
PB4Y2	0.85		1.5			2.6				4.5	

500 FEET

AIRCRAFT	300	500	600	700	1,000	1,200	1,400	1,500	2,000	2,400	3,000
B-17 I		0.67			1.25				1.7		
P2V											4.5
CL-215				0.95			3.1				
C-119											
B-17A									1.7 2.1		
PB4Y2			0.6			1.7				4.5	

Figure B3. Eta Values, Low and Moderate Altitude Tests

700 FEET

AIRCRAFT	700	1,400
B-17 I		
P2V		
CL-215	0.4	2.7
C-119		
B-17A		
PB4Y2		

1,000 FEET

AIRCRAFT					
B-17 I		0.92		1.3	
P2V					2.0
CL-215	1.2		1.8 1.3		
C-119					
B-17A					
PB4Y2					

Figure B4. Comparative Data at High Altitudes (Eta)

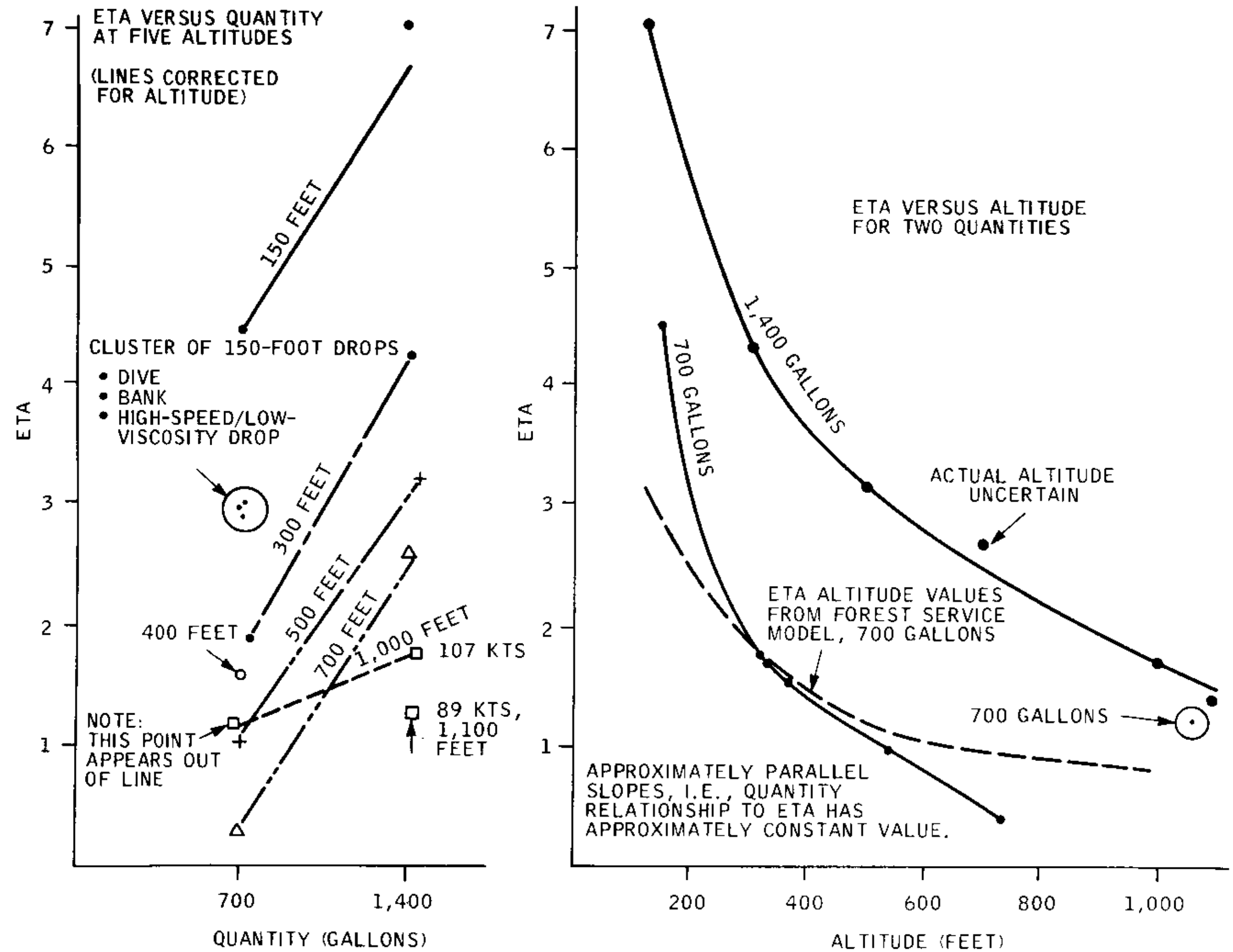


Figure B5. Eta Values for CL-215

Table BI. Recovered Retardant Phoschek ® XA, CL-215

DROP NO.	ALTITUDE (FEET)	GALLONS	RECOVERED		<0.2 (GPC)	0.2 TO 0.99 (GPC)	1.0 TO 1.99 (GPC)	2.0 TO 2.99 (GPC)	3.0 TO 3.99 (GPC)	4.0 TO 4.99 (GPC)	>5.0 (GPC)	PERCENT
5	150	700	516	GALLONS PERCENT CUMULATIVE PERCENT	28.6 5.5	74.2 14.4 19.9	58.0 11.3 31.2	75.4 14.6 45.8	56.5 11.0 56.8	17.6 3.4 60.2	205.2 39.8	73.7
16	150	1,400	1,187	GALLONS PERCENT CUMULATIVE PERCENT	37.2 3.1	77.9 6.5 9.6	122.1 10.3 19.9	135.9 11.5 31.4	131.9 11.0 42.4	70.8 6.0 48.0	711.5 50.0	89.8
4	300	700	637	GALLONS PERCENT CUMULATIVE PERCENT	113.7 18.0	99.2 15.5 33.5	138.8 21.8 55.3	89.0 14.0 69.3	84.1 13.2 82.5	24.9 3.9 86.4	87.6 13.5 100.0	91.0
21	300	1,400	1,256	GALLONS PERCENT CUMULATIVE PERCENT	33.8 2.7	109.4 8.7 11.4	221.2 17.6 29.0	178.0 14.1 43.5	156.4 12.4 55.9	125.2 10.0 65.9	423.3 33.8 100.0	89.7
26	500	700	541	GALLONS PERCENT CUMULATIVE PERCENT	49.9 9.2	96.5 17.8 27.0	222.4 41.2 68.2	98.9 18.3 86.5	31.8 5.9 92.4	18.2 3.4 95.6	22.9 4.2	77.3
31	500	1,400	1,191	GALLONS PERCENT CUMULATIVE PERCENT	29.5 2.5	129.3 10.9 13.4	192.2 16.1 29.5	212.7 17.8 47.3	256.4 21.5 68.8	139.9 11.7 80.5	231.3	85.1
[illegible]	750	700	525	GALLONS PERCENT CUMULATIVE PERCENT	31.8 6.1	222.6 42.4 48.5	250.2 48.0 96.5	20.4 3.9				75.0
65	750	1,400	1,215	GALLONS PERCENT CUMULATIVE PERCENT	25.0 2.05	97.5 8.0 10.0	220.4 18.2 28.2	259.2 21.4 49.6	367.4 30.4 80.0	146.1 12.0 92.0	99.7	86.8
45				GALLONS PERCENT CUMULATIVE PERCENT	20.9 3.6	105.9 18.4 22.0	292.3 50.7 72.7	140.4 24.4 97.1	17.3 3.0			82.4
46	1,000	1,400	1,122	GALLONS PERCENT CUMULATIVE PERCENT	20.1 1.8	115.9 10.3 12.1	378.8 33.7 45.8	476.0 42.5 88.3	127.7 10.3 98.0	5.4 4.8		80.1

