WATER APPLICATION DEPTHS REQUIRED FOR EXTINGUISHEMENT OF LOW INTENSITY FIRES IN FOREST FUELS

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ABSTRACT

An airtanker drop simulator was designed to apply water to burning fuels, to measure the effectiveness of water as a fire suppressant and to permit the evaluation of different water bombers on the basis of their drop contour patterns.

Problems associated with burning insitu fuelbeds are discussed and details of fuel conditioning, fuelbed preparation and fuelbed characteristics are presented.

The necessity to use red pine needles and each of the slash fuels (balsam fir, black spruce and white spruce) individually in test fires is discussed. The associated problems are presented to indicate that fire intensity is a poor measure of fire severity in the determination of depth of applied water required to extinguish different intensity fires for different fuels. Curves for water versus intensity for each type of fuel are presented to denote the zone of extinguishment, the zone of delayed extinguishment and the zone of reignition.

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INTRODUCTION

The use of water as a forest fire suppressant attained universal acceptance primarily because of its availability and its ease of transfer and application by as simple a utensil as a bucket as well as by such an intricate contrivance as a pumper. People were not perturbed about the fact that no one could really predict how uch water could be considered "enough" for a given situation. However, the need to relate water application depths with fire intensity did arise when aerial application by aircraft became a reality. The cost of water delivered to the fireline by airtankers is substantially greater than by conventional ground application systems, hence the need to evaluate the aircraft in its new role warranted priority. A procedure to evaluate ground distribution patterns for water dropping aircraft was developed (Hodgson, 1967) and drop contour patterns were determined for the airtankers flown in Canada (MacPherson, 1967). Although the water dispersal patterns had been determined (Appendix A) there was no method of relating the different contour depths with aircraft effectiveness. The question still to be answered was "How much water is required to extinguish a fire of a given intensity?" Until such time as some numerical relationship between water application depths and fire intensity (I)** could be determined, it was assumed that the 0.07 inch contour (Hodgson, 1969) would be the minimum amount required to retard a fire, hence all effective pattern configurations were based on this criterion.

The parameters that could not be controlled if aircraft were actually used in the field to evaluate the effectiveness of water, could however be minimized if airtanker drops were simulated. The guideline objectives which were established were:

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** Fire intensity (I) is the product of the heat yield of a unit weight of fuel, the fuel loading per unit square area, and the rate of linear fire spread per second.

(1) Simulate aircraft water drops by using a hydraulic spray system to approximate freefall drops acting only under the force of gravity.

(2) Determine equivalent depth of water required to extinguish fires in forest fuels burning at known intensities.

(3) Evaluate the various types of forest fire retardant chemicals relative to water.

EXPERIMENTAL METHODS

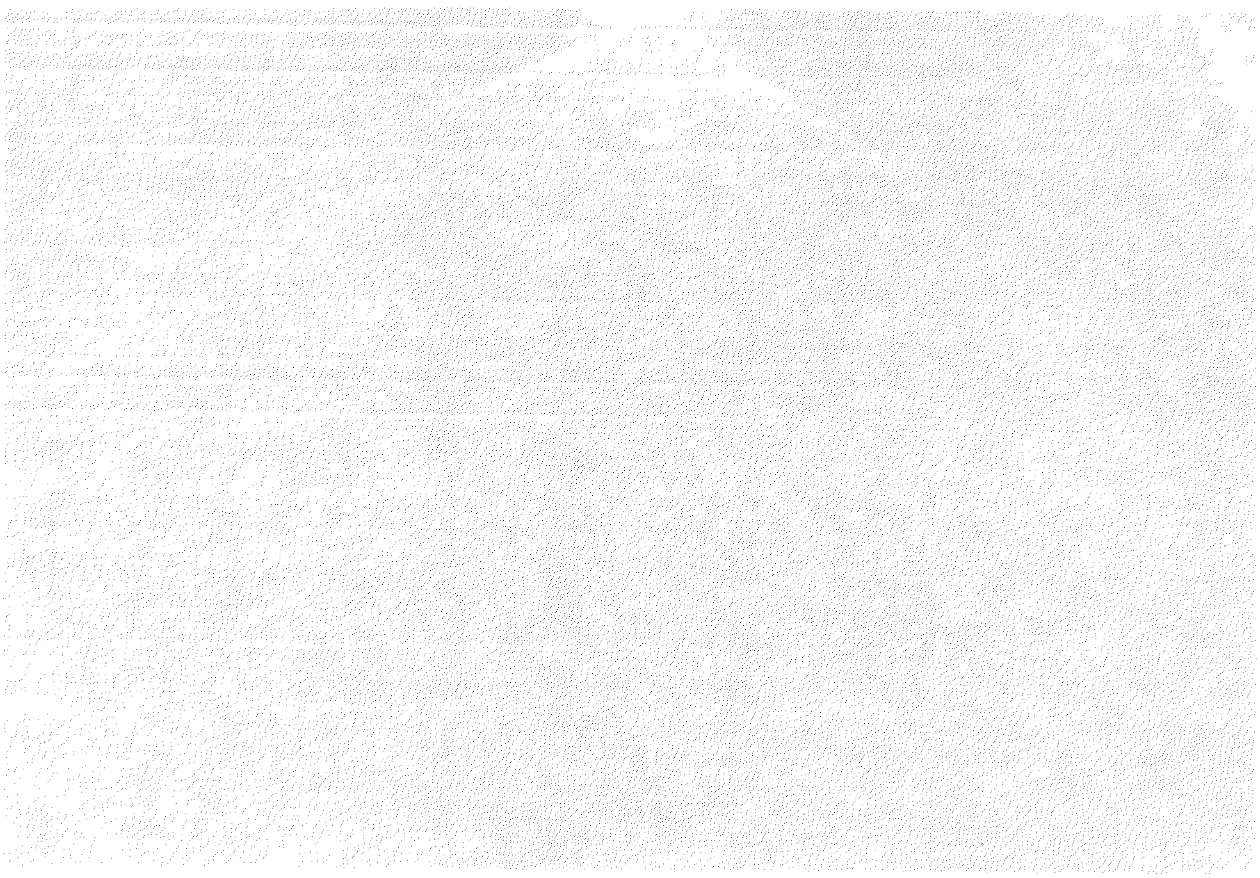
Developmental Stages

The initial work involved the selection of a water application system which would in essence apply a blanket of water of uniform depth over a sizeable area. The problems associated with the use of a stationary nozzle device (Hodgson, 1968) led to a mobile trolley system equipped with a "Flood Jet" nozzle fed by a pressurized water system (Fig. 1). Although the principles of operation did not change, the configuration of the simulator underwent several changes during developmental and in-use periods.

The apparatus illustrated in Figure 2 was used in the initial burning tests on a site in a Red Pine (*Pinus resinosa* Ait.) plantation. The system proved workable, however, lack of control over fuelbed parameters indicated that a new approach was needed. The change from an insitu situation to an artificially laid needle bed prompted the replacement of the mobile pressurizing system with a stationary external unit having a large water reservoir pressurized by compressed nitrogen as shown in Figure 3. This simulator functioned effectively for the low intensity fires but it was prone to periodic failure when fire intensity was increased. Although the fuel-bed problem had been solved, weather still dictated if and when tests could be conducted, therefore the third modification phase was launched. The track system was rebuilt from an eleven-foot clear spray span located five feet above the ground to a sixteen foot clear span at a height of nine feet. The simulator was now housed in an enclosure where fire parameter variability could be better controlled (Fig. 4).

By varying trolley travel speed and by using nozzles having different orifice diameters, it was possible to get application depths from 0.01 inch to 0.18 inch with reasonable uniformity across the pertinent portion of the fuelbed. The nozzles were mounted on the trolley singly (Fig. 5), or in tandem (Fig. 6), or set laterally five feet apart and positioned to permit a uniform overlap (Fig. 7).

The water drop distribution for each nozzle was determined by setting out a grid of 63 vials. Three rows, each made up of 21 vials set six inches apart longitudinally along the test bed from station 2 to station 12, were used to get replication and thus facilitate derivation of a mean application depth at one-half foot intervals along the drop pattern. Sample calibration curves are shown in Figure 8 for a single and a dual nozzle output arrangement.



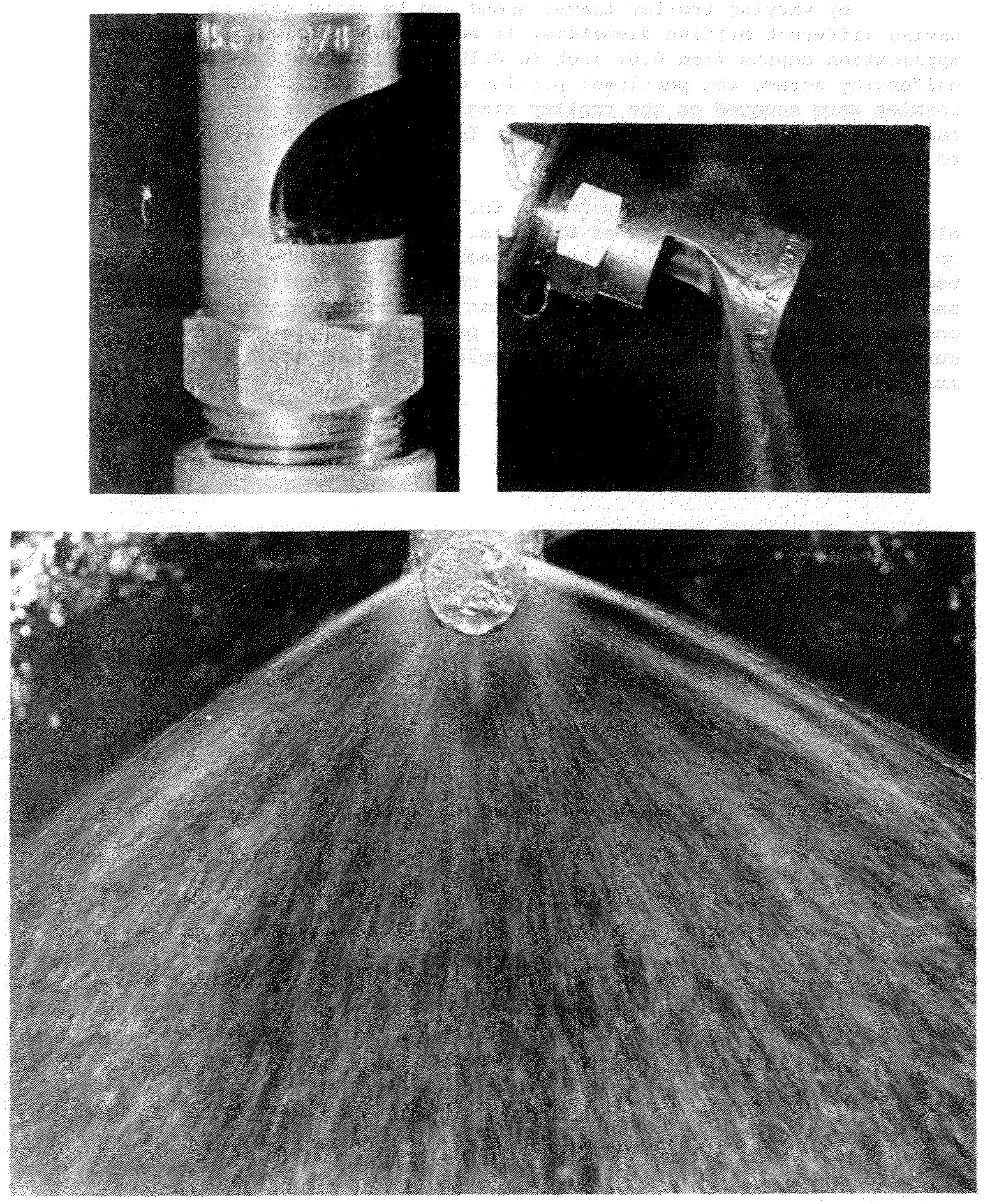


FIGURE 1. Floodjet nozzle used in the airtanker simulator. Water ourput was 8.3 Imperial gallons per minute at 30 psi.

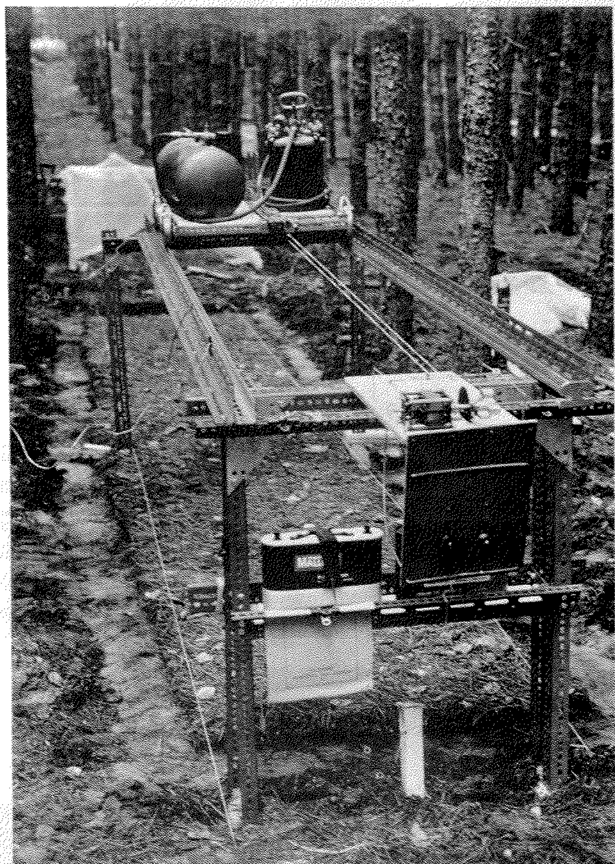


FIGURE 2. Original simulator set up over red pine needle (in situ) fuel bed. Water reservoir and pressure vessel are carried on the trolley.

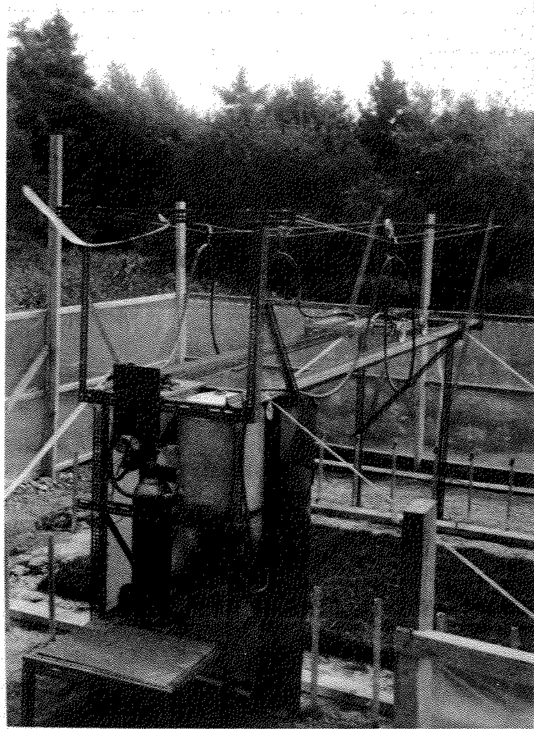


FIGURE 3. Remodelled simulator set at right angles to the fuel bed. Water reservoir and pressurizing cylinder are stationary.

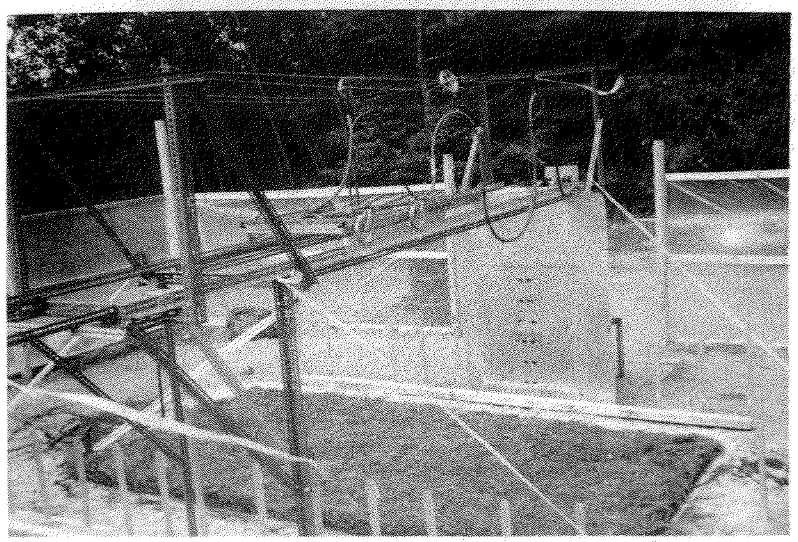


FIGURE 3a. As trolley travels from left to right, water is carried to nozzles by suspended hose lines.

