1960

Laboratory evaluation of aerially applied forest fire retardants

S. John Muraro
The University of Montana

Recommended Citation

Muraro, S. John, "Laboratory evaluation of aerially applied forest fire retardants" (1960). *Graduate Student Theses, Dissertations, & Professional Papers*. 2801.
https://scholarworks.umt.edu/etd/2801

A LABORATORY EVALUATION OF AERIALLY APPLIED FOREST FIRE RETARDANTS

by

S. John Muraro

B. S. MONTANA STATE UNIVERSITY, 1960

Presented in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN FORESTRY

MONTANA STATE UNIVERSITY

1960

Approved by:

Chairman, Board of Examiners

Dean, Graduate School

NOV [illegible] 1960

Date

TABLE OF CONTENTS

CHAPTER PAGE

I. INTRODUCTION 1

II. REVIEW OF THE LITERATURE 3

History and Theories 3

Aerial Application of Contained Retardants 6

Aerial Application of Bulk Retardants 7

Results of Current Studies 9

III. COLLOIDAL SUSPENSIONS AND CATION EXCHANGE 15

IV. MATERIALS TESTED 19

Sodium Calcium Borate 19

South Dakota Bentonite 19

O'Keefe Creek Bentonite 21

Vermiculite 22

Airport Clay 24

Sodium Hexametaphosphate 24

Monoammonium Phosphate 24

Diammonium Phosphate 25

V. TESTING EQUIPMENT AND PROCEDURES 26

PRELIMINARY TESTS 26

Cation Analysis 26

Mixing Characteristics 26

Specific Gravity 27

pH 28

Viscosity 28

Adherence to Vegetation 28

CHAPTER PAGE

Water Retention Test 29

BURNING TESTS 30

Ignition and Fire Intensity Tests 30

VI. PRESENTATION OF DATA 36

Preliminary Tests 36

Water Retention Tests 37

Ignition Delay 37

Intensity of Burn 37

Resistance to Burning Index 39

Duration of Burn 40

Analysis of Regression and Correlation 42

VII. DISCUSSION OF RESULTS 45

Sodium Calcium Borate 45

Sodium Trisilicate 50

South Dakota Bentonite 51

O'Keefe Creek Bentonite 58

Ammonium Phosphates 60

Water 63

VIII. SUMMARY 65

Conclusions 67

Suggestions 68

BIBLIOGRAPHY 70

EXPLANATION OF APPENDIX 76

APPENDIX 78

PLATES

1. Photograph of modified fire tube apparatus used for burning dowels.

2. Fire tube apparatus for use in burning dowels.

3. Picture 1 - Water-treated dowel after burning 1.4 minutes.

   Picture 2 - South Dakota bentonite + PMF vermiculite treated dowel after 1.4 minutes.

   Picture 3 - (from left to right) Unburned water-treated dowel, burned water-treated dowel, burned South Dakota bentonite + PMF vermiculite treated dowel and unburned South Dakota bentonite + PMF vermiculite treated dowel. All dowels burned immediately after dipping.

LIST OF TABLES IN APPENDIX

Table I.	Chemical and physical analysis of water used for mixing - from U. S. Forest Service, Aerial Fire Depot, Missoula, Montana.
Table II.	Chemical analysis of sodium calcium borate, vermiculite, South Dakota bentonite expressed in percent.
Table III.	Cation exchange and total analyzed exchangeable cations expressed in milli-equivalents per 100 grams of dry retardant.
Table IV.	Some physical and chemical characteristics of retardants used in the burning tests.
Table V.	Mean weight in grams and in percent over dry weight of dowels pretreated with Class I retardants at the indicated drying times and temperatures.
Table VI.	Mean weight in grams and in percent over dry weight of dowels pretreated with class II retardants at the indicated drying times and temperatures.
Table VII.	Ignition time in minutes of treated and untreated dowels after different drying times.
Table VIII.	Mean quarter-minute temperature/range in °C. of burning dowels pretreated with class I retardants - wet.
Table IX.	Mean quarter-minute temperature/range in °C. of burning dowels pretreated with class I retardants - dry.
Table X.	Mean quarter-minute temperature/range in °C. of burning dowels pretreated with class II retardants - wet.
Table XI.	Mean quarter-minute temperature/range in °C. of burning dowels pretreated with class II retardants - dry.
Table XII.	Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 1, sodium calcium borate plus Calgon) after different drying times.
Table XIII.	Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 2 sodium calcium borate) after different drying times.
Table XIV.	Mean Quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 4 sodium calcium borate) after different times.