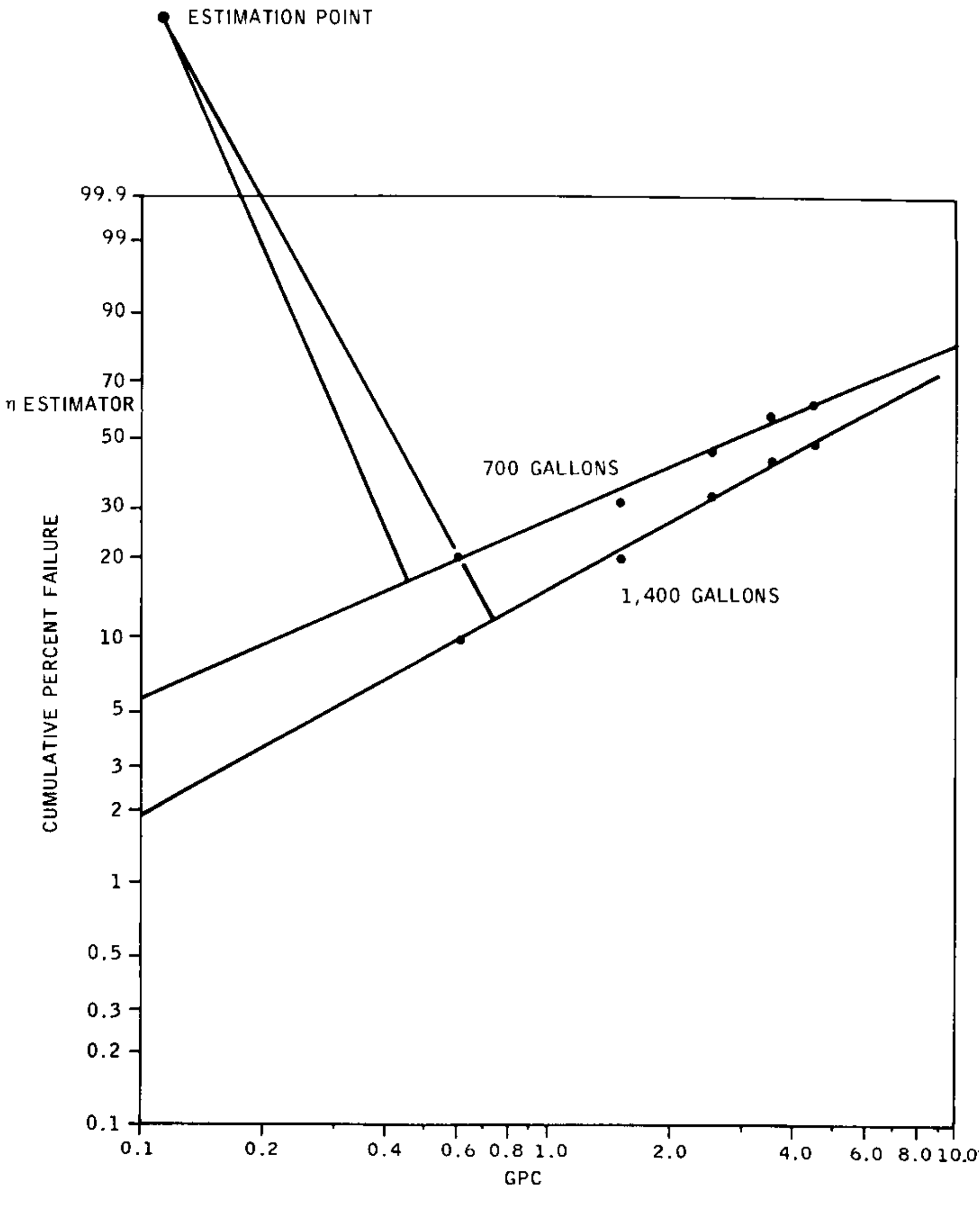


Figure B6. Weibull Probability Chart, 150-Foot Altitude, CL-215

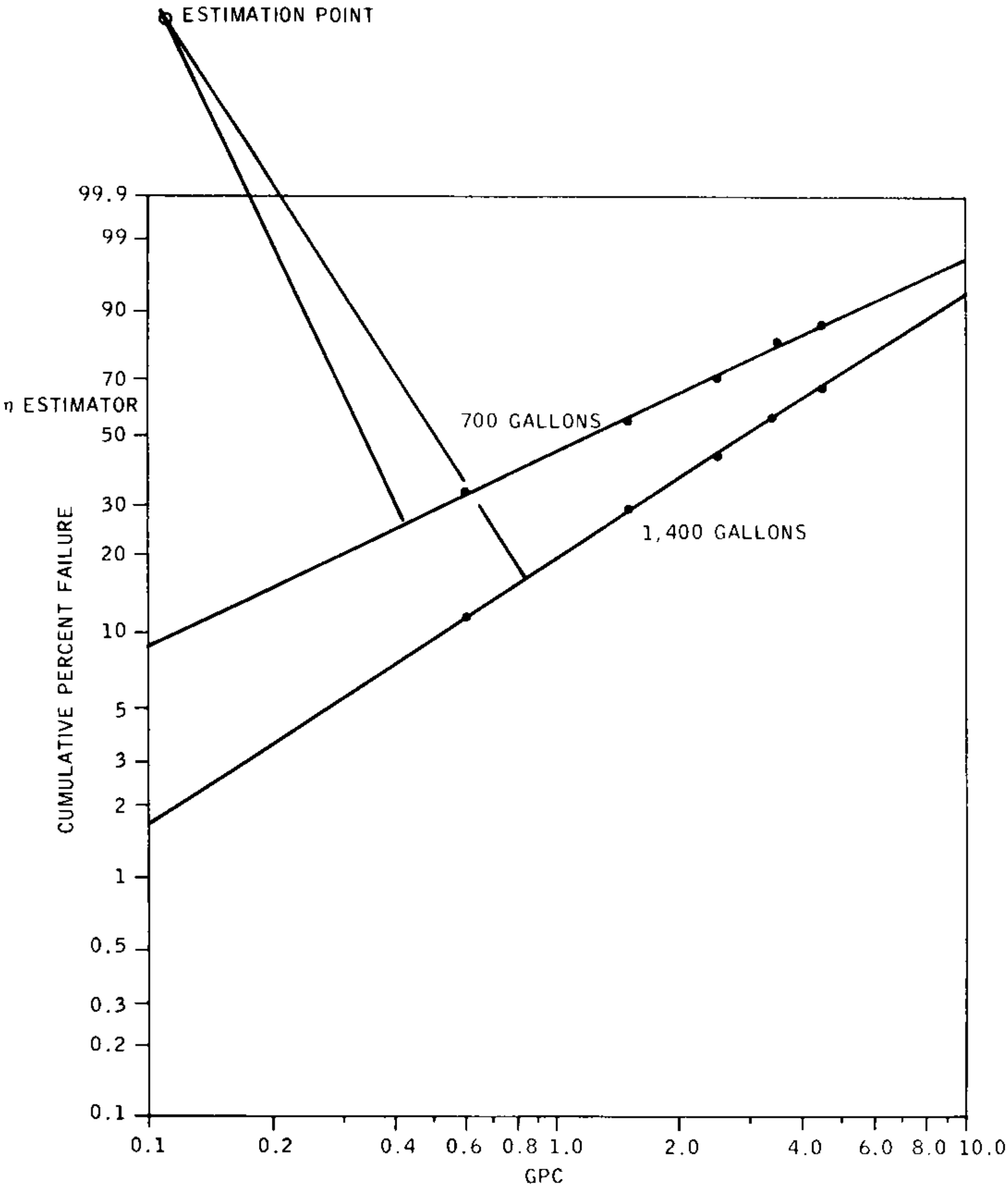


Figure B7. Weibull Probability Chart, 300-Foot Altitude, CL-215

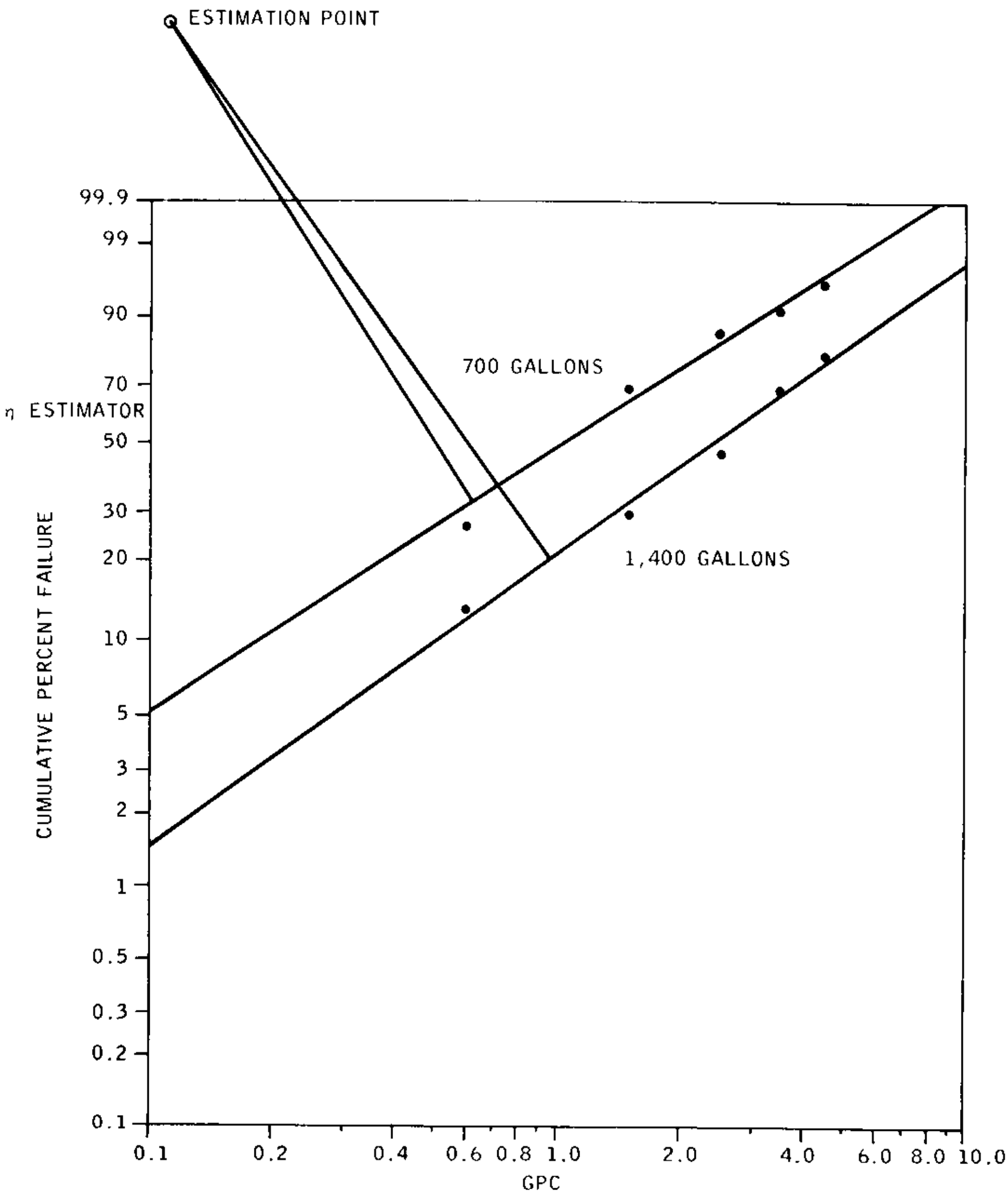


Figure B8. Weibull Probability Chart, 500-Foot Altitude, CL-215

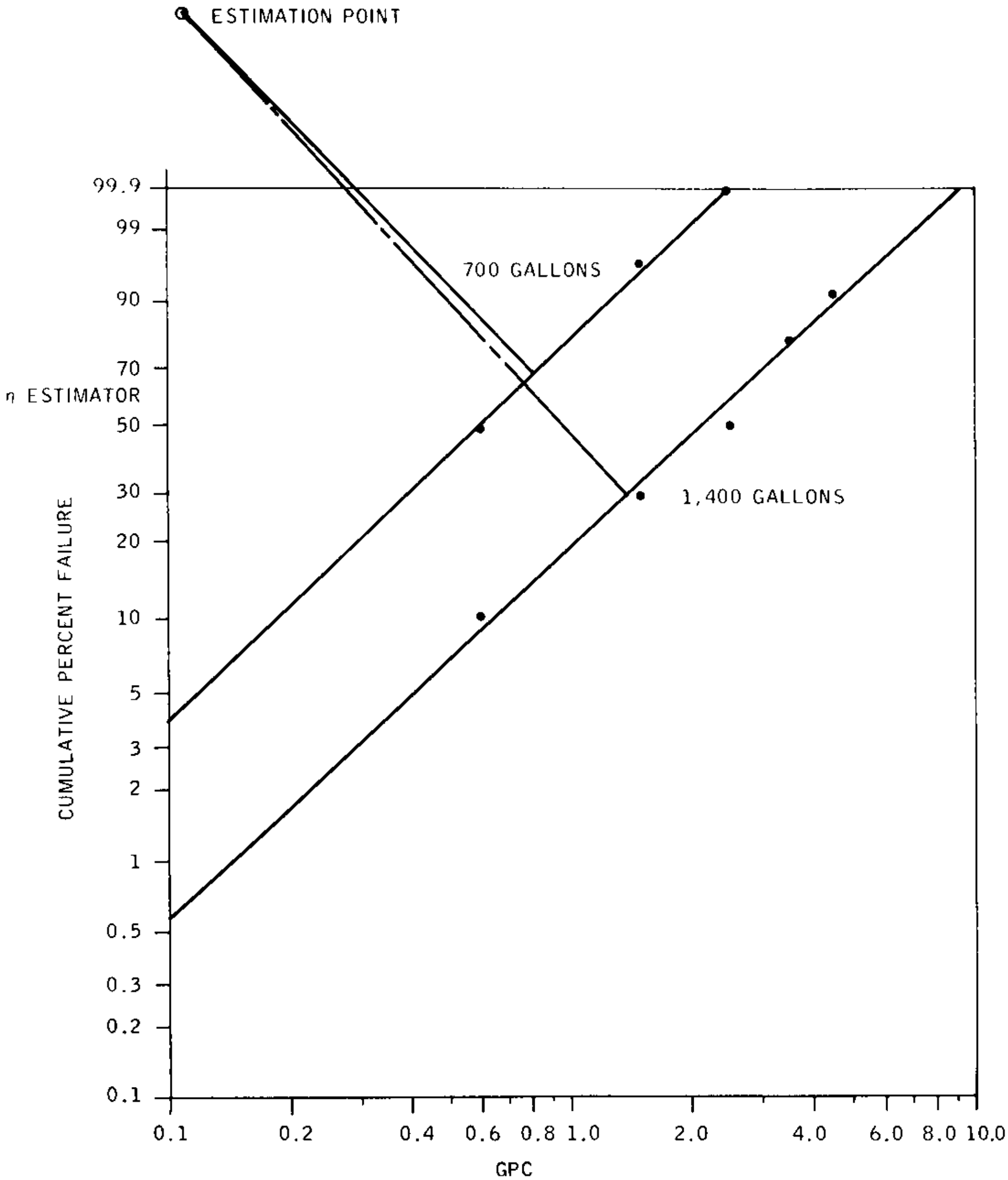


Figure B9. Weibull Probability Chart, 750-Foot Altitude, CL-215

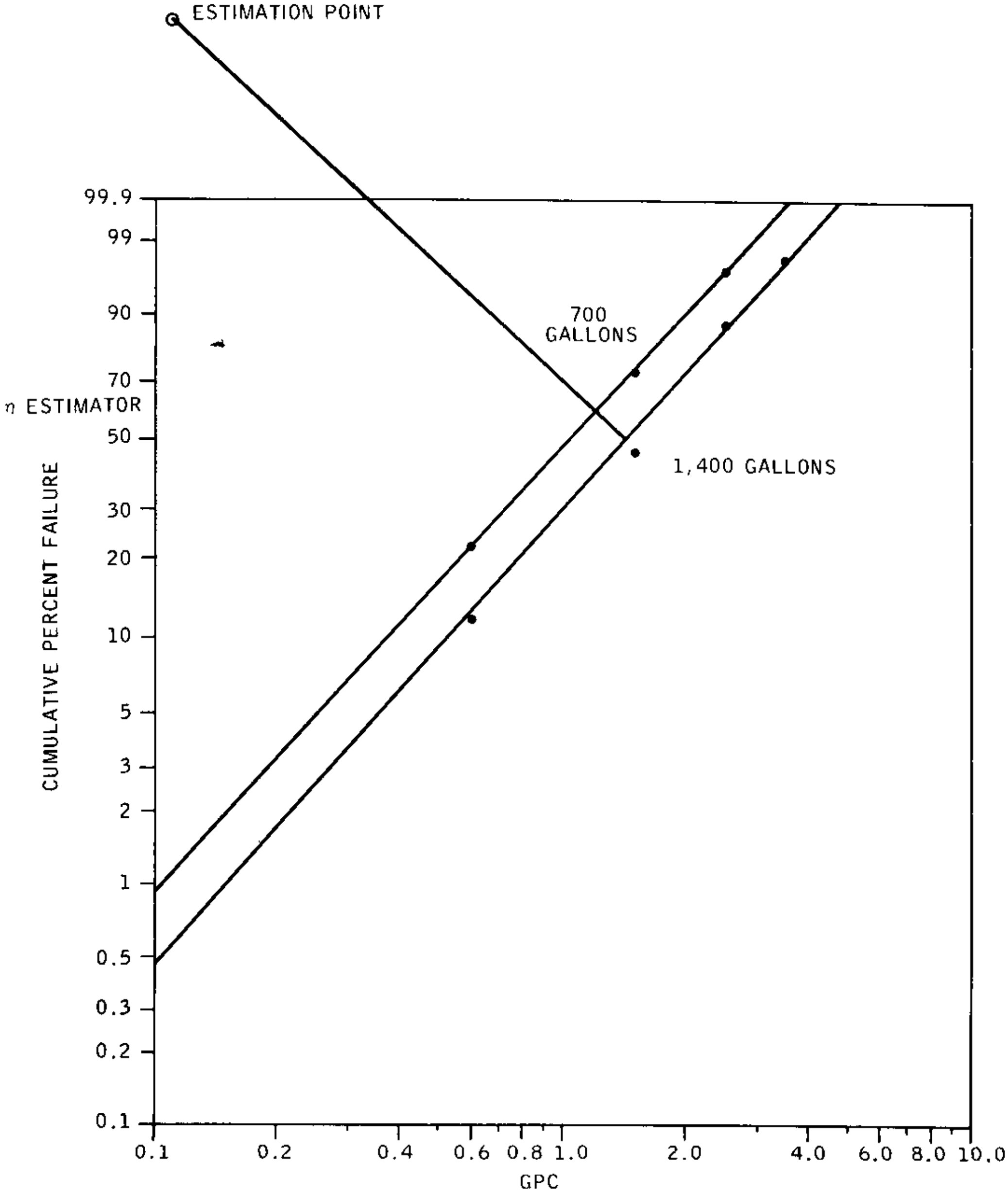


Figure B10. Weibull Probability Chart, 1,000-Foot Altitude, CL-215 data to the Weibull distribution. (Distributional fits to other aircraft in the series are similar.)

A linear multiple regression analysis was conducted on the CL-215 data up to 500 feet to assess the relative effects of velocity, altitude, viscosity, and quantity. The results in terms of η are:

$$\eta = B_1 V_{A/C} + B_2 \text{ Altitude} + B_3 \text{ Viscosity} + B_4 \text{ Quantity.}$$