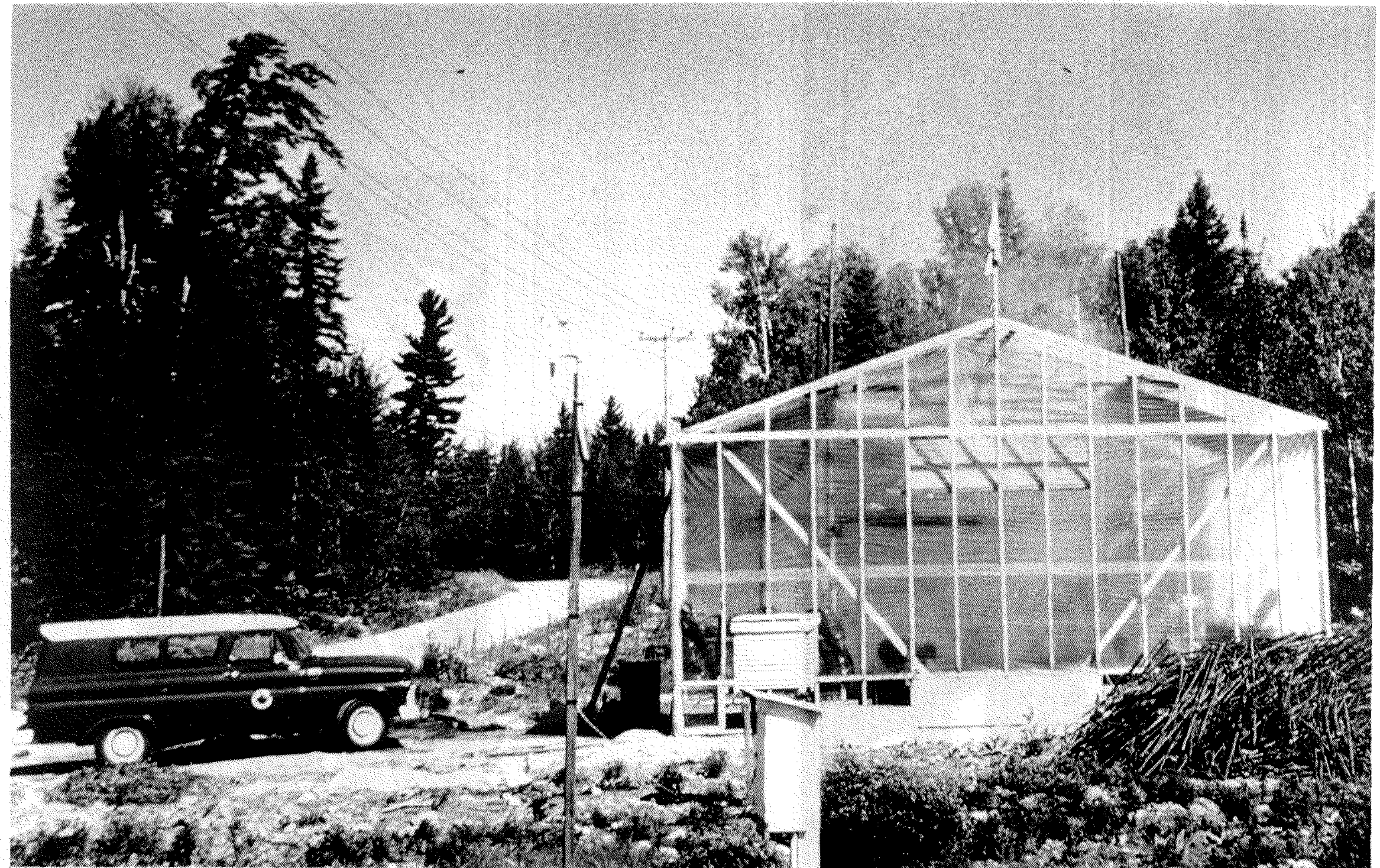


FIGURE 4. Polyethylene covered shelter with smoke from test fire issuing through opened roof. Two sliding doors permit 232 square feet of the roof area to be opened for smoke venting and the removable 2 x 4 foot plywood panels along the base of each wall permit draft control.

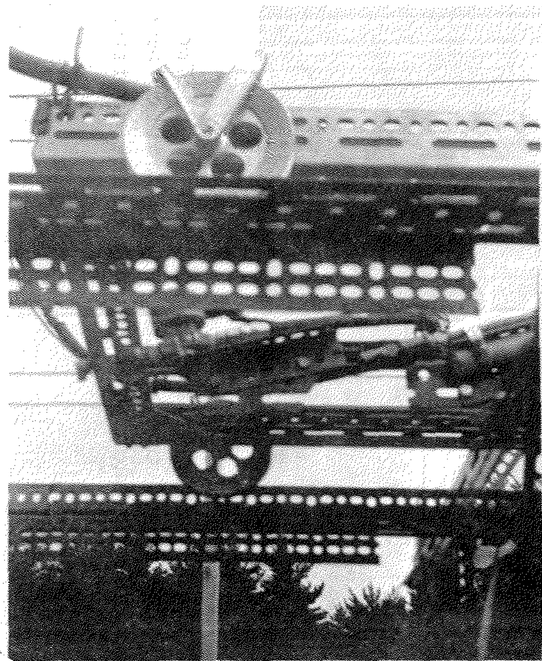


FIGURE 6. Tandem nozzle arrangement mounted on trolley.

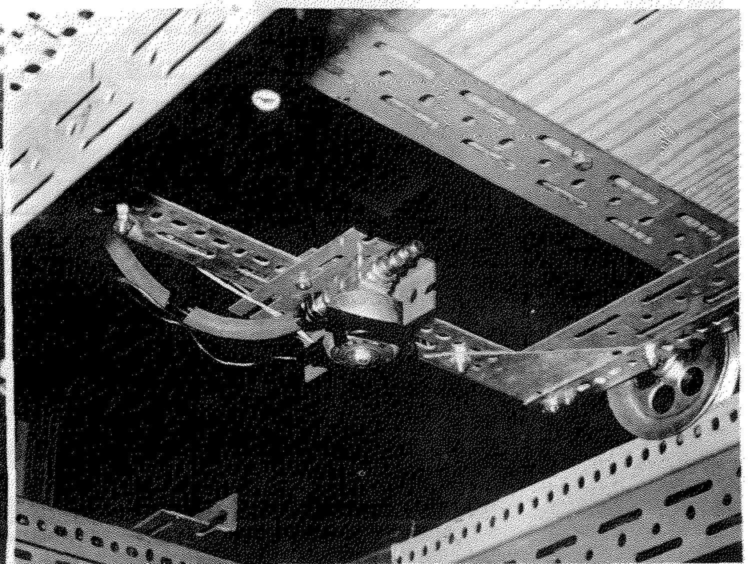


FIGURE 5. Single nozzle mounted on mobile trolley.

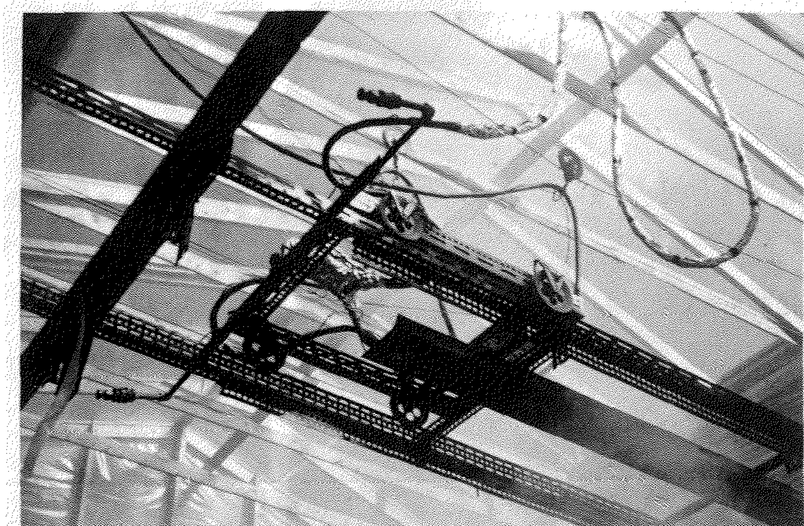


FIGURE 7. Double nozzle arrangement mounted five feet apart on mobile trolley.

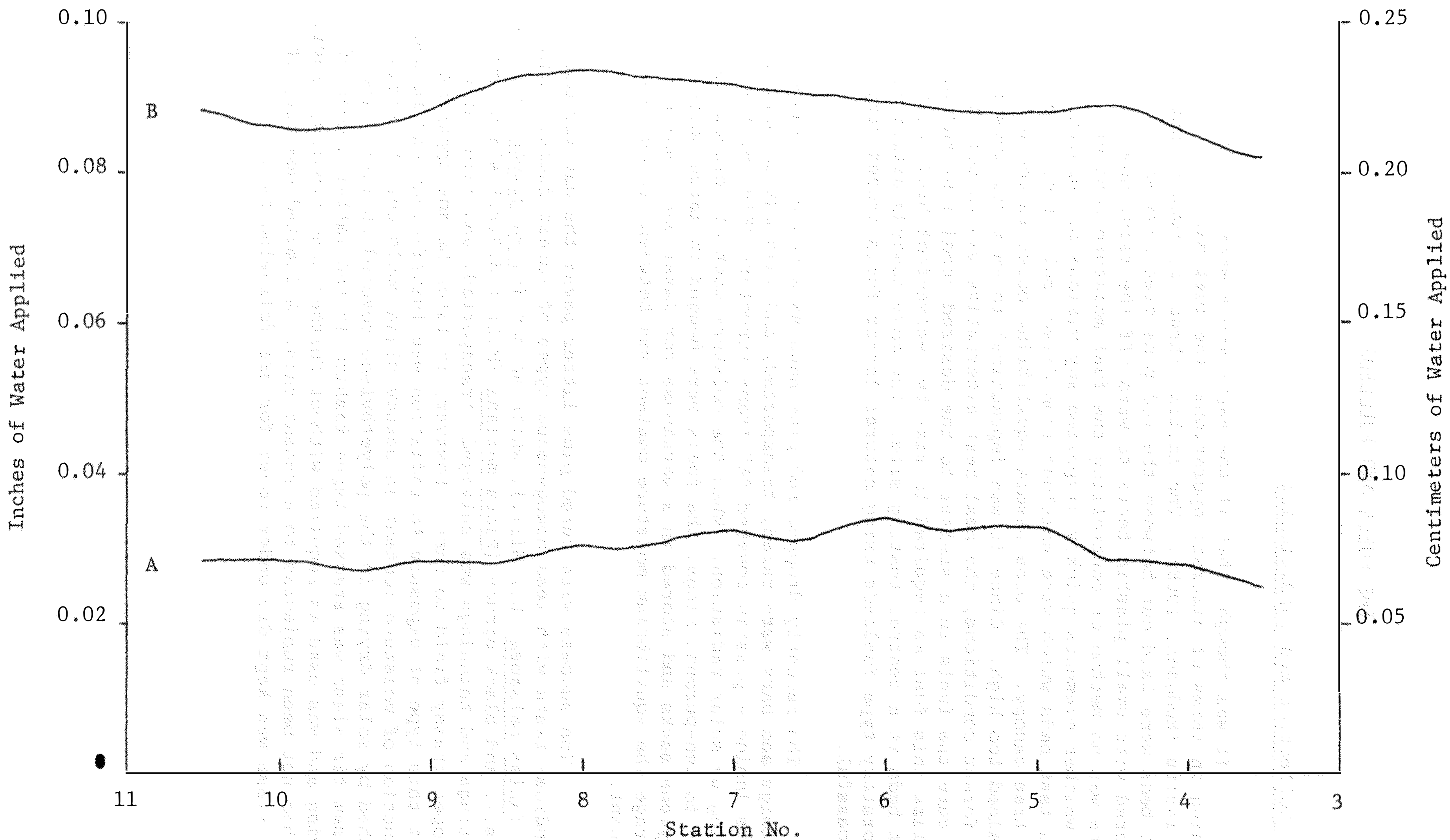


FIGURE 8. Nozzle output profiles along the length of the fuel bed. Centerline of nozzle spray pattern is at Station 7. Curve A is drop profile for one 3/8 K 40 nozzle travelling at 0.32 ft-sec^{-1} (9.9 cm-sec^{-1}) and curve B is for dual 3/4 K 120 nozzle unit moving at 0.24 ft-sec^{-1} (7.2 cm-sec^{-1}).

THE FUELS AND FUELBEDS

Fuel Collection and Conditioning

It was thought that if the experiments were to have any meaning in terms of aircraft operations, the fuel had to be natural and insitu (Hodgson, 1968). The initial three- by twenty-foot test beds were laid out between the red pine tree rows and covered with small plastic tents to ward off the rain, however, there was no method of controlling the fuel moisture content. The weather elements quickly dispelled any visions of burning in-situ test beds which were shielded from direct solar radiation by the tree canopy. The pine needle equilibrium moisture content remained too high. Since it was impractical to wait for unusually dry forest conditions, the next best alternative was to collect and cure the fuels in a shelter to the desired conditions and to utilize this fuel as required in six- by twelve-foot hand-built test beds at a central testing site. The move towards artificial laboratory type fuelbeds using natural forest fuels proved very successful.

The recently dropped red pine needles along with fragments of twigs and bark were raked, transported, and laid out on screened flats inside a plastic covered "A" frame structure (Fig. 9) for curing by solar radiation. When the moisture content reached the six- to ten-percent range, the fuels were bagged in large polyethylene sacks and stored in a warehouse for later use. While in storage the equilibrium moisture content was between ten and eleven percent.

The success with cured pine litter paved the way for more grandiose tests with less homogeneous types of forest fuels. Balsam fir (*Abies balsamea* (L.) Mill.), white spruce (*Picea glauca* (Moench) Voss.), and black spruce (*Picea mariana* (Mill.) B.S.P.) slash from cuttings and thinnings was salvaged, transported, and laid out on an open grassy field to cure. However, it later became apparent that this type of exposure to radiation was insufficient and further reduction of moisture content in spruce slash could only be accomplished by solar drying in the polyethylene covered shelter. The balsam fir slash was stacked tepee fashion in the latter stages of drying and was used as required without further conditioning, provided it had not been subjected to a recent rain. A limited quantity of fir slash was kept dry under cover for use following rain.

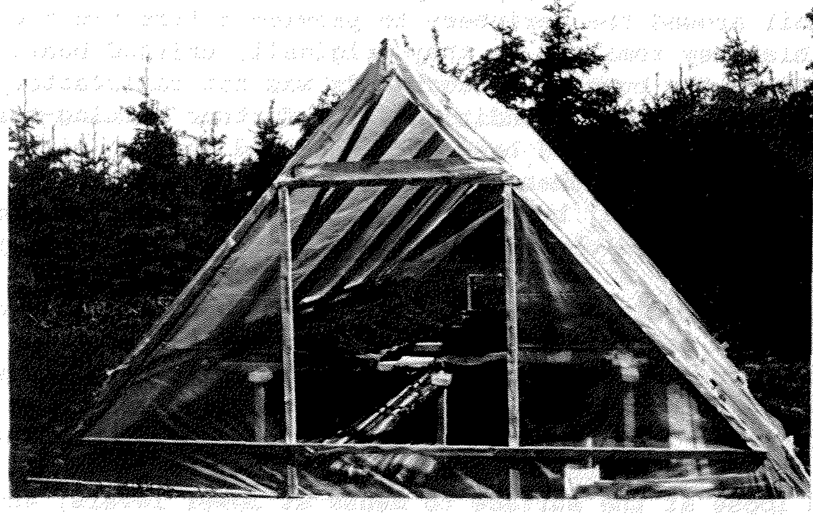


FIGURE 9. Polyethylene covered drying shelter containing red pine needles on screened lath flats.

FIGURE 10. Red pine needle bed ready for ignition.

The Fuelbed

The initial three- by twenty-foot fuelbeds were trenched to mineral soil around the periphery to provide a fire break but apart from this they remained as they originally existed beneath the trees. Since the burning of such beds was not satisfactory due to unfavourable weather conditions, all further burning-test beds were hand laid on a sand base at a selected burning site. The bed configuration was changed to the six- by twelve-foot size to provide a wide (6-foot) burning front to reduce the development of a single concentrated convection column at the mid-bed position.

The pine needle fuel was loosely laid to approximate an uncompacted random particle oriented mat (Fig. 10). There was no control over fuel voidage. Needle breakup during handling was inevitable hence voidage decreased as the proportion of broken needles increased. This resulted in greater compaction of fuel particles. While an insitu fuelbed has a compaction gradient ranging from loose at the surface to dense at lower levels, any attempt to duplicate natural conditions on a seventy-two square foot bed proved impractical.

The spruce slash shed its needles in the early drying stages and only stems, twigs and twiglets remained. The balsam fir retained its needles in the brown state for the duration of the summer and needle drop was experienced only when the slash was subjected to excessive handling. Trial tests indicated that woody stems having a diameter greater than 5/8 inch did not burn beyond the superficial charring stage, hence they did not contribute toward increasing fire intensity in terms of BTU's released. Branches and stem tops were cut from the trees at the 5/8 inch diameter and were cut into lengths from four to twenty-four inches, depending on their configuration. They were cut short enough to permit them to lie flat and form a compact and reasonably homogeneous structured type of fuelbed (Fig. 11).