Table XV. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 5 South Dakota bentonite plus Calgon) after different drying times.

Table XVI. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 6 South Dakota bentonite plus No. 4 exfoliated vermiculite) after different drying times.

Table XVII. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 7 South Dakota bentonite plus PMF vermiculite) after different drying times.

Table XVIII. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 8 South Dakota bentonite plus micronized vermiculite) after different drying times.

Table XIX. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 9 South Dakota bentonite plus sodium calcium borate) after different drying times.

Table XX Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 10 South Dakota bentonite plus airport clay) after different drying times.

Table XXI. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 11 O'Keefe Creek bentonite 3 pounds/gallon) after different drying time.

Table XXII. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 12 O'Keefe bentonite 4 pounds/gallon) after different drying times.

Table XXIII. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 13 monoammonium phosphate $NH_4H_2PO_4$) after different drying times.

Table XXIV. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 14 diammonium phosphate $(NH_4)2HPO_4$) after different drying times.

Table XXV. Mean quarter-minute temperature/range in °C. of burning dowels (pretreated with retardant No. 15 - water) after different drying times - also untreated dowels.

Table XXVI. Resistance to burning index of the various retardants computed from the temperature curves shown on graphs 9 - 22 inclusive.

Table XXVII. Mean weight summary of class I retardant treated dowels.

Table XXVIII. Mean weight summary of class II retardant treated dowels.

LIST OF GRAPHS IN APPENDIX

Graph 1. Class I retardants; hourly weight of treated dowels in percent over dry weight when dried for 5 hours at 50° C. and for 19 hours at 103° C.

Graph 2. Class II retardants; hourly weight of treated dowels in percent over dry weight when dried for 5 hours at 50° C. and for 19 hours at 103° C.

Graph 3. Class I retardants; ignition time in minutes plotted over hours of drying at 50° C. after treatment.

Graph 4. Class II retardants; ignition time in minutes plotted over hours of drying at 50° C. after treatment.

Graph 5. Comparative mean temperature curves of wet, class I retardant treated dowels plus untreated dowels. Temperature plotted over every .25 minutes of exposure in the tube until peak temperature is reached.

Graph 6. Comparative mean temperature curves of dry, class I retardant treated dowels plus untreated dowels. Temperature plotted every .25 minutes of exposure in the tube until peak temperature is reached.

Graph 7. Comparative mean temperature curves of wet, class II retardant treated dowels plus untreated dowels. Temperature plotted every .25 minutes of exposure in the tube until peak temperature is reached.

Graph 8. Comparative mean temperature curves of dry, class II retardant treated dowels plus untreated dowels. Temperature plotted every .25 minutes of exposure in the tube until peak temperature is reached.

Graph 9. Comparative mean temperature curves of burning dowels pretreated with retardant No. 1, sodium calcium borate plus Calgon after 0 and the mean 1, 2, 3, 4 and 5 hours of drying compared to untreated dowels.

Graph 10. Comparative mean temperature curves of burning dowels pretreated with retardant No. 2, sodium calcium borate after 0, 1 and the mean of 2, 3, 4 and 5 hours of drying compared to untreated dowels.

Graph 11. Comparative mean temperature curves of burning dowels pretreated with retardant No. 4, South Dakota bentonite after 0, 1, 2, 3 and the mean of 4 and 5 hours of drying compared to untreated dowels.

Graph 12. Comparative mean temperature curves of burning dowels pretreated with retardant No. 5, South Dakota bentonite ± Calgon after 0, 1 and the mean of 2, 3, 4, and 5 hours of drying, compared to untreated dowels.

Graph 13. Comparative mean temperature curves of burning dowels pretreated with retardant No. 6, South Dakota bentonite plus No. 4 exfoliated vermiculite after 0, 1, 2, 3 and the mean of 4 and 5 hours of drying compared to untreated dowels.

Graph 14. Comparative mean temperature curves of burning dowels pretreated with retardant No. 7, South Dakota bentonite plus PMF vermiculite after 0, 1, 2 and the mean of 3, 4 and 5 hours of drying compared to untreated dowels.

Graph 15. Comparative mean temperature curves of burning dowels pretreated with retardant No. 8, South Dakota bentonite plus micronized vermiculite after 0, 1, 2, 3 and the mean of 4 and 5 hours of drying compared to untreated dowels.

Graph 16. Comparative mean temperature curves of burning dowels pretreated with retardant No. 9, South Dakota bentonite plus sodium calcium borate after 0 and the mean of 1, 2, 3, 4 and 5 hours of drying compared to untreated dowels.