	B	Standard Error	Order of Importance
B_1 $V_{A/C}$ (10 knots)	0.143	0.147	2
B_2 Altitude (10 feet)	-0.082	0.024	3
B_3 Viscosity (poise)	0.035	0.092	4
B_4 Quantity (100 gallons)	0.389	0.074	1

Multiple correlation value = 0.934

F-test on regression value = 8.56

Although the correlation is meaningful, the significance of the variables is difficult to assess except in the case of quantity and altitude, the effects of which were previously known. The surprise is that velocity has a positive coefficient (η increases with velocity); however, when a similar set of data were run with tank exit time as a fifth parameter, both exit time and aircraft velocity became negative.

2. B-17 INTERMOUNTAIN

A similar analysis was conducted on the B-17 data where larger ranges in viscosity were evaluated. The results were:

$$\eta = B_1 \text{ Velocity of A/C} + B_2 \text{ Altitude} + B_3 \text{ Viscosity} + B_4 \text{ Quantity}$$

	B	Standard Error	Order of Importance
B_1 $V_{A/C}$ (10 knots)	0.094	0.015	2
B_2 Altitude (10 feet)	-0.029	0.004	3
B_3 Viscosity (poise)	0.010	0.005	4
B_4 Quantity (100 gallons)	0.113	0.011	1

Multiple correlation value = 0.963

F-tests on regression value = 53.44

The multiple correlation value, which shows a "goodness of fit" of the resultant regression as it approaches unity, was 0.96+. The dominant factor was quantity followed by aircraft velocity and altitude. Viscosity appears to be only a second order effect, i.e., viscosities from zero to 40 poise, a range wider than that actually tested, would show only a 0.4 change in the η value, roughtly on the order of the velocity induced change. Again the coefficient for velocity was positive, but may be subject to the same ambiguities shown in the CL-215.