The Test Burns

The insitu red pine needle fuelbeds were difficult to ignite and did not maintain an acceptable fire front. The data from these test fires were considered as exploratory research only.

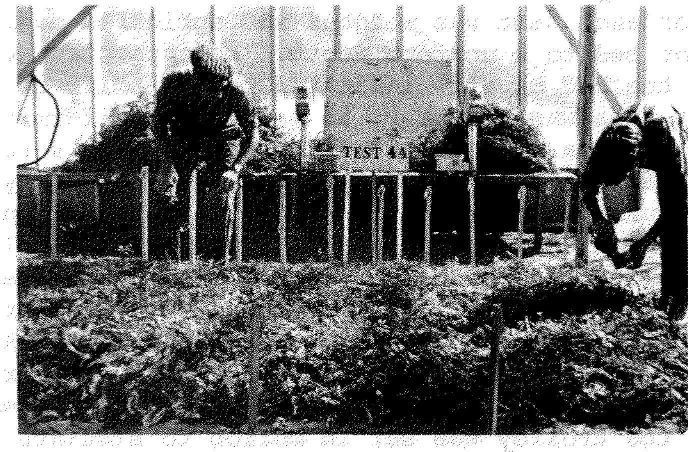


FIGURE 11. Balsam fir slash fuel bed ready for ignition.

FIGURE 12. Simultaneous fuel bed ignition produced by placing a flaming, fuel oil soaked board at Station 0 (Ignition Zone).

The variation in pine needle particle size affected volumetric loading and this in turn, had some effect on the resulting fire intensity. Nevertheless, fuel loading (weight per unit area) was the criterion used to obtain different fire intensities and the interaction of compaction was disregarded. The desired amount of needle fuel for each test was weighed and sprinkled over the seventy-two square foot bed to a uniform depth. A depth check at several points across the bed usually indicated that a shift of some fuel to a deficient area was necessary to get depth uniformity. Letting the needles drop in a free-fall fashion resulted in a random fuel particle orientation. Two samples of fuel were randomly picked from each bed surface for moisture content determination. Simultaneous fuelbed ignition was achieved by momentarily holding a flaming fuel oil soaked seven-foot ignition board to the fuelbed at station (St.) 0 (Fig. 12). Observations of fire characteristics were recorded for each station (sample forms in Appendix B), during the pre- and post-spraying periods. When the fire front reached the fuelbed centerline at St. 7, the spray system was activated and the trolley was set in motion to simulate an airtanker flight path parallel to the fire front (Fig. 13). Nozzle size and trolley speed for each test were preselected on the basis of the effectiveness of the previous drop relative to fuel loading. The burned portion was mapped after spraying and depth measurements were taken along the bed length to determine depth of water penetration in the unburned portion and the depth of charred and unburned fuel in the burned portion. If the fire was extinguished or died within three minutes (Fig. 14) it was considered as "out". If it continued to smolder and burn (Fig. 15), then its rate of rate of progress through the now moistened fuel was recorded periodically for 20 minutes or more from the time of water application to indicate the degree of retardation achieved. Since aircraft waterdrop effectiveness decreases rapidly when the turnaround time exceeds 15 minutes, a 20 minute time limit for the purposes of this project, appeared adequate. To determine the change in the mean moisture content of the fuelbed in the unburned portion after a simulated drop, a circular fuel sample through the full depth of the bed was extracted at or near mid-bed St. 8 position 10 minutes after spraying.

To ensure that each slash fuelbed had the same ratio of fine particles to larger branch wood across its entirety, the weighed fuel was distributed throughout the bed area piece by piece to form a compact bed of uniform depth (Fig. 11). Compaction was kept uniform by controlling particle arrangement which minimized the variation of fire spread rates between comparative tests. Fuel loading per unit area was the criterion used in selecting expected fire intensity. The test procedures during the pre- and post-burning and spraying were the same as for the pine needle beds.

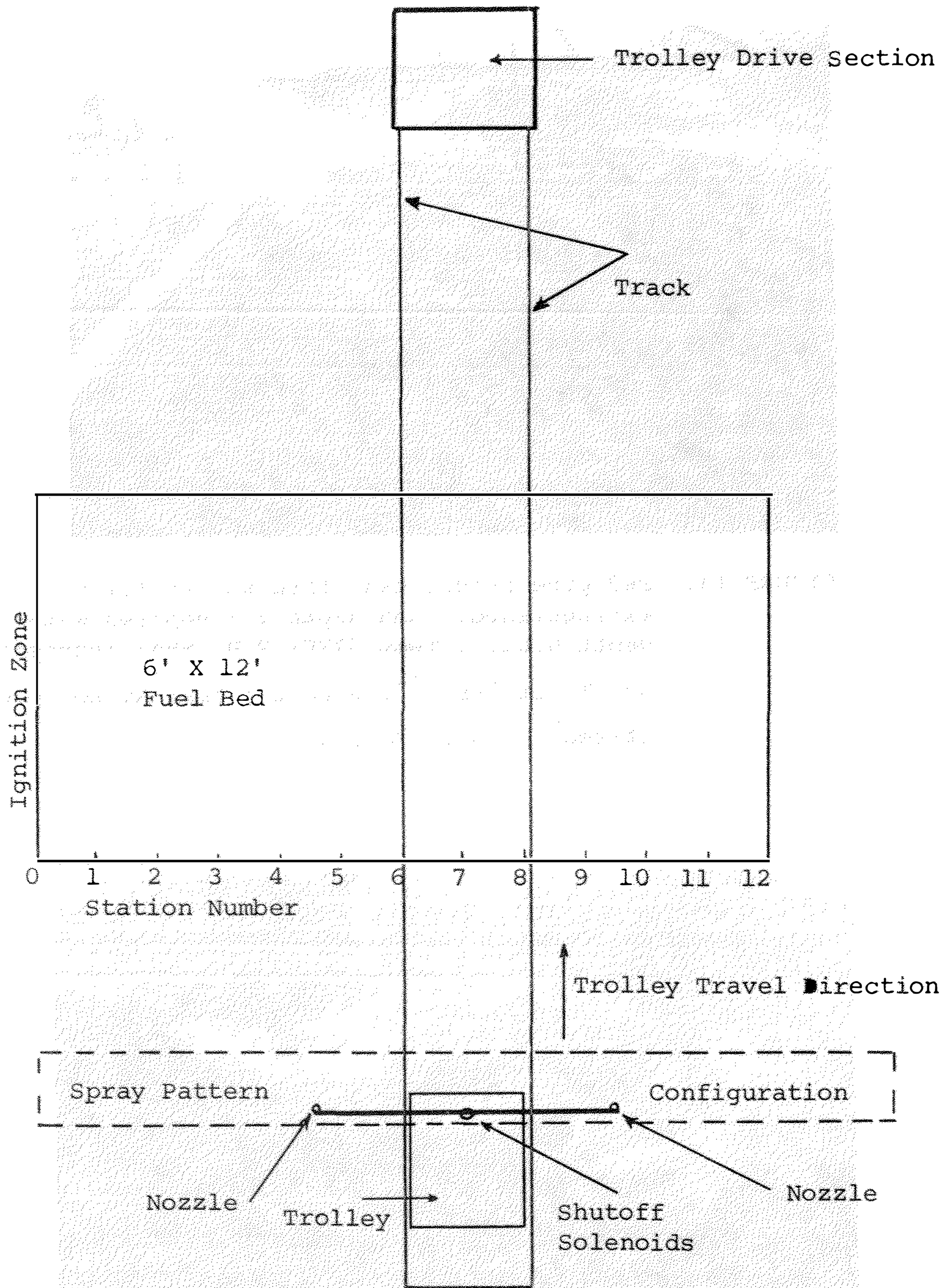


FIGURE 13. Sketch of fuel bed relative to the simulator and the spray pattern.

FIGURE 14. Red pine needle test fire successfully extinguished. Bed depth 2"; Applied water depth 0.027"; Temp 57^{o}F; R.H. 88%; Intensity 53 BTU-ft^{-1}-sec^{-1}; wind 1.6 fps; Av.ROS 0.016 ft-sec^{-1}; Fuel m/c 9.4%.

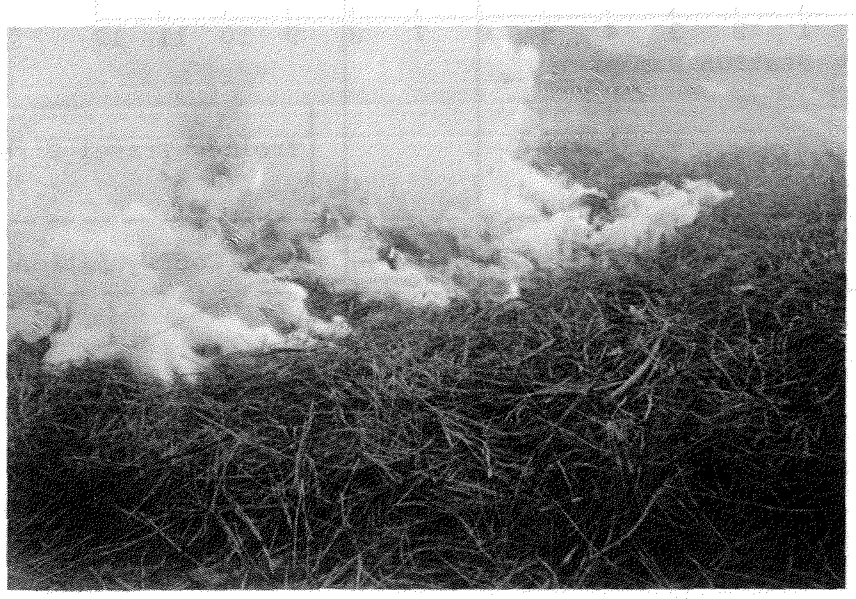


FIGURE 15. Red pine needle fuel bed reignition.

TEST FIRE RESULTS

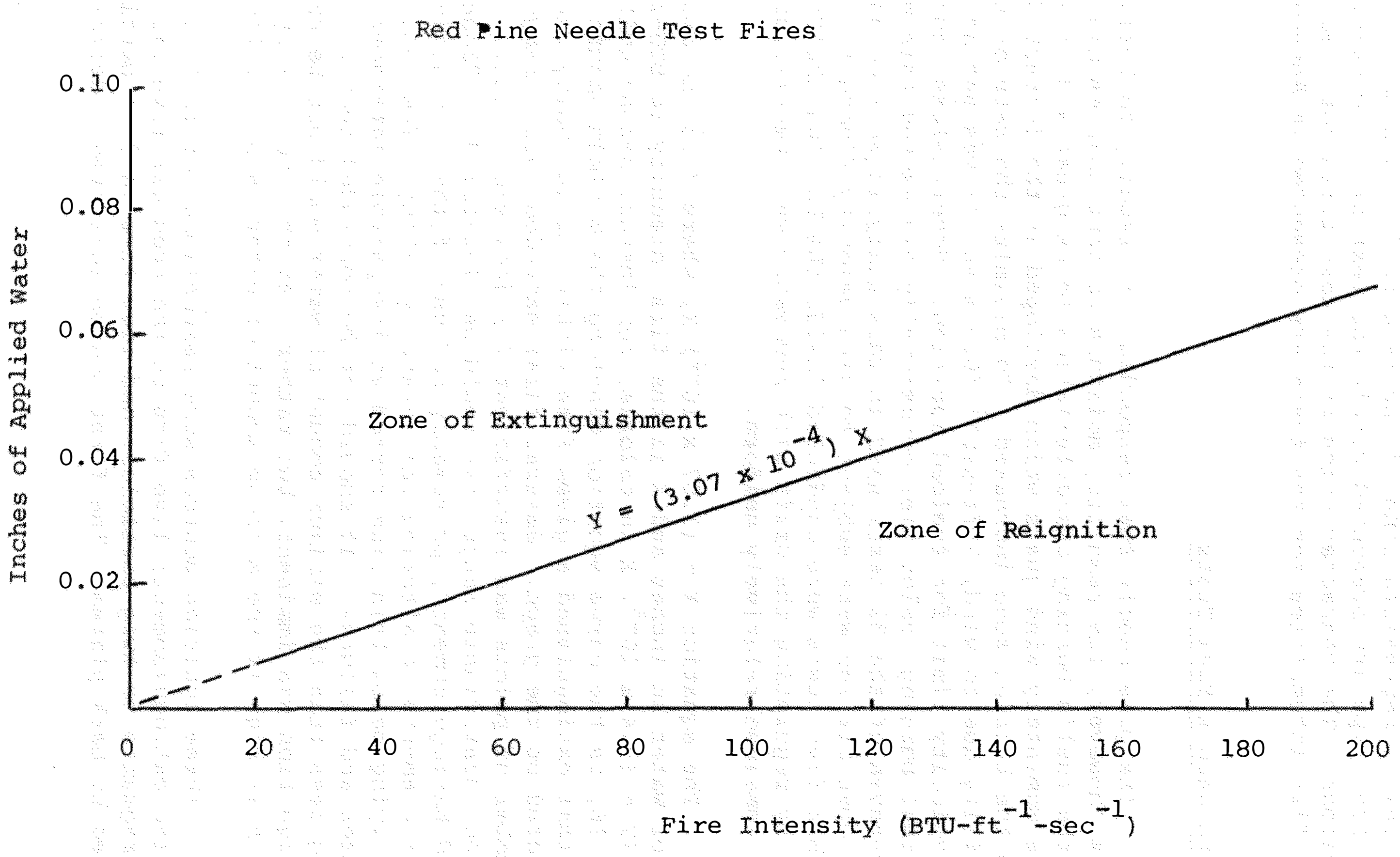
The data for each individual test appear in Appendix C. The graphical representations of the results for each particular forest fuel type are presented within the text of the ensuing discussions. The characteristics of the test fires for thedifferent fire intensities for the fuels are presented in Appendix D.

Red Pine Needle Fuel Tests

The pine needle fuel responded very readily to humidity changes, however, the resulting moisture content changes did not alter the fuel's burning characteristics to as great a degree as did the momentary wind gusts which developed as the indraft of air to the burning zone increased. To minimize the rate of spread variability due to wind, 3 $ft\text{-}sec^{-1}$ (0.9 $m\text{-}sec^{-1}$) was set as the upper velocity limit for fuelbed ignition. Nevertheless, during the actual burning, velocities occasionally did exceed this maximum. Twenty-seven of the 32 tests used in this analysis were conducted in the open air and were subject to wind velocity fluctuations but the other five tests were conducted inside the burning shelter, where, by regulating the draft with removable wall panels, air influx remained relatively uniform.

The equation $Y = (3.07 \times 10^{-4})\ X$, where Y is the applied depth of water in inches and X is the fire intensity in $BTU\text{-}ft^{-1}\text{-}sec^{-1}$ ($Y = (9.4 \times 10^{-5})\ X$ in calorie, centimeter, second units) in Figure 16, is the curve equation denoting the minimum amount of water that extinguished a given fire within the intensity range designated on the graph. Several fires exceeded this I range but the number of points was insufficient for inclusion. There appeared to be no identifiable range that could be classified as "Zone of Delayed Extinguishment", presumably because of the interaction of weather elements in altering the intensity rating. The test plot points lying below this line formed an inseparable interspersion of successes and failures. It should not be concluded that fires receiving less than the minimum amount of water would not be extinguished and reignition was imminent, but rather that the probability of reignition is high if the minimum amount of water is not applied.

Three ignition sources were responsible for failure in attaining extinguishment; live fire on the needles; live fire in wood fragments or twig particles; and live fire in fuel particles shielded by bark plates. The first source indicated a deficiency



FIGUR 16. Applied water depth versus fire intensity curve delineating minimum requirements for extinguis ment of fire in red pine needles.

of water: the second source like the third, indicated shielding action as well as a deficiency of water. The degree of bark platelet contribution towards reigniting the bed depended on platelet size and orientation, that is, it depended on the amount of live fire remaining unsuppressed under cover and the ability of these glowing particles to dry out and spread into the surrounding dampened fuels. Fires that were classed in the delayed extinguishment zone were usually those which smoldered as a result of a reignition source but were unable to spread through the surrounding fuels which were moist and not receptive to fire propagation.

Varying fire intensity by varying the fuel loading did not generally produce the expected fire intensity. The deviations above and below the average fuel consumption of 83.7 percent per test could not be related to changes in fuel moisture content, relative humidity, wind velocity, or fuel loading. It is possible that the interactions among these contributing factors masked the influence of any one individual factor. The inability to predict the weight of fuel that would be consumed (W) even if the heat yield (H) and the rate of spread (R) remained constant, resulted in an uneven sampling distribution along the intensity (I where I = HWR) scale. Fuelbeds in excess of three inches in depth (7.5 cm) burned deeper where voidage was greater hence a "hummock and hollow" type of smoldering fuelbed was evident after the main fire front had passed. Test fires with irregular burning depths proved difficult to extinguish due to lack of water penetration to the base of the bed. Increasing the applied depth of water made a further reduction in the rate of fire spread but penetration depth did not increase appreciably. The charred surface fuel layer became much wetter but the fire was still able to burn below the line of water penetration. The decrease in fuel consumption during the burning of deep variable-voidage test beds resulted in low intensity ratings which were not consistant with other burn data. The water versus intensity relationship was modified to the degree that intensity alone was not an adequate measure of fire severity insofar as extinguishment with water was concerned. It was evident that this fine particled fuel limited the experimental test fire intensity to the 0 to 200 BTU-ft^{-1}-sec^{-1} (0 to 1650 cal-cm^{-1}-sec^{-1}) range hence other forest fuels had to be used to get uniform burning, high intensity fires.