Graph 17. Comparative mean temperature curves of burning dowels pretreated with retardant No. 10, South Dakota bentonite plus airport clay after 0, 1, 2 and the mean of 3, 4 and 5 hours of drying compared to untreated dowels.

Graph 18. Comparative mean temperature curves of burning dowels pretreated with retardant No. 11, O'Keefe Creek bentonite (3 pounds/gallon) after 0, 1, 2 and the mean of 3, 4 and 5 hours of drying compared to untreated dowels.

Graph 19. Comparative mean temperature curves of burning dowels pretreated with retardant No. 12, O'Keefe Creek bentonite (4 pounds/gallon) after 0, 1, 2 and the mean of 3, 4 and 5 hours of drying compared to untreated dowels.

Graph 20. Comparative mean temperature curves of burning dowels pretreated with retardant No. 13. monoammonium phosphate after 0 and the mean of 1, 2, 3, 4 and 5 hours of drying compared to untreated dowels.

Graph 21. Comparative mean temperature curves of burning dowels pretreated with retardant No. 14, diammonium phosphate after 0 and the mean of 1, 2, 3, 4 and 5 hours of drying compared to untreated dowels.

Graph 22. Comparative mean temperature curves of burning dowels pretreated with No. 15,((water) after) and the mean of 1, 2 and 3 hours of drying compared to untreated dowels.

Graph 23. Class I retardants - percent of wood loss per minute plotted as a function of drying time in hours.

Graph 24. Class I retardants - regression line showing the average percent of wood loss per minute of burn as a function of weight of slurry in percent of dry weight.

CHAPTER I

INTRODUCTION

Bulk-dropping of forest fire retardants from aerial tankers has become firmly established as a new fire control tool. This valuable but costly tool can be used to advantage either as a method of initial attack on small fires or as a method of ground-force support on large fires. Aircraft rental, which in Region 1 of the U. S. Forest Service is on a per-hour-of-flight basis, is the largest single cost involved in an aerial tanker operation. So far this cost has remained independent of the type and effectiveness of the fire retardant carried. In view of this large fixed cost, a retardant should be used which is most restrictive to combustion, provided it can satisfy other limiting criteria. Comparative laboratory testing is a relatively inexpensive and highly indicative method of determining the effectiveness of a fire retardant.

An aerially applied forest fire retardant must meet many requirements which most commercial compounds used for fireproofing wood by pressure treatments cannot satisfy. Primarily the cost-benefit ratio of a forest fire retardant must be favorable in order that its use may be justified. It must mix with water or other liquid to form a good stable colloidal suspension with a minimum amount of trouble and time. It must be neither corrosive nor abrasive to equipment used for mixing nor to aircraft used for application. It definitely cannot be toxic nor irritating in any degree to personnel engaged either in the mixing operation or on the fireline. The dropping qualities must be such that good canopy penetration and maximum effective dispersion is attained. The retardant must adhere well to both deciduous and coniferous vegetation and dry in such a manner that the fuels are not exposed by cracking and peeling. Finally, the retardant should not act as a plant dessicator nor as a soil sterilizer.

Largely due to these and other lesser criteria, the field of aerially applied fire retardants has been confined mainly to clays or clay-like materials, which in themselves are relatively inert but when mixed with water, form either a dispersed, flocculated or thixotropic colloidal system. These materials act generally as a carrying agent for water which cools the fuels and raises ambient humidity as well as forming a coating which inhibits the free access of oxygen and heat to the fuel and the free egress of volatile products from the fuel.

In the course of this study, eleven combinations of clay or clay-like materials which formed colloidal suspensions with water and two chemicals which formed true solutions with water were tested for use as aerially applied forest fire retardants. Water, without additives of any sort was also tested. Toxicity, abrasiveness and corrosiveness of the various retardants were not tested, although materials which were known to be toxic, corrosive or abrasive to a degree which would necessitate extra protective measures were initially discarded.

The reader must understand that at the very best, these, and similar tests are indicative only of materials which make a good aerially-applied retardant. Evaluation of canopy penetration, manner of drop and dispersion cannot be tested in the laboratory. Until correlative studies of field results and laboratory tests have been made, the final choice of retardant must be based on accurately conducted field trials.