It is clear from these analyses that tanking variability is significant enough to create substantial noise that cannot be statistically eliminated with the number of sample points available. This, then, is one reason for the design of a standard test tank that can yield data to reduce these differences to quantitative understanding.

Figure B11 is a scattergraph of the η-versus-altitude data with estimated η-versus-quantity data. The effect of increased quantity is not as great as that in the CL-215, nor is the initial value of η comparable. The initial value difference is substantially attributable to flow rate, whereas the η rate of change with quantity reflects characteristics of multiple tank opening.

3. PB4Y2

In the remainder of the tanking systems examined there is limited data, and consequently the analysis can only be conducted in a qualitative sense. Figure B12 shows PB4Y2 data. In this case, the managed flow from the tank differentiates the system from others, as does the method of combining tanks. The 600-gallon drops are formed from longitudinally separated 300-gallon tanks; 1,200-gallon drops are from a line of 300-gallon tanks, and 2,400-gallon drops are generated from the side-by-side addition of 1,200-gallon increments.

4. C-119

Figure B13 shows comparative data on the C-119 that shows the first major departure from the relatively linear development of pattern values with quantity. This is attributed to the fundamental lateral separation of the two tanks used in the 1,200-gallon drop (two outboard tanks). The net quantity addition contributes to area development rather than the increase in coverage level. Only at higher altitudes does some mixing occur. Again, data are