Balsam Fir Slash Tests

The problem associated with variable voidages in the needle fuelbeds was not detected in the 43 balsam fir slash test fires that were successfully executed. The plot of water applied versus intensity for these tests indicated that water requirements were greater for slash fires than for pine needle fires of the same intensity. This may have been directly related to particle size. On a per particle basis, the surface area undergoing com ustion on a twig was substantially larger than on a pine needle, consequently the portion of the twig undersurface shielded from direct contact with water was able to retain live fire longer and acted as an ignition source for the adjacent very fine particled, highly volatile fir needles.

Water requirements for the I range of 40 to 200 BTU-ft^{-1}-sec^{-1} (330 to 1650 cal-cm^{-1}-sec^{-1}) are presented in Figure 17. Several tests beyond this range indicated that an extension of the two curves, $Y = 0.014 + (3.55 \times 10^{-4})\ X$, and $Y = 0.002 + (3.17 \times 10^{-4})\ X$, ($Y = 0.036 + (1.09 \times 10^{-4})\ X$ and $Y = 0.005 + (9.7 \times 10^{-5})\ X$ in calorie, centimeter, second units) would fit fires of higher intensity as well. The balsam fir slash fire spread rates, which were nearly twice the rates for equivalent loadings of red pine needles, indicated that propagation was dependent on the fuelbed bulk density. An approximate slash to needle bulk density ratio of 2:3 resulted in a 2:1 ratio of their respective spread rates. Fires that rekindled after water application, flamed freely and combustion continued with a minimum of visible smoke but the rate of linear spread was greatly reduced.

The extinguishment of the fires which were in the "Delayed Extinguishment Zone" (went out within 20 minutes after water application) depended to a great degree on the rate of water evaporation from the bed and on water adsorption by the fuel particles. The degree of increase in fuel moisture content determined the time lapse between water application and fire cessation. Smoldering spots were generally confined to localized areas in the charred fuels and died when their intensity decreased to a level too low to preheat the adjacent moistened fuels.

Black Spruce Slash Tests

The tests thus far had been conducted with fuels that were relatively fine or contained a reasonable proportion of fine particles in their makeup. Water requirements for fires in balsam fir slash were considerably higher than for those in red pine needles but the still unanswered question was whether a fire in twigs and branchwood, a fuel devoid of needles, responded in a similar fashion. Since spruce slash drops its needles as soon as drying commences, it was an ideal fuel for comparative testing. Seven tests were conducted to

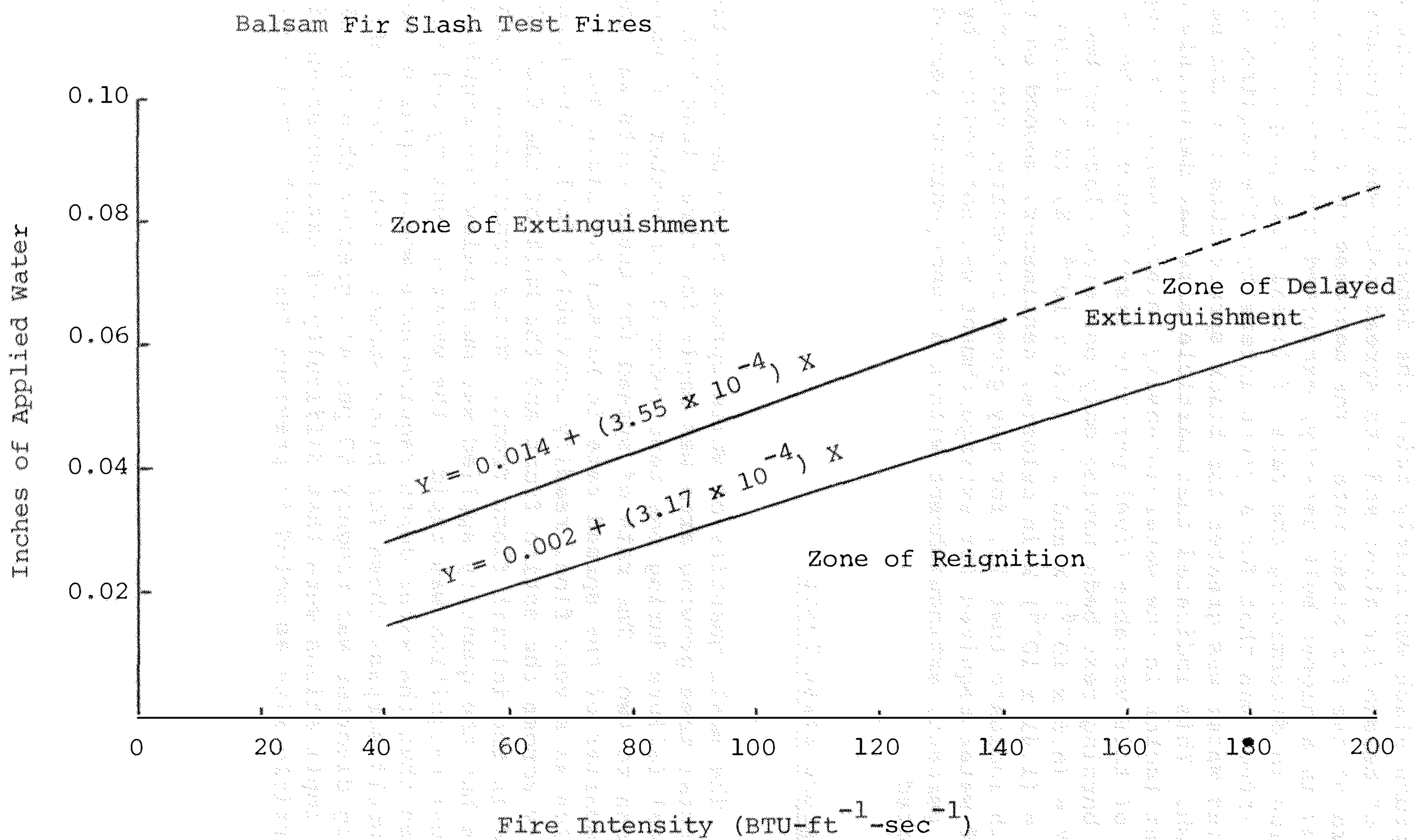


FIGURE 17. Applied water depth versus fire intensity curves delineating the extinguishment zone, the delayed extinguishment zone and the zone of reignition for balsam fir slash fires.

get comparative values but unfortunately the tests did not cover the entire intensity range under study. The lineal rate of spread increased with increases in fuel loading therefore I values were affected by changes in R as well as in W. The bulk density for black spruce slash was nearly twice the density for the same weight loading of balsam fir slash and its spread rate was approximately one-third of the fir slash rate. The decrease in void space, as reflected in a higher bulk density, exhibited the influence of bed compaction in determining the rate of lineal fire propagation. The net effect was that for a given intensity, the required depth of applied water was greater for black spruce than for the balsam fir slash. This indicated that particle size was definitely an important factor in the water-intensity relationship. The implications of this variable (fuel particle size) could not be deduced without burning test beds having only one size class per bed. The curves $Y = (6.6 \times 10^{-4})\ X$ and $Y = (4.6 \times 10^{-4})\ X$, ($Y = (2.03 \times 10^{-4})\ X$ and $Y = (1.41 \times 10^{-4})\ X$ in calorie, centimeter, second units) in Figure 18 indicate that if, for any given intensity, the minimum depth of water required for extinguishment was not reduced by more than 30 percent, extinguishment within a twenty-minute period could be expected.

White Spruce Slash Tests

The small quantity of white spruce slash salvaged from an experimental tree growing area was ample for three test beds. Mechanical failure during one test reduced the number of successful executions to two. The rate of spread for these tests was one-third to one-quarter of the spread rate in balsam fir slash due to the lack of needles as a very fine, readily ignitable, fuel. The fires burned uniformly across the entire front and the bulk of the fuel (89%) was consumed in the initial flame front. Water penetration appeared adequate but the quantity applied was much below the required depth, hence fuel reignition was rapid. The water-intensity relationship indicated that the water depth requirements would equal or more likely would surpass those for black spruce slash fires. White spruce mean twig diameter was roughly 50 percent greater than the black spruce and the implications were that difficulty of extinguishment increased with particle size as noted in previous tests with other fuels.

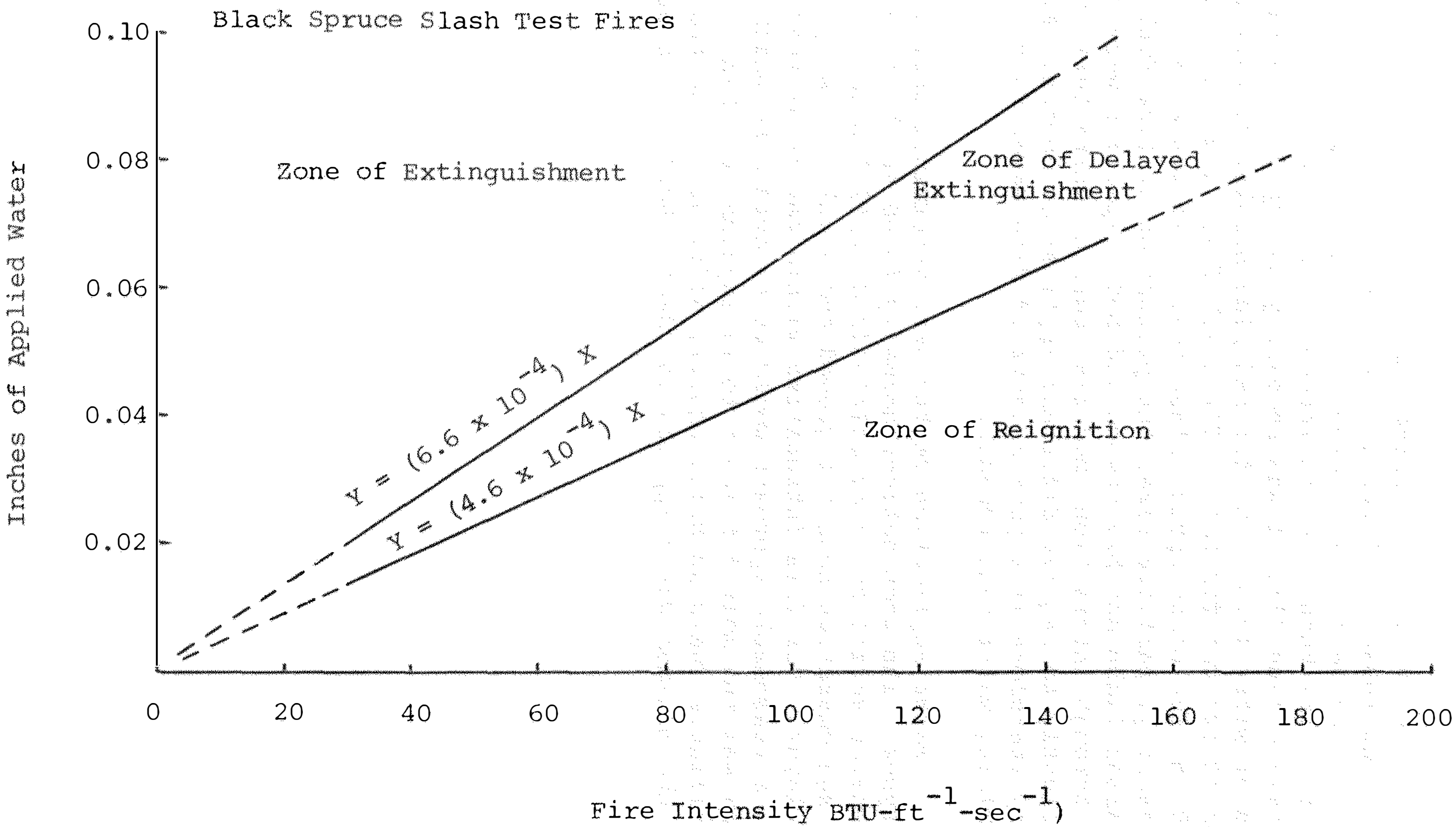


FIGURE 18. Applied water depth versus fire intensity curves delineating the extinguishment zone, the delayed extinguishment zone and the zone or reignition for black spruce slash fires.

CONCLUSIONS

The tests demonstrated that the required depth of water for extinguishment of fires in forest fuels could not be determined by considering fire intensity alone. To attain extinguishment of a fire burning at an intensity of 100 BTU-ft^{-1}-sec^{-1} (826 cal-cm^{-1}-sec^{-1}), it was necessary to apply a minimum of 0.031 inches of water (9.079 cm) for red pine needles of fuels, 0.050 inches (0.127 cm) for balsam fir slash fuels and 0.066 inches (0.168 cm) for black spruce slash fuels. It was evident that fuel bulk density, particle size, the proportion of fine fuel particles to coarser limbs and branchwood and bed compaction were variables which through interaction, modified burning characteristics sufficiently to require different application depths. Fire intensity therefore is a poor measure of fire severity to use in determining water requirements.

Water application depths were deter ined only for single fuel types. The combinations normally found in the forest range from sparce aerial fuels of multi-sized particles to a more compact slash agglomeration near the ground and a multi-density fine fuel slash layer. For fire intensities within the range that was investigated, a reasonable approach would be to deter ine which fuel in the complex was the most difficult to extinguish and then to regard all the available fuels as being equally difficult to control. On this basis the minimum water application depth should be determined.

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APPENDICES

APPENDIX A

Airtanker Water Drop Contour Patterns

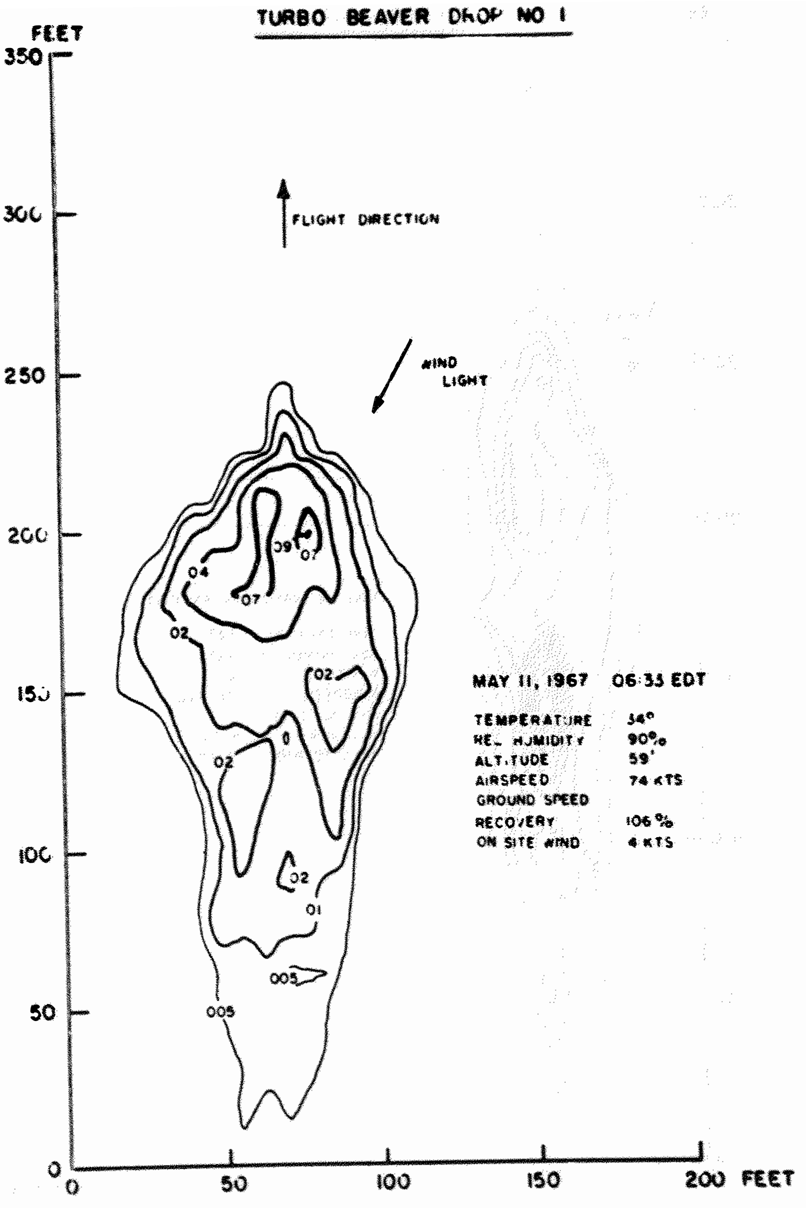


FIGURE 19. DHC-2. Turbo beaver drop contour pattern.