CHAPTER II

REVIEW OF LITERATURE

History and Theories

The art of flameproofing and fire retarding both with coatings and impregnation treatments is old and varied. Herodotus (26) wrote that the ancient Egyptians steeped wood in alum to make it fire resistant. Later the Romans soaked wood in vinegar and alum, (19) (25) or coated it with clay, lime or other incombustible material using an organic binding material (19). In 1638 Nikolas Sabbatini recommended fire resistant coatings of clay or gysum for theatres in Italy (45). According to Garratt (17), in 1895 the United States Navy inaugurated the use of fire retardants in the United States. In 1899 the New York City building code made it mandatory that wood used for interior finish in buildings 12 stories high or higher be fireproofed.

The explanation of flameproofing includes the following theories: coating, thermal, gas and chemical (32) all of which may act either independently or as an interaction (12). In 1821 Gay-Lussac (18) recommended ammonium phosphate, mixtures of ammonium phosphate with ammonium chloride, and ammonium chloride with borax for fireproofing wood and wood-fiber materials. From his work in this field Gay-Lussac (18) advanced two theories of the action of retardant coatings, one of which is still current. He claimed that the escape of volatile combustion products from the wood and the free access of oxygen to the wood can be prevented or inhibited by chemicals that melt and coat the wood fibers with a liquid or glassy layer (9) (14).

Browne (12) stated that an ideal fire retardant would be a chemical that melts near 200°C. evolving nonflammable gases, in combination with another chemical that melts just prior to the beginning of active pyrolysis producing a stable foam. He also noted that the tars formed during the pyrolysis of untreated wood readily produce a foam that is stable in high temperatures. Browne (12) speculated that a desirable fire retardant should also direct pyrolysis toward maximum production of charcoal, water and carbon dioxide and toward the minimum production of tars which contain the flammable gases. Thermal theories are of three kinds (12). Thermal insulation to retard access of heat to the wood, thermal conductivity to dissipate the heat more rapidly and thermal absorption to reduce the heat available for pyrolysis. Gas theories are of two kinds; the retardant and that of catalytical inhibition of flaming radicals (12). According to Gooch and associates (20) the halogens fluorin, bromine, chlorine and iodine, or their acids accomplish this catalytical inhibition of flaming radicals mentioned by Browne (12).

Browne (12) stated that in the chemical theory the action of chemicals is chiefly by means of the decomposition of cellulosic material toward the formation of less tars and more charcoal and water. This is partially confirmed by the fact that, "the majority of retardants impair the strength of cotton fabrics to some extent even at ordinary or slightly elevated temperature" (14). In his conclusion Browne (12) states, "No single theory completely described the manner in which resistance to fire is imparted to wood."

Studies conducted mainly at the Forest Products Laboratory* in 1953 and 1954 (35) (36) and earlier from 1929 to 1935 (47) (29) (30) (24) (49) (48) determined:

1. That a fire tube apparatus developed by M. E. Dunlap and described by Truax and Harrison (47) can give dependable and reproductible results when used for determining the fire retarding effect of various compounds.
2. That if wood is pressure-impregnated with from 1 to 7 pounds of certain chemicals per cubic foot of dry wood, the tendency of that wood to support combustion is minimized. Diammonium phosphate ($(NH_4)2HPO_4$);monoammonium phosphate($NH_4H_2PO_4$); zinc chloride ($ZnCl_2$) and ammonium sulphate ($(NH_4)2\ SO_4$) in that order were found to be particularly effective.
3. That the melting and boiling points of chemicals are not related to their effectiveness as fire retardants.
4. That in most cases the effectiveness of a particular retardant is determined by the concentrations used.
5. That moisture percentages of from 6 to 20 percent give approximately the same percent weight loss due to burning but that the rate of weight loss differs, indicating a reduction in the intensity of burning.
6. That no direct correlation can be expressed between the rates at which salts affect the moisture content of wood and the

---

*The Forest Products Laboratory is operated in cooperation with the University of Wisconsin at Madison, Wisconsin.

effectiveness of those salts as a fire retardant.

7. That a rate of combustion can be determined by dividing the weight of wood lost during burning, by the duration of burn and that this rate of weight loss is a more complete picture of the retardant action than is indicated by a measure of the total weight of wood loss.

Aerial Application of Contained Retardants

Aerial application of retardants on forest fires, because of the rather recent invention of a practical flying machine, is a relatively young concept. Serious thought by Forest Service officials was first given to the loss of dropping water in the early 1920's (2). Hanson and Tebbe (23) report.