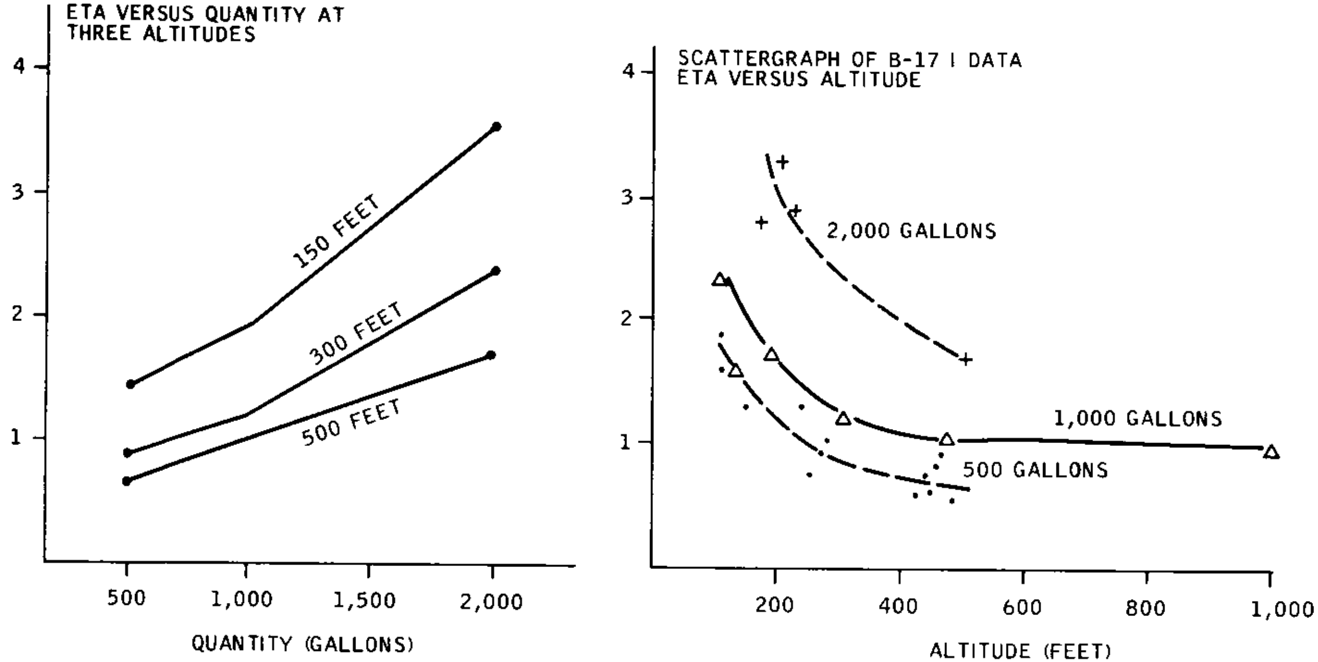


Figure B11. B-17 I Eta Values

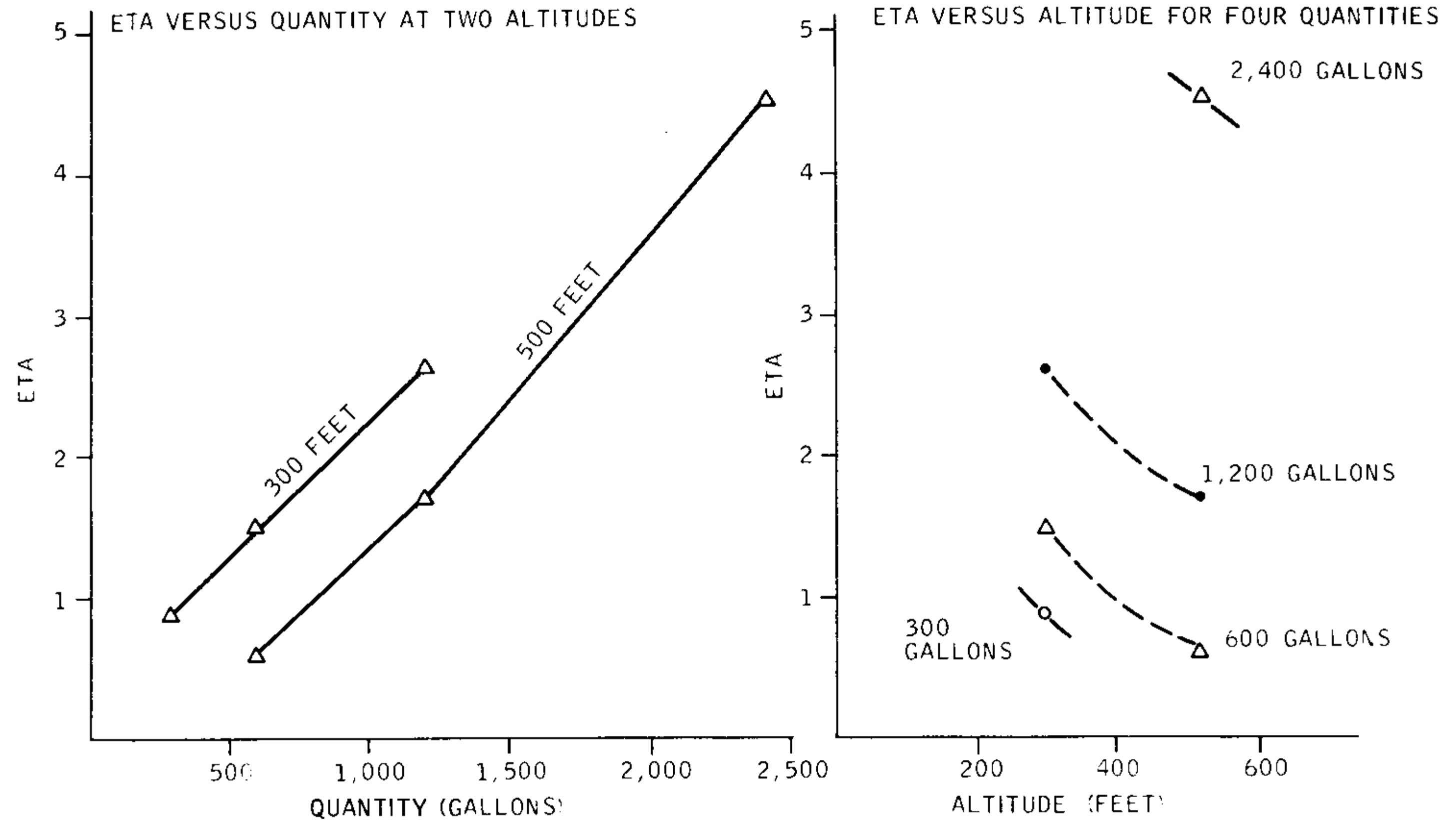