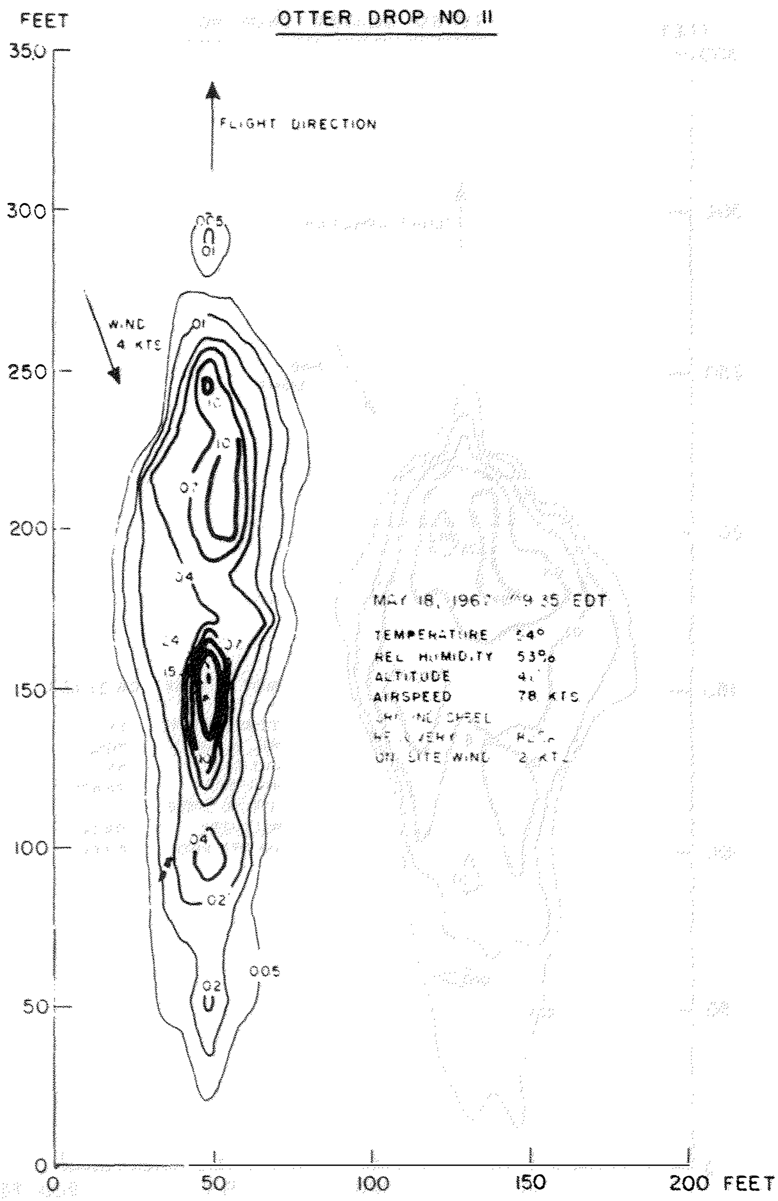


FIGURE 20. DHC-3. Otter drop contour pattern.

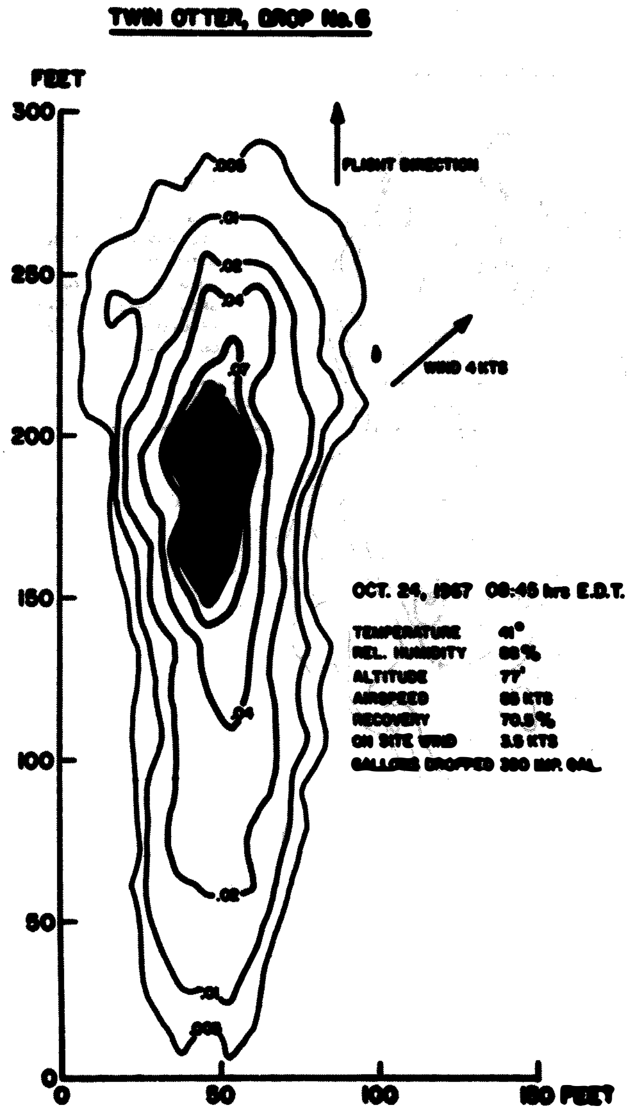


FIGURE 21. DHC-6. Twin otter drop contour pattern.

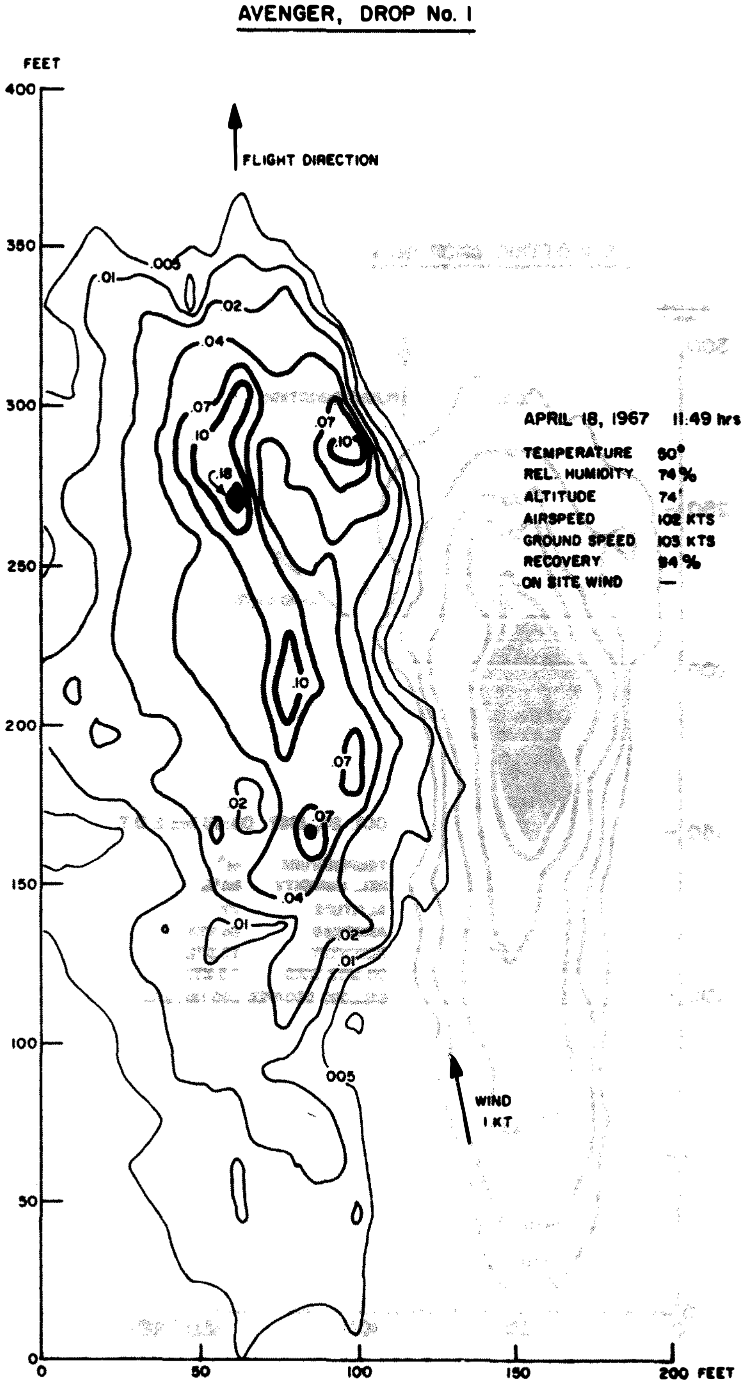


FIGURE 22. TBM. Avenger drop contour pattern.

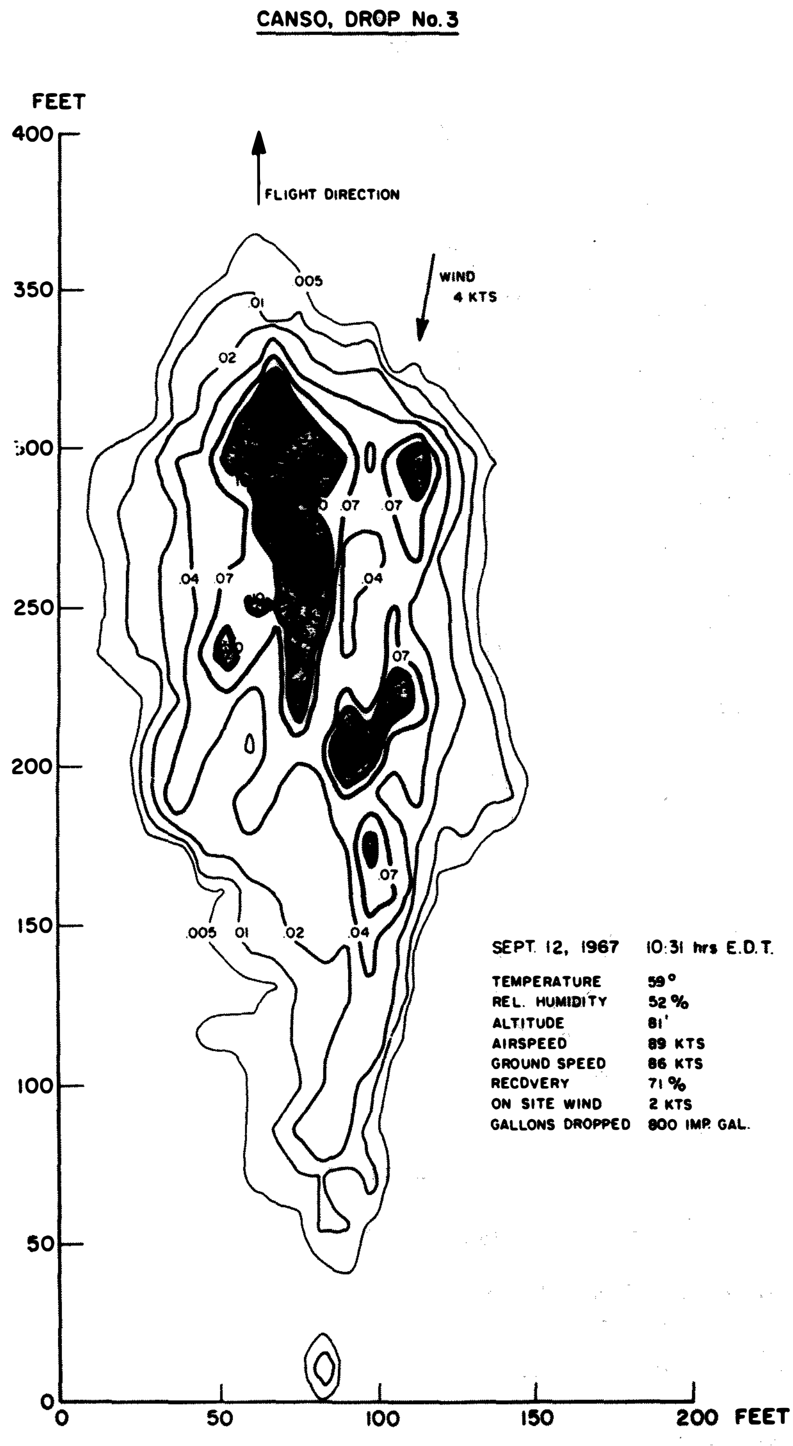


FIGURE 23. PBY-5a. Canso drop contour pattern.

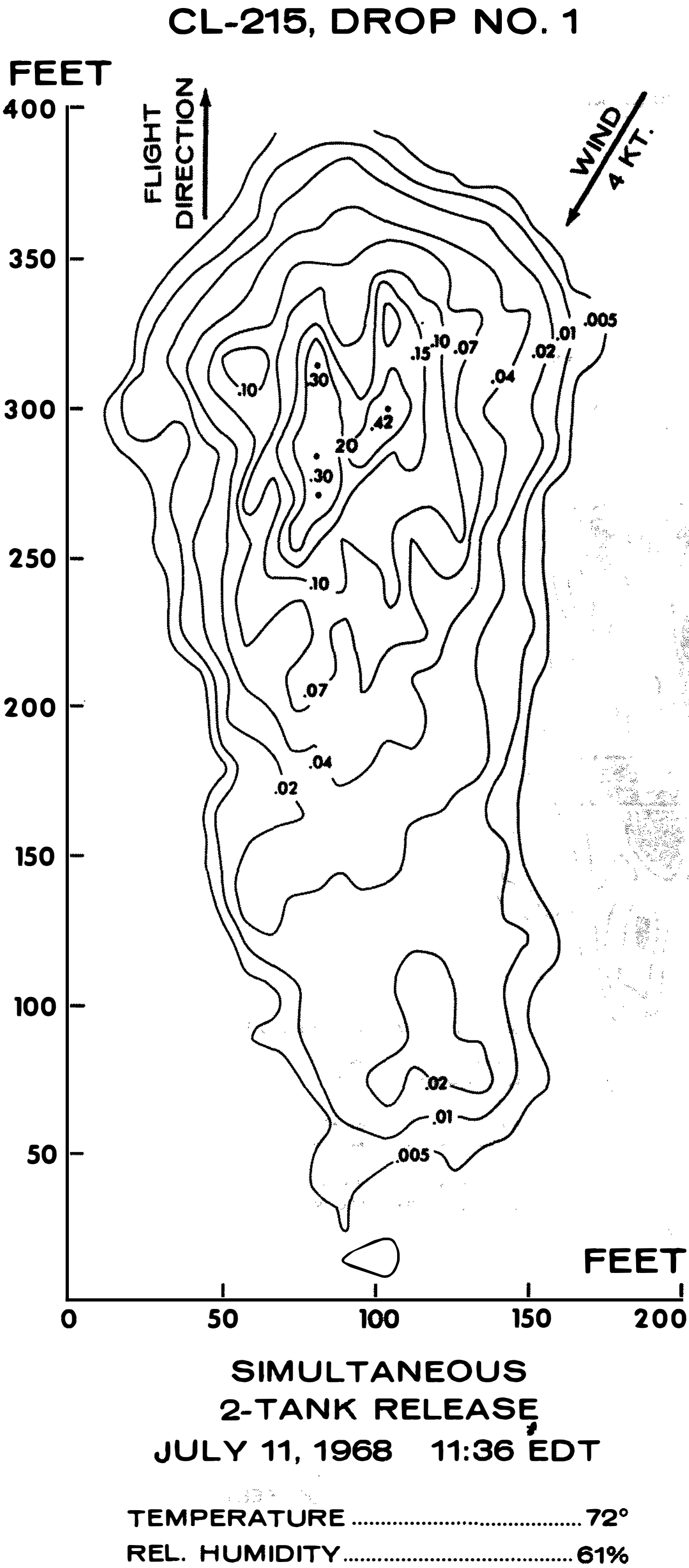


FIGURE 24. Canadair CL-215 drop contour pattern.

TEMPERATURE .... 72°
REL. HUMIDITY 61%
ALTITUDE .... 118'
AIRSPEED .... 104 KT.
GROUND SPEED .... 100 KT.
RECOVERY 80%
ON SITE WIND .... 4 KT.
GALLONS DROPPED .... 1200 IMP. GAL.