> More than 15 years ago the Forest Service Fire Chief of the Northern Region, Howard Flint, kicked a beer keg full of water out the door of an airplane flying over Felts Field, Spokane. He wanted to see how much area would be covered by the splash. The result was not promising. Five-gallon cans filled with water were then tried, and at the Johnson Brothers Airport at Missoula, large paper bags filled with foamite were thrown at the perimeter of a 50-foot circle drawn on the ground to simulate the perimeter of a forest fire. Still other tests with various containers and fillings were conducted by the Forest Service in California.

The U. S. Forest Service, in 1936, carried out a study on the use of containers for dropping liquid, foam and dust suppressants to determine their falling, bursting and dispersion characteristics. They concluded that container drops can be effective on small fires but that drops made from small aircraft flying in mountainous terrain cannot attain the accuracy necessary to hit the fires consistently enough to make the operation practical (2).

Studies conducted in 1947 and 1949 in Region 1 using modified 165-gallon wing tanks as containers filled with monoammonium phosphate and foam dropped from B-29 Superfortresses and P-47 Thunderbolts were reported by Hanson and Tebbe (23).

These intial attack practices were discontinued largely for the same reason as were earlier attempts (26).

Mackey (34), Grimshaw (22) and Wood and Cooke (51), report on drops made in Canada prior to 1957 using 3½-gallon water-proofed paper bags filled with water. The bags were dropped singly or in strings of eight. The eight-bag string dropped from a DCH-2 (Beaver) wet a 10-foot by 90-foot area. This technique was used with some success on fires, but the delay incurred while loading limited its widespread usage.

Recent work in Australia reported by Ellwood (15) made use of 65-gallon wing tanks and 50-gallon drums containing monoammonium phosphate. An area of 30 by 150 feet was effectively covered by a concentration of about 1 gallon per 100 square feet.

Many of these methods showed some success, especially the latter two but it is rather obvious that "bombing fires with droppable container.. in fact, any projectile ... cannot be tolerated in populated areas or as close support to ground firefighting forces" (2).

Aerial Application of Bulk Retardants

In 1953 a 2400-gallon bulk water drop from a DC-7 was attempted in California. The water was released through 6-inch gates, in varying amounts and at varying elevations. The pattern varied from 125 to 300 feet wide and was approximately 4,000 feet long. Rain gauges placed along the drop line recorded up to .001 of an inch of water (1).

In 1954 a bulk retardant drop was made by Major Warren Schroeder, USMCR at El Toro Marine Base. A 250-gallon napalm bomb tank was fitted with glass plates in place on the ends of the tank. When attached to a Douglas AD-2 fighter the glass plates could be broken by the triggering device. Using this arrangement, water-foam solution was dropped from an altitude of about 35 feet at an airspeed of 160 miles per hour. The visible pattern was about 50 feet wide by 300 feet long. A foam depth of 1/2 to 3/4 of an inch deep in a 15-foot wide center strip was reported (4). But again the danger of flying debris was present in a very lethal form - broken glass traveling at well over 100 miles per hour.

In California Operation Firestop* carried on bulk water drops in 1955 (2) using a converted TBM torpedo bomber. From the drops made, it was concluded that it is feasible to apply water on noncorrosive fire retardants from fixed wind aircraft without the use of containers, but that this type of attack will not replace ground forces.

According to Grimshaw (22), Wood and Cooke (51) in 1957, the Ontario Department of Lands and Forests, Air Service, designed a system of two rotating tanks attached to the floats of a DHC-3 Otter aircraft. The tanks having an operational load of 80 imperial gallons each, can be filled by the use of waterscoops in 18 seconds from the time of touchdown to the time of take-off. Results obtained using this method on fires varying from spots to 100 acres, were so encouraging that the smaller DCH-2 Beaver was equipped with 50-gallon tanks the next year.

---

*Firestop is a one-year operational study designed to explore certain aspects of mass-fire buildup and behavior and to provide the fire services with some new aids to mass-fire prevention and control.

Results of Current Studies.

The use of retardants is still being investigated by agencies located in areas where lack of water is a problem. Fons (16), in 1960 made laboratory tests with fuels pretreated with retardant solutions compared to water-treated fuels by use of a fire wheel apparatus. The relative rate of heat output of burning retardant-treated fuels was compared to the heat output of burning water-treated fuels. Further laboratory tests made by Operation Firestop 1955 (7) and 1958 (3) measured the heat output by use of a Gier and Dunkle directional radiometer and continuously recorded it with a potentiometer. Characteristics of ignition, fire intensity and flame suppression, were tested. It was reported that the ignition time for fuels treated with chemicals which are dehydrating agents or chemicals which form dehydrating agents when heated, was shortened when compared to the ignition time of water-treated fuels. Thus chemical solutions of dehydrating agents would be undesirable for treating fuels outside of a fireline. Those chemicals that tend to form a coating on the fuel increased ignition time.