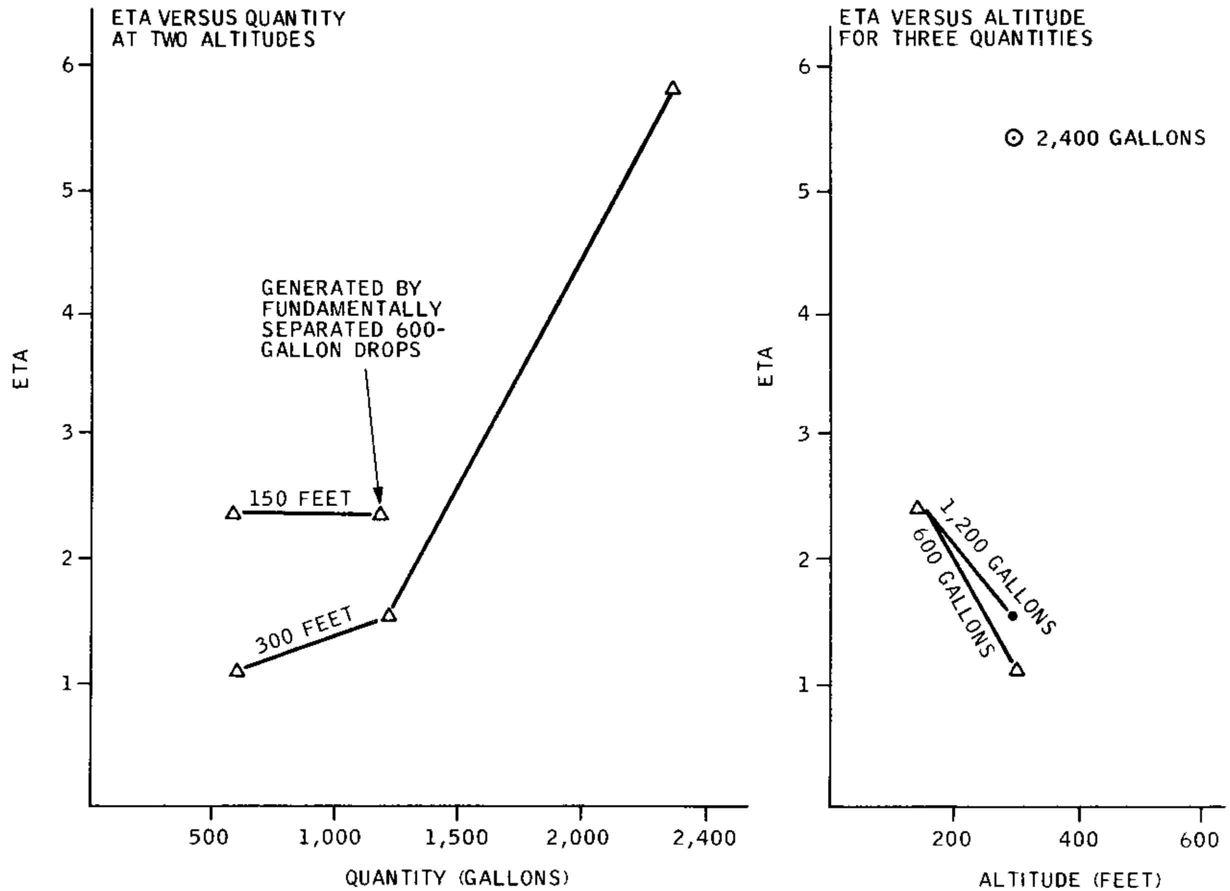


Figure B12. Eta Pattern Values for PB4Y2



NOTE: ALL DROPS HAD A RELATIVELY LOW VISCOSITY.