APPENDIX B

Burning Test Data Forms

WATER DROP SIMULATION

Project F-67

Forest Fire Research Institute

Test No.________ Date________________1970 Time__________hours

Nozzle Size__________ No.______ Water Pressure________psi

Nozzle Size__________ No.______ Inches Applied Water______

Nozzle Speed:1.5 meters in ______ sec. Motor rpm ______

Fuel Moisture :	Tin No.	M/C %	Avg.M/C %
1- Before Ignition	______	______	______
2- 10 Min. after spray	______	______	______

Wind:Code No. of Tape________ Mean Velocity________mph

Psychrometer :Dry_____ °F. Wet_____ °F. Relative Humidity________%

Fuel:Type____

Air Dry Wt.__________kg Oven Dry Wt.____________kg

Fuel Bed: Length 366 cms Width 183 cms Area 66978 cm^2

Avg Depth______cms O.D. Loading____________gr/cm^2

Volume__________cm^3 Vol O.D. Loading__________gr/cm^3

AFTER SPRAYING:

1- Unburned Fuelbed: Length______cms Width 183 cms

Area ______cm^2 O.D. Weight________grams

2- Charred Fuelbed: Length______cms Width 183 cms

Depth ______cms Volume____________cm^3

O.D. Weight____________grams

3- Fuel Consumed: Area of Burn__________cm^2 Net O.D.Loading

__________gr/cm^2

O.D. Weight of Fuel Burned____________grams

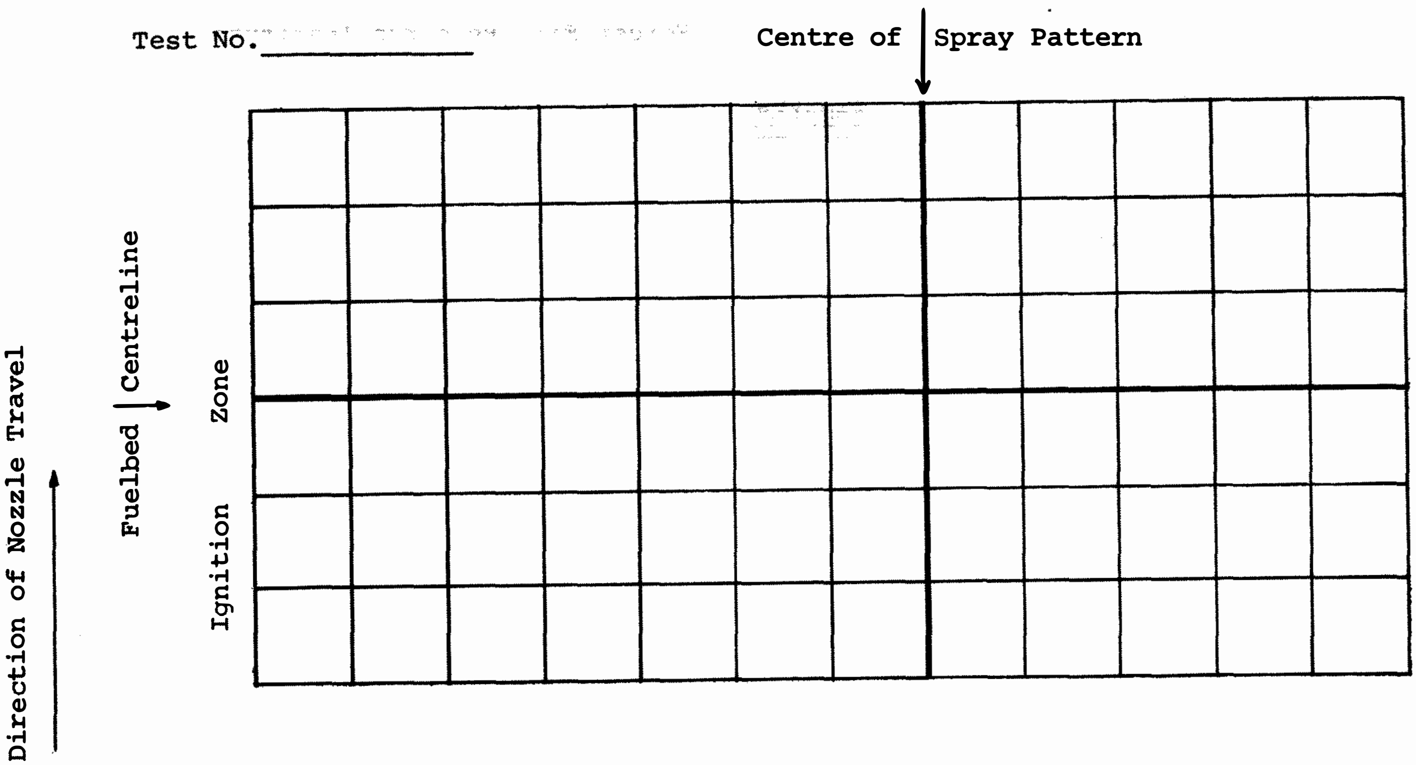
Fire Extinguished or Burned out:

__________min. ________sec. after ignition

WATER DROP SIMULATION

Project F-67

Test No.____________



Station No 0	1	2	3	4	5	6	7	8	9	10	11	12
Fire Advance												
Time (min/sec)												

Flame Ht (ft)												
Flame Depth												
Smoke Vol/colour												
Air Movement												

C/L Spray Time	X	X	X	X	X	X		X	X	X	X	X
H_2O Penetr (cm)												

Residual Fuel												
Depth (cm)												
Charred Fuel												
Depth (cm)												

ROS (cm/sec)												

Avg. ROS (cm/sec) Sta. #2 to #7: ____________ Sta. # ____ Sta. # ____ : ____

WATER DROP SIMULATION Project F-67

Forest Fire Research Institute

Test No.___________ **Remarks**

1- Before Ignition:

2- During Burning:

3- After Spraying:

WATER DROP SIMULATION Project F-67

Forest Fire Research Institute

Test No.________

Heat Yield of Fuel ____________________________________ BTU/lb.

Fuel Consumed ____________________________________ lbs/sq.ft.

Initial Rate of Spread (Station #2 to #____) __________ ft/sec.

Fire Intensity ____________________________________ BTU/ft/sec.

Equivalent Depth of Water Applied ______________________ inches

Reignition Time Lapse ______________ min. ________________ sec.

Final Rate of Spread (Station #_____ to #_____)________ ft/sec.

METRIC VALUES

Test No.________

Heat Yield of Fuel ____________________________________ cal/gram

Fuel Consumed ____________________________________ $grams/cm^2$

Initial Rate of Spread (Station #2 to #_____) _________ cm/sec.

Fire Intensity ____________________________________ cal/cm/sec.

Equivalent Depth of Water Applied _______________________ cms.

Reignition Time Lapse ____________ min. __________________ sec.

Final Rate of Spread (Station #_____ to #_____)________ cm/sec.

APPENDIX C

Basic Test Fire Data

TABLE I

RED PINE NEEDLE TEST FIRE DATA

Status[2] Code	Intensity[1] $Cal/cm^{-1}/sec^{-1}$	Water Depth cm	Bed Depth cm	Spread Rate cm/sec^{-1}	Fuel Burned gm/cm^{-2}	Fuel MC %	Test No.
O	152	0.06	2.5	0.31	0.10	13.3	2
O	241	0.06	2.5	0.49	0.10	11.8	3
O	259	0.06	5.0	0.79	0.07	13.9	1
O	295	0.58	5.0	0.46	0.13	12.2	134
O	407	0.08	6.0	0.62	0.14	13.7	136
O	440	0.07	5.0	0.49	0.18	9.4	19
O	459	0.12	9.0	0.56	0.17	12.4	137
O	536	0.03	6.0	0.64	0.17	10.2	23
O	580	0.16	10.0	0.65	0.18	10.1	148
O	582	0.18	10.0	0.49	0.24	11.3	149
O	666	0.04	4.0	1.25	0.11	12.1	11
O	715	0.05	7.5	0.67	0.22	11.7	32
O	768	0.06	4.0	1.49	0.11	10.4	6
O	870	0.06	4.0	1.71	0.10	10.3	7
O	1211	0.15	7.5	1.34	0.18	8.3	15
GO	406	0.02	2.0	1.04	0.08	9.1	27
GO	680	0.05	5.5	0.82	0.17	12.0	10
GO	710	0.05	5.0	1.19	0.12	10.8	9
GO	850	0.06	4.5	2.04	0.09	10.4	5
GO	1503	0.22	10.5	1.04	0.30	9.0	17
GO	2382	0.19	11.0	1.68	0.30	12.6	36

...cont.

TABLE I (Continued)

Status Code	Intensity (1) Cal/cm^{-1}/sec^{-1}	Water Depth cm	Bed Depth cm	Spread Rate cm/sec^{-1}	Fuel Burned gm/cm^{-2}	Fuel MC %	Test No.
DR	624	0.08	7.5	0.46	0.28	10.9	14
DR	1045	0.15	10.0	0.70	0.30	9.1	16
DR	1051	0.03	5.0	1.37	0.16	8.0	21
DR	1248	0.06	7.5	1.22	0.21	10.2	12
R	358	0.03	4.0	0.58	0.13	9.2	30
R	837	0.06	6.0	1.10	0.16	11.2	4
R	880	0.06	9.5	0.76	0.24	7.9	8
R	1263	0.05	5.0	1.31	0.20	7.4	20
R	1301	0.06	7.5	1.22	0.22	10.5	13
R	1384	0.06	10.0	0.91	0.31	9.9	34
R	1447	0.02	5.0	2.29	0.13	8.7	28
R	3184	0.12	11.0	2.20	0.30	12.5	35

(1) Heat Yield Used = Heat of combustion (5275 cal/gr) - Heat of reaction (302 cal/gr) - Heat correction for moisture content.

(2) Status Code symbols:

- O Fire extinguished or dies within 3 minutes after water was applied.
- GO Fire goes out from 3 to 20 minutes after water was applied.
- DR Delayed reignition - fire persists more than 20 minutes after water was applied.
- R Fire rekindles within 3 minutes and progresses through the balance of the fuel bed.

TABLE IA

RED PINE NEEDLE TEST FIRE DATA

Status Code	Intensity[1] $BTU/ft^{-1}/sec^{-1}$	Water Depth inches	Bed Depth inches	Spread Rate ft/sec^{-1}	Fuel Burned lb/ft^{-2}	Fuel MC %	Test No.
O	18	0.022	1.0	0.010	0.21	13.3	2
O	29	0.023	1.0	0.016	0.21	11.8	3
O	31	0.022	2.0	0.026	0.14	13.9	1
O	48	0.030	2.4	0.020	0.28	13.7	136
O	53	0.027	2.0	0.016	0.38	9.4	19
O	54	0.046	3.6	0.018	0.34	12.4	137
O	65	0.013	2.5	0.021	0.35	10.2	23
O	81	0.017	1.5	0.041	0.22	12.1	11
O	86	0.018	3.0	0.022	0.45	11.7	32
O	93	0.023	1.5	0.049	0.22	10.4	6
O	105	0.023	1.5	0.056	0.21	10.3	7
O	146	0.059	3.0	0.044	0.38	8.3	15
GO	35	0.023	2.0	0.015	0.27	12.2	134
GO	49	0.009	0.75	0.034	0.16	9.1	27
GO	69	0.064	4.0	0.021	0.38	10.1	148
GO	69	0.070	4.0	0.016	0.50	11.3	149
GO	82	0.019	2.25	0.027	0.35	12.0	10
GO	86	0.019	2.00	0.039	0.25	10.8	9
GO	103	0.023	1.75	0.067	0.18	10.4	5
GO	182	0.085	4.25	0.034	0.61	9.0	17

...cont.

TABLE IA (Continued)

Status Code	Intensity (1) $BTU/ft^{-1}/sec^{-1}$	Water Depth inches	Bed Depth inches	Spread Rate ft/sec^{-1}	Fuel Burned lb/ft^{-2}	Fuel MC %	Test No.
GO	288	0.074	4.5	0.055	0.60	12.6	36
DR	76	0.031	3.0	0.015	0.57	10.9	14
DR	126	0.059	4.0	0.023	0.62	9.1	16
DR	127	0.013	2.0	0.045	0.32	8.0	21
DR	151	0.022	3.0	0.040	0.43	10.2	12
R	43	0.010	1.5	0.019	0.26	9.2	30
R	101	0.023	2.5	0.036	0.32	11.2	4
R	106	0.023	3.75	0.025	0.48	7.9	8
R	153	0.020	2.0	0.043	0.39	7.4	20
R	157	0.022	3.0	0.040	0.45	10.5	13
R	167	0.024	4.0	0.030	0.63	9.9	34
R	175	0.009	2.0	0.075	0.26	8.7	28
R	385	0.048	4.5	0.072	0.61	12.5	35

(1) Heat yield used = Heat of combustion (9490 BTU/lb) - Heat of reaction (543 BTU/lb) - Heat correction for moisture content.

TABLE II

BALSAM FIR SLASH TEST FIRE DATA

Status Code	Intensity(1) Cal/cm^{-1}/sec^{-1}	Water Depth cm	Bed Depth cm	Spread Rate cm/sec^{-1}	Fuel Burned gm/cm^{-2}	Fuel MC %	Test No.
O	627	0.10	12.0	0.98	0.14	15.6	125
O	708	0.08	10.0	1.45	0.10	13.8	108
O	1552	0.11	14.0	2.88	0.12	13.8	105
GO	447	0.06	11.0	1.02	0.09	12.5	110
GO	650	0.10	11.0	1.25	0.11	14.8	124
GO	667	0.06	13.0	1.04	0.14	13.6	120
GO	799	0.04	13.0	1.49	0.11	14.3	118
GO	823	0.08	14.0	1.27	0.14	13.7	113
GO	861	0.09	12.0	1.41	0.13	13.7	103
GO	996	0.06	13.0	1.84	0.12	10.2	111
GO	1007	0.09	14.0	1.51	0.14	13.2	112
GO	1106	0.12	16.0	1.48	0.16	13.0	106
GO	1220	0.10	19.0	1.44	0.18	14.9	122
GO	1258	0.09	16.0	1.64	0.16	16.1	129
GO	1292	0.13	17.0	1.42	0.19	16.7	132
GO	1338	0.10	16.0	1.73	0.17	16.2	114
GO	1429	0.12	16.0	1.79	0.17	14.7	127
GO	1506	0.14	16.0	2.03	0.16	14.2	102
GO	1656	0.15	18.0	1.95	0.18	15.8	139
GO	1826	0.18	19.0	1.93	0.20	15.2	141

...cont.

TABLE II (Continued)

Status Code	Intensity[1] $Cal/cm^{-1}/sec^{-1}$	Water Depth cm	Bed Depth cm	Spread Rate cm/sec^{-1}	Fuel Burned gm/cm^{-2}	Fuel MC %	Test No.
GO	1946	0.13	19.0	2.24	0.19	13.9	117
GO	2133	0.20	20.0	2.12	0.22	15.3	143
DR	1539	0.11	19.0	1.71	0.19	16.2	133
R	434	0.04	11.5	0.95	0.10	13.3	109
R	749	0.06	12.0	1.07	0.15	15.1	126
R	1058	0.09	18.0	1.36	0.17	16.2	116
R	1097	0.04	13.0	1.77	0.13	14.8	119
R	1162	0.07	15.0	1.57	0.16	15.9	128
R	1256	0.08	16.0	1.62	0.17	13.8	115
R	1592	0.09	19.0	1.84	0.19	15.2	130
R	1610	0.10	18.0	1.69	0.20	15.3	142
R	1821	0.14	19.0	2.03	0.19	14.2	107
R	1900	0.07	17.0	2.38	0.17	14.1	101
R	1946	0.15	20.0	2.21	0.19	15.3	140
R	1986	0.15	20.0	1.93	0.22	16.3	144

(1) Heat yield used = Heat of combustion (5091 cal/gr) - Heat of reaction (302 cal/gr) - Heat of correction for moisture content.

TABLE IIA

BALSAM FIR SLASH TEST FIRE DATA

Status Code	Intensity[(1)] BTU/cm^{-1}/sec^{-1}	Water Depth inches	Bed Depth inches	Spread Rate ft/sec^{-1}	Fuel Burned lb/ft^{-2}	Fuel MC %	Test No.
O	76	0.041	4.8	0.032	0.28	15.6	125
O	86	0.030	4.0	0.048	0.21	13.8	108
O	187	0.043	5.6	0.094	0.24	13.8	105
GO	55	0.024	4.4	0.034	0.19	12.5	110
GO	79	0.041	4.4	0.041	0.23	14.8	124
GO	80	0.024	5.2	0.034	0.28	13.6	120
GO	96	0.016	5.2	0.049	0.23	14.3	118
GO	100	0.030	5.6	0.042	0.28	13.7	113
GO	103	0.036	4.8	0.046	0.27	13.7	103
GO	120	0.024	5.2	0.060	0.24	10.2	111
GO	121	0.036	5.6	0.049	0.29	13.2	112
GO	135	0.046	6.4	0.049	0.33	13.0	106
GO	147	0.041	7.6	0.047	0.37	14.9	122
GO	153	0.036	6.4	0.054	0.34	16.1	129
GO	157	0.051	6.8	0.047	0.40	16.7	132
GO	162	0.040	6.4	0.057	0.34	16.2	114
GO	173	0.049	6.4	0.059	0.35	14.7	127
GO	183	0.053	6.4	0.067	0.32	14.2	102
GO	200	0.060	7.2	0.064	0.37	15.8	139
GO	220	0.070	7.6	0.063	0.41	15.2	141

...cont.