Figure B13. Eta Values for C-119

limited; viscosities in the subject drops were somewhat low (10 to 15 poise) and it is difficult to assess the tank comparatively for these reasons.

5. P2V

Figure B14 shows the limited P2V data and annotates possible noise sources. Here the 1,500-gallon drop is also a fundamentally separated tank release composed of adjacent 500-gallon tanks plus a third 500-gallon tank separated from the 1,000-gallon bulk. These drops were also of relatively low viscosity complicating the analysis.

6. AERO UNION B-17

Figure B15 presents data for the Aero Union B-17. The abnormal value (very low η at 150 feet) is unexplained. The pattern itself appears unaccountable.

7. CONCLUSIONS

Although data are severely limited and compounded by tanking variables, the effect of quantity and altitude on pattern values appears to dominate viscosity and velocity; however, there is some indication that the Weibull η provides some resolution of these second order effects. An additional variable appears to relate to the method by which tanks are added together to achieve higher pattern values. These, then, are items to be evaluated further in the test tanking system.

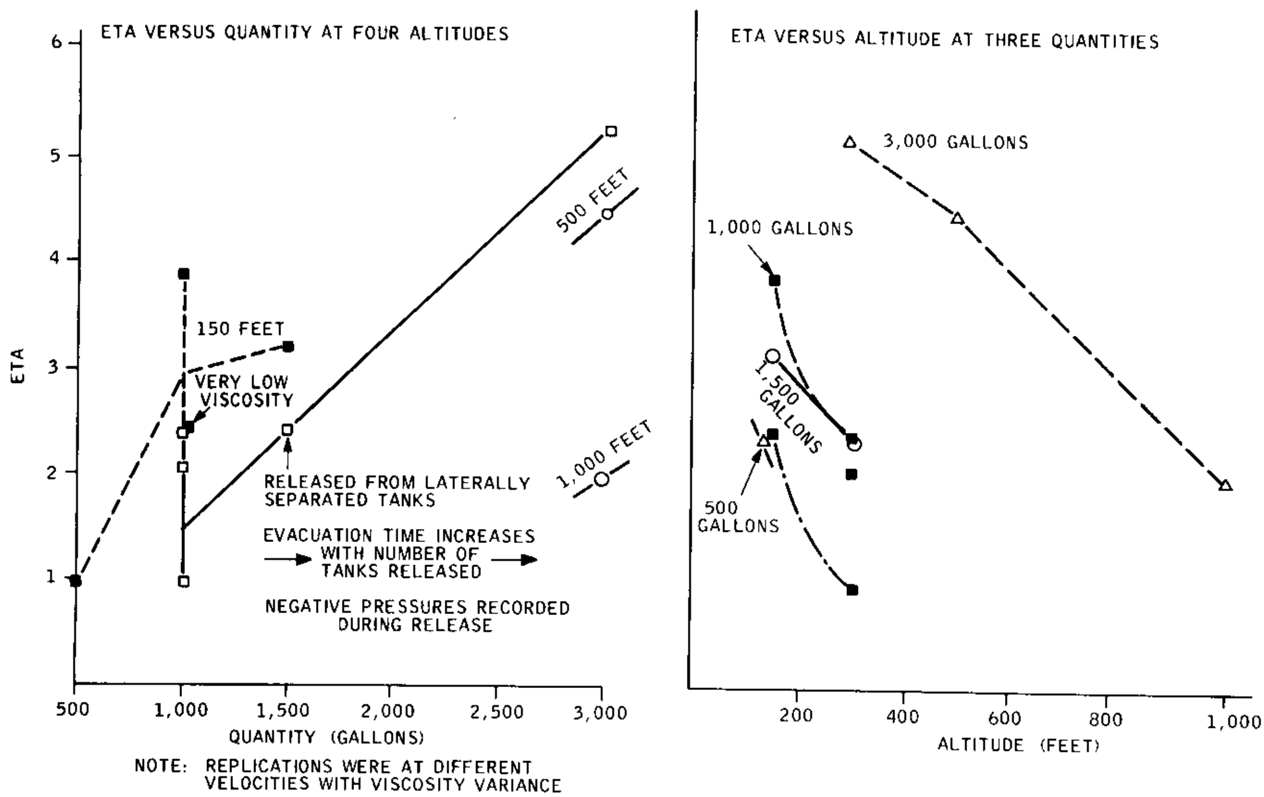


Figure B14. Eta Values for P2V

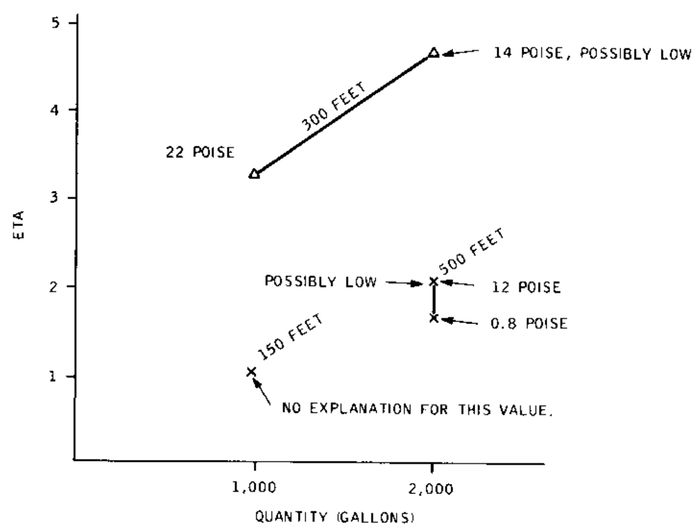


Figure B15. Eta Values for B-17A

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