TABLE IIA (Continued)

Status Code	Intensity (1) $BTU/cm^{-1}/sec^{-1}$	Water Depth inches	Bed Depth inches	Spread Rate ft/sec^{-1}	Fuel Burned lb/ft^{-2}	Fuel MC %	Test No.
GO	234	0.050	7.6	0.073	0.38	13.9	117
GO	256	0.080	8.0	0.069	0.44	15.3	143
DR	185	0.045	7.6	0.056	0.39	16.2	133
R	52	0.016	4.6	0.031	0.20	13.3	109
R	91	0.023	4.8	0.035	0.31	15.1	126
R	129	0.036	7.2	0.045	0.34	16.2	116
R	132	0.016	5.2	0.058	0.27	14.8	119
R	139	0.029	6.0	0.051	0.32	15.9	128
R	151	0.030	6.4	0.053	0.34	13.8	115
R	192	0.036	7.6	0.060	0.38	15.2	130
R	193	0.040	7.2	0.055	0.42	15.3	142
R	221	0.055	7.6	0.067	0.39	14.2	107
R	229	0.028	6.8	0.078	0.35	14.1	101
R	234	0.059	8.0	0.072	0.39	15.3	140
R	239	0.060	8.0	0.063	0.45	16.3	144

(1) Heat yield used = Heat of combustion (9165 BTU/lb) - Heat of reaction (543 BTU/lb) - Heat of correction for moisture content.

TABLE III

BLACK SPRUCE SLASH TEST FIRE DATA

Status Code	Intensity[1] Cal/cm^{-1}/sec^{-1}	Water Depth cm	Bed Depth cm	Spread Rate cm/sec^{-1}	Fuel Burned gm/cm^{-2}	Fuel MC %	Test No.
O	325	0.08	8.0	0.40	0.17	14.9	152
O	545	0.13	12.0	0.42	0.28	14.8	151
GO	501	0.08	12.0	0.46	0.23	14.7	153
GO	780	0.08	15.0	0.68	0.25	15.4	154
GO	1022	0.14	17.0	0.67	0.33	17.4	156
R	750	0.08	16.0	0.53	0.31	16.3	155
R	1102	0.10	17.0	0.73	0.33	18.4	157

(1) Heat yield used = Heat of combustion (5028 cal/gr) - Heat of reaction (302 cal/gr) - Heat of correction for moisture content.

TABLE IIIA

BLACK SPRUCE SLASH TEST FIRE DATA

Status Code	Intensity[1] $BTU/ft^{-1}/sec^{-1}$	Water Depth inches	Bed Depth inches	Spread Rate ft/sec^{-1}	Fuel Burned lb/ft^{-2}	Fuel MC %	Test No.
O	38	0.031	3.2	0.013	0.36	14.9	152
O	67	0.052	4.8	0.014	0.58	14.8	151
GO	60	0.031	4.8	0.015	0.48	14.7	153
GO	93	0.031	6.0	0.022	0.51	15.4	154
GO	124	0.053	6.8	0.022	0.68	17.4	156
R	89	0.031	6.4	0.017	0.63	16.3	155
R	134	0.040	6.8	0.024	0.68	18.4	157

(1) Heat yield used = Heat of combustion (9051 BTU/lb) - Heat of reaction (543 BTU/lb) - Heat of correction for moisture content.

TABLE IV

WHITE SPRUCE SLASH TEST FIRE DATA

Status Code	Intensity[1] $Cal/cm^{-1}/sec^{-1}$	Water Depth cm	Bed Depth cm	Spread Rate cm/sec^{-1}	Fuel Burned gm/cm^{-2}	Fuel MC %	Test No.
R	461	0.04	10.0	0.54	0.19	9.9	145
R	557	0.74	14.0	0.54	0.23	12.7	146

(1) Heat yield used = Heat of combustion (4954 cal/gr) - Heat of reaction (302 cal/gr) - Heat of correction for moisture content.

TABLE IVA

WHITE SPRUCE SLASH TEST FIRE DATA

Status Code	Intensity[1] $BTU/ft^{-1}/sec^{-1}$	Water Depth inches	Bed Depth inches	Spread Rate ft/sec^{-1}	Fuel Burned lb/ft^{-2}	Fuel MC %	Test No.
R	57	0.016	4.0	0.018	0.38	9.9	145
R	69	0.029	5.6	0.018	0.47	12.7	146

(1) Heat yield used = Heat of combustion (8919 BTU/lb) - Heat of reaction (543 BTU/lb) - Heat of correction for moisture content.

APPENDIX D

Test Fire Flame Front Characteristics

FIRE CHARACTERISTICS

Visually noted fire characteristics other than flame height, flame front depth and rate of fire spread were descriptive in nature and thereby were considered to be non-comparative information. The mean flame height, the depth of the flame front and the rate of spread for each test were quantitatively determined and recorded as the fire progressed from station to station along the fuelbed. The two nearly identical white spruce tests did not provide sufficient data for graphical representation, therefore, the Figures 19, 20 and 21 illustrate red pine needles, balsam fir slash and black spruce slash fires respectively.

For the fire intensity range below 200 $BTU\text{-}ft^{-1}\text{-}sec^{-1}$, the comparative flame heights for the three aforementioned fuels are presented in Figure 22, the flame front depths in Figure 23 and the rates of spread in Figure 24.

In examining the significance of the differences between the respective curves for the different fuels, it should be borne in mind that fuel particle characteristics, fuelbed voidage and fuel bulk density were sufficiently dissimilar for tests of the same fire intensity.

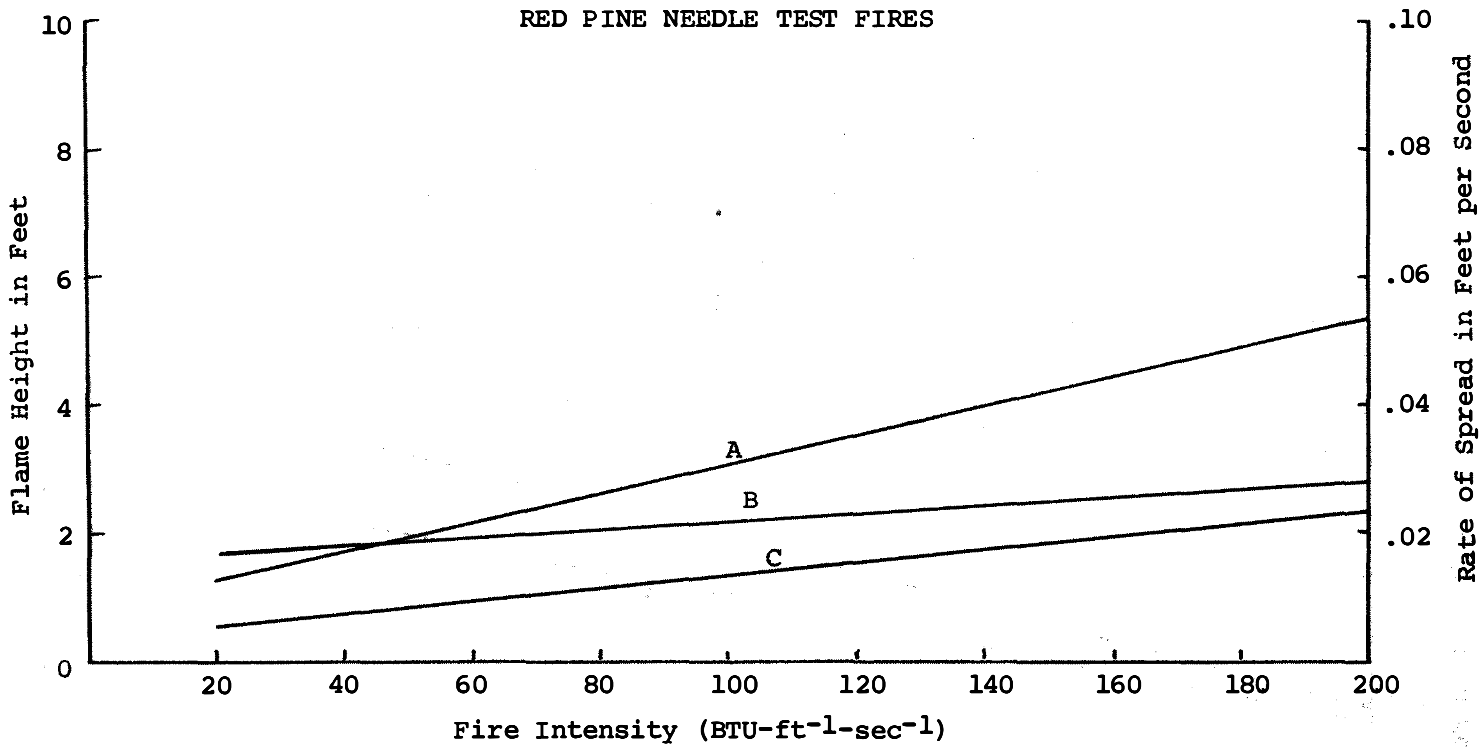


FIGURE 25. Red pine needle test fire flame height is given by curve B, the depth of the flaming zone by curve C and the rate of fire spread by curve A, for the 20 to 200 $BTU\text{-}ft^{-1}\text{-}sec^{-1}$ intensity range.

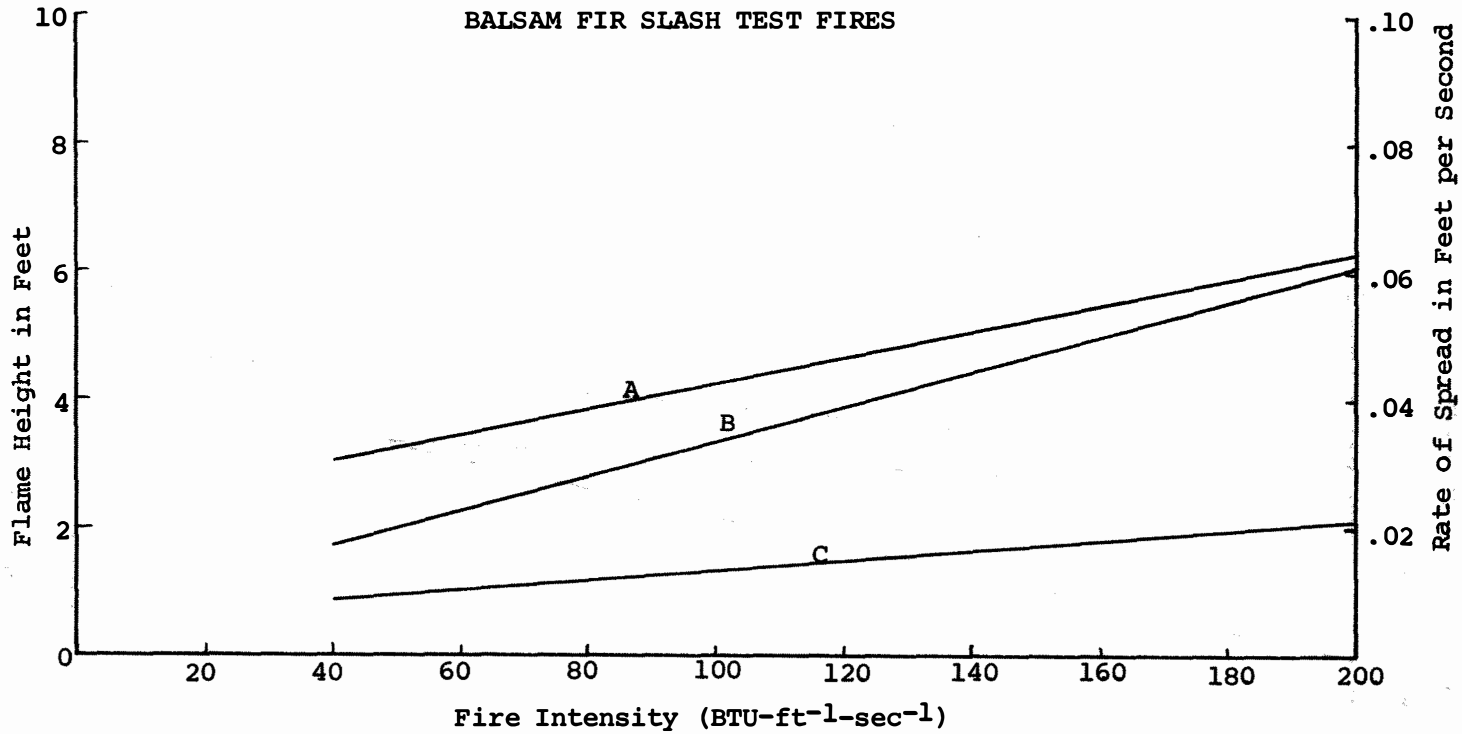


FIGURE 26. Balsam fir slash test fire flame height is given by curve B, the depth of the burning zone by curve C and the rate of fire spread by curve A, for the 40 to 200 BTU-ft^{-1}-sec^{-1} intensity range.

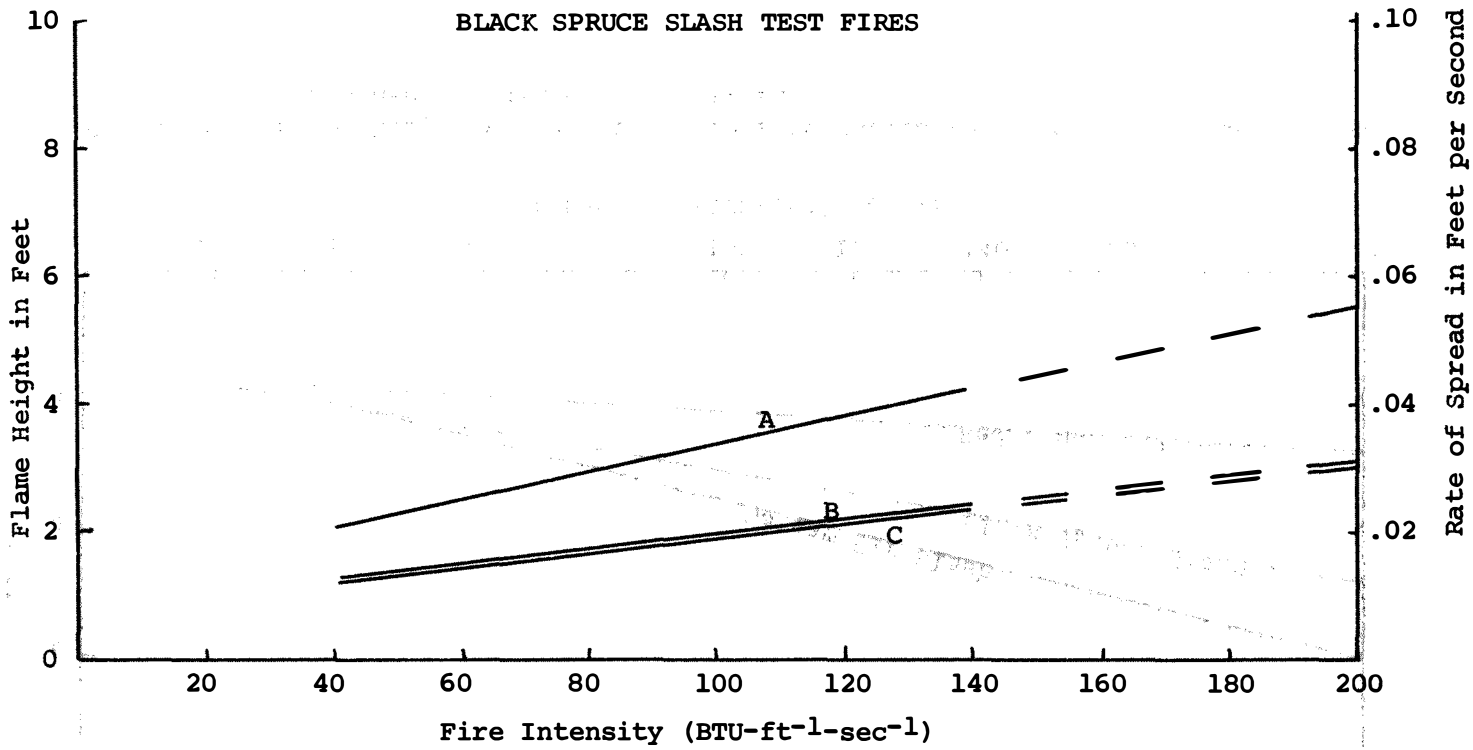


FIGURE 27. Black spruce slash test fire flame height is given by curve A, the depth of the flaming zone by curve B and the rate of fire spread by curve C for the 40 to 200 BTU-ft^{-1}-sec^{-1} intensity range.

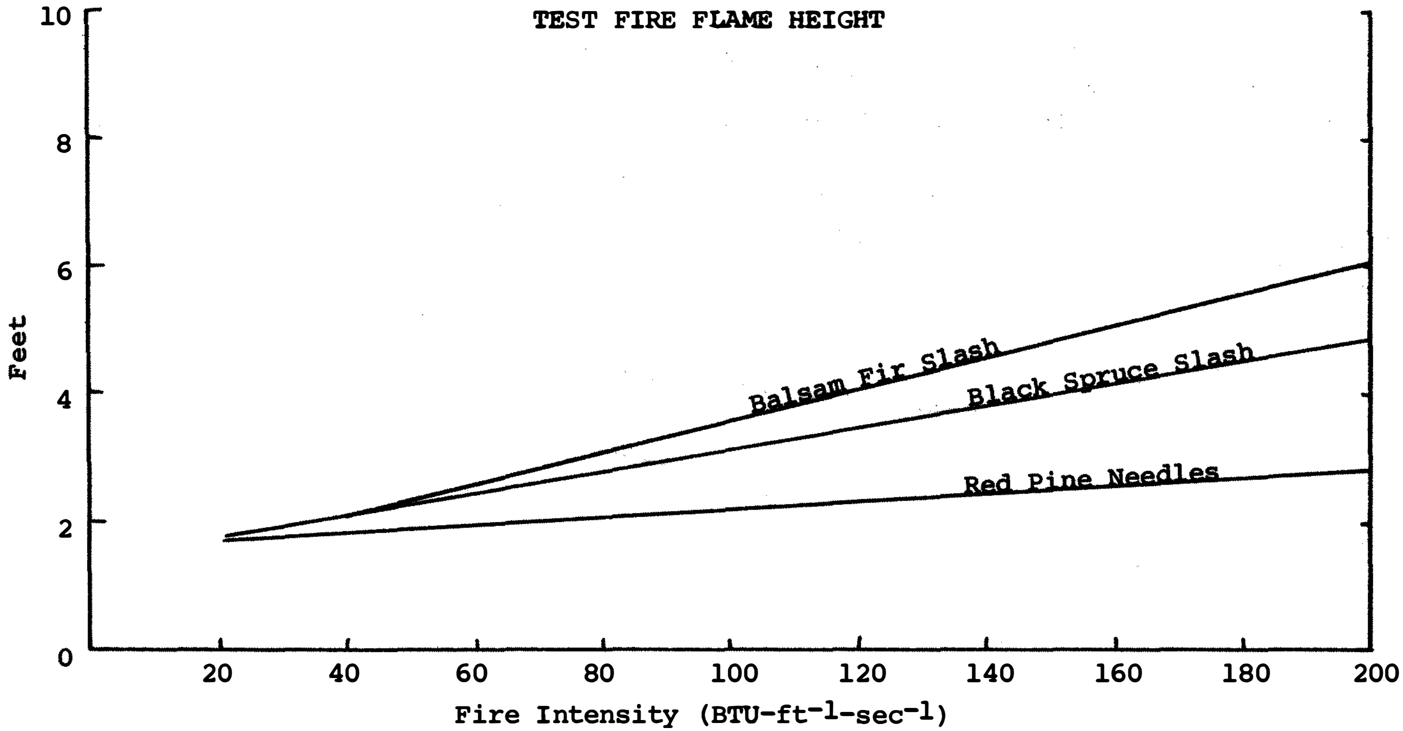


FIGURE 28. Flame height versus fire intensity curves for red pine needles, balsam fir slash and black spruce slash.

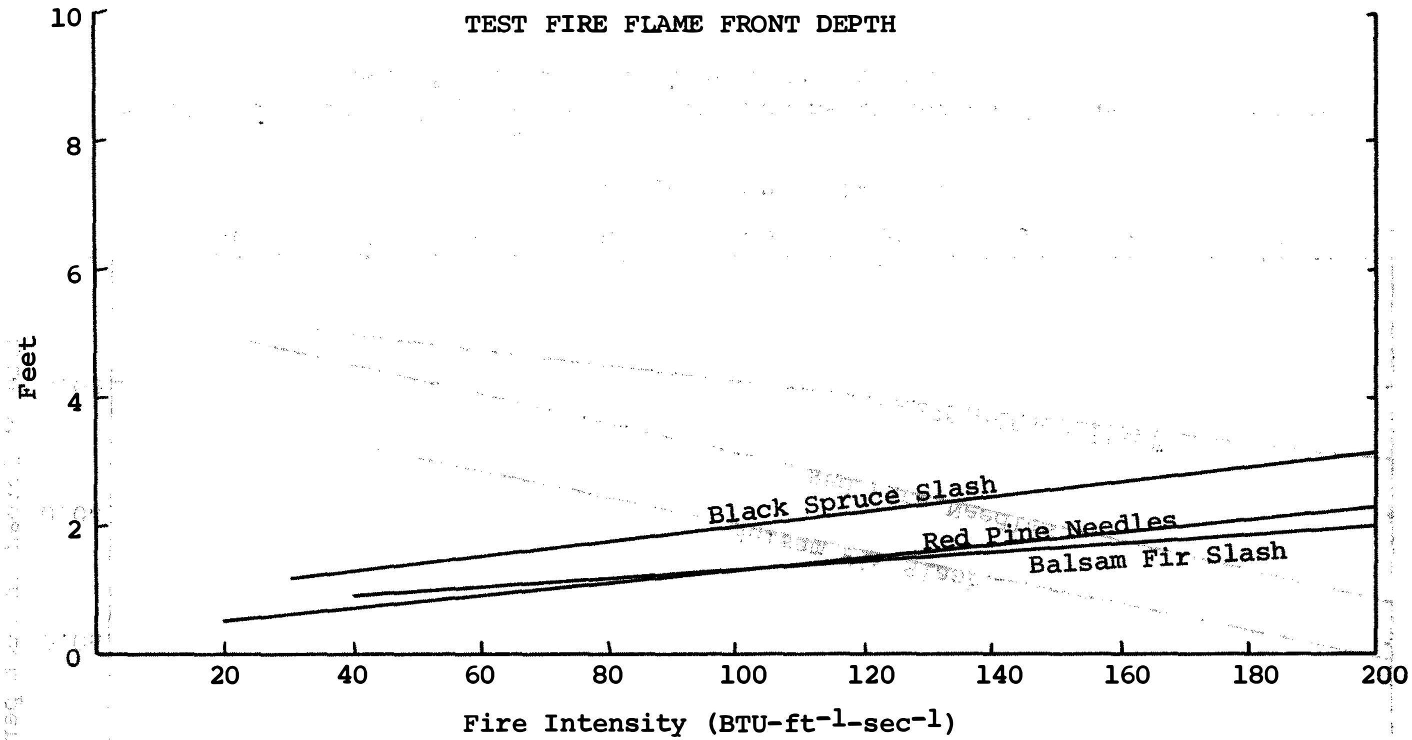


FIGURE 29. The depth of the flaming zone versus fire intensity curves for red pine needles, balsam fir slash and black spruce slash.

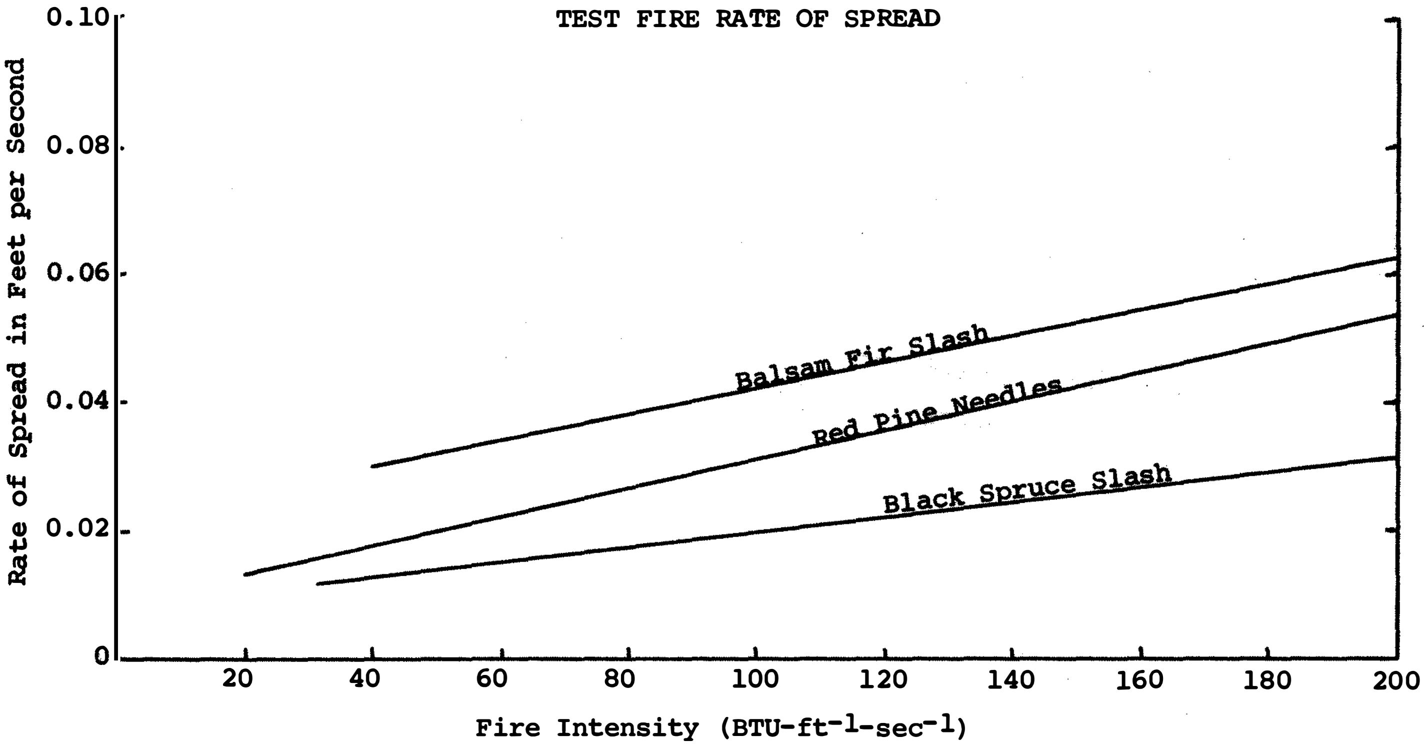


FIGURE 30. Rate of spread versus fire intensity curves for red pine needles, balsam fir slash and black spruce slash.

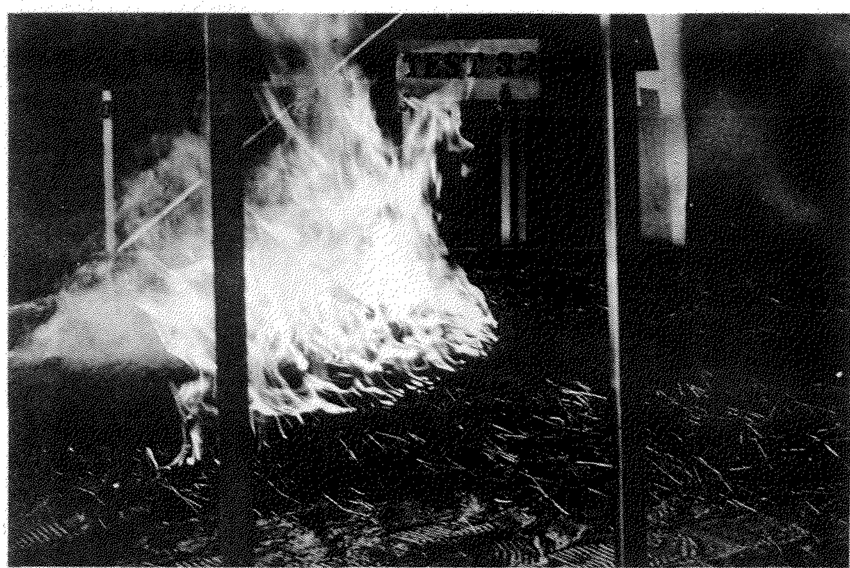


FIGURE 31. Red pine needle test fire burning at an intensity of 86 $BTU\text{-}ft^{-1}\text{-}sec^{-1}$.

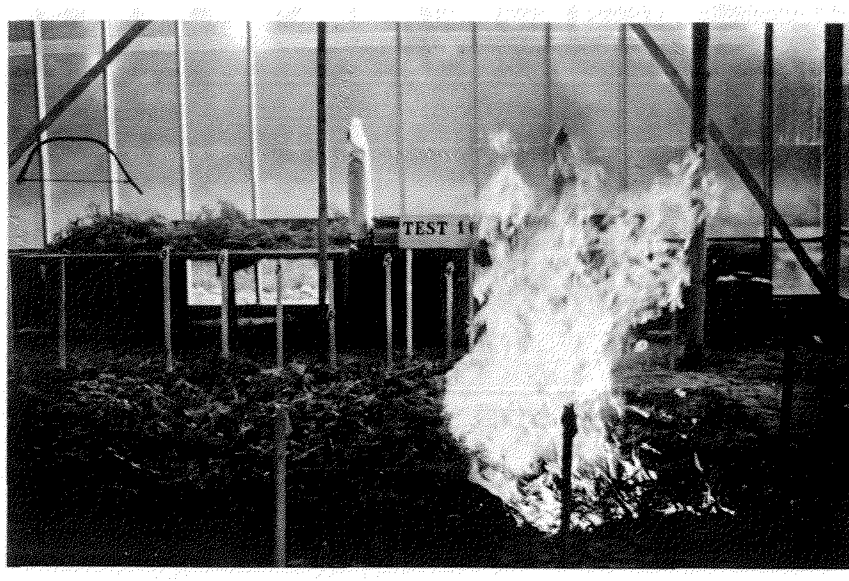


FIGURE 32. Balsam fir slash test fire burning at an intensity of 129 $BTU\text{-}ft^{-1}\text{-}sec^{-1}$.

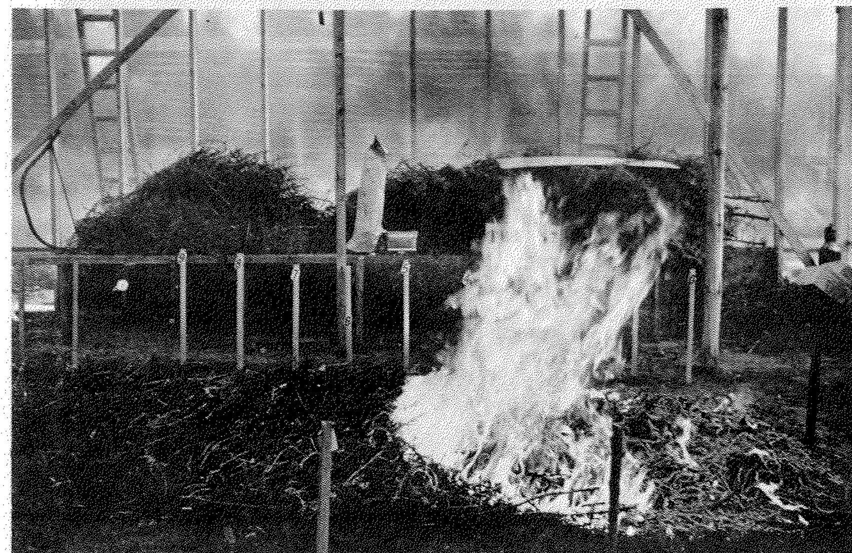


FIGURE 33. Black spruce slash test fire burning at an intensity of 134 BTU-ft^{-1}-sec^{-1}.

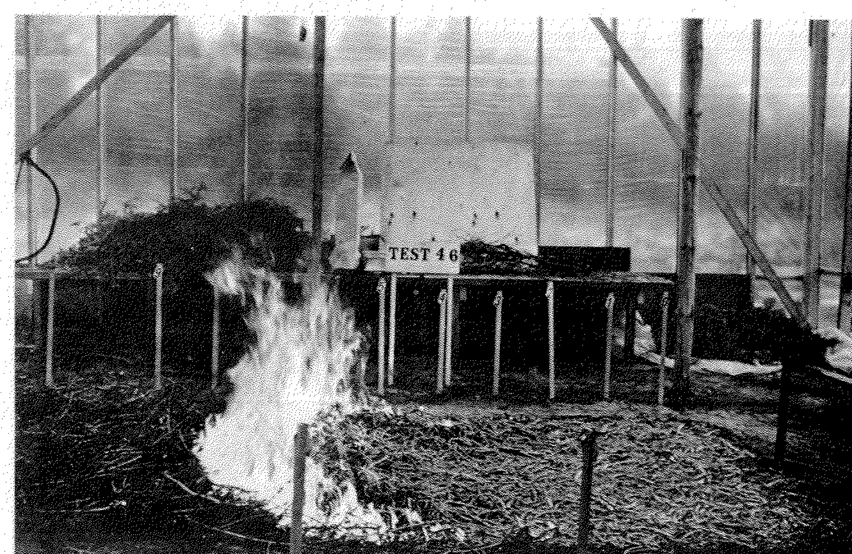


FIGURE 34. White spruce slash test fire burning at an intensity of 69 BTU-ft^{-1}-sec^{-1}.