Three principal ways in which a chemical fire retardant may function are:

> By quenching the flame upon application, by preventing or slowing down ignition, and by reducing the intensity of burn.

The report (7) concluded that both ignition time and fire intensity tests showed that fuel treated with retardants will ignite and burn as long as sufficient heat is available. Thus, fire burning into treated fuels can be expected to burn as long as the rate of heat output is great enough to cause ignition of the treated fuel. The tests also indicated that the effectiveness of any one retardant becomes less as the intensity of burn increases.

According to ground application tests conducted by Operation Firestop in 1955 (2) at least 4 gallons of water carrying 4 to 8 pounds of chemicals per 100 square feet of area are needed to produce significant retardant effects in light fuels and grasses.

Miller (37) reported that field trials using sodium calcium borate on California fires in 1955 by ground and aerial application showed that it was one chemical that could improve the striking power of water dropped on fires. For control of brush and grass fires a slurry of sodium calcium borate and water proved to be more effective than water alone because it remained effective for a longer time and thus permitted treating the fuel well in advance of the fire.

Further reports of 1956 field trials compiled by Miller and Wilson (39) in 1957 substantiated the 1955 findings. Sodium calcium borate was applied both by ground and airtankers. Difficulty was experienced in mixing until the advent of the injector mixer designed and constructed by the Western Fire Equipment Company. Their findings concluded that the chemical could be successfully used by ground tankers and airtankers for direct attack on fires in heavy or light fuels and for pretreatment of inaccessible areas as well as in control burning, control of spot fires and for backfiring line. The authors noted that for effective application, half the load of retardant should fall on the burning portion of the fire and the other half on the unburned fuel. Emphasis was placed on the fact that the retardant cannot knock down hot, rolling fires in brush or timber. Drops made on four large southern California fires led the author to report "the drops were wasted on fast-moving fronts" (39). Abrasiveness, cost, and the amount of dry material per gallon of water necessary were recognized as the major drawbacks of this retardant. The same report mentions the use of wetting agents in combination with the slurry. Some wetting agents caused an increase in dispersion of the slurry, as well as increasing the rate at which the powder was moistened when mixing. Other wetting agents increased the corrosiveness of the slurry.

In 1958 Miller and Phillips (38) did further testing, using the fire wheel apparatus for testing the fire intensity and the muffle furnace for testing the ignition delay of treated fuels. They reported that sodium calcium borate was very effective in delaying ignition but was less effective in reducing fire intensity when compared to bentonite and California Flameproofing Company compound. They claim that all the compounds acted mainly by insulating the fuel from the heat and also by preventing free access of oxygen to the burning surface. This report (38) also lists the following ideal characteristics that a compound to be used should have, in addition to being effective as a retardant:

1. Reasonably inexpensive.
2. Mixes into suspension or solution easily.
3. Remains in suspension overa long period of time.
4. Not toxic to plants or animals.
5. Not corrosive or abrasive to materials used in equipment.
6. Adheres well to any type of vegetation.
7. Will not crack and crumble under extreme drying conditions.
8. Does not increase specific gravity excessively.
9. Requires a small amount of material per gallon of water to give a good slurry thus minimizing transportation storage and handling costs.

10. Easily removed from any surface by washing with water.

11. Readily available in large quantities in many areas.

12. Not a dessicant to vegetation.

Sodium calcium borate is an effective fire retardant (38) but is undesirable because of high cost, it is a soil sterilant, a large quantity of dry material per gallon has to be used and it is abrasive to equipment. Bentonite meets most of the above requirements but several of its characteristics have not been tested.

Robinson 1959 (43) reports that a combination of South Dakota bentonite and number 4 exfoliated vermiculite produced a light slurry which afforded a good coating and stayed wet longer than any other mixture tested. This combination also prevented bentonite from peeling although alligatoring did occur. Flame tests of this retardant showed better resistance to ignition than other retardants, bentonite and sodium calcium borate included. It was also stated that the thickness of the coating on the fuel influences the amount of water held. A point made by the author states that the weight of number 4 exfoliated vermiculite is not constant while the volume is constant.

Laboratory tests conducted in 1959 by Powell and Perrine (42) in the Zonolite Company's Chicago laboratory showed that South Dakato bentonite plus PMF vermiculite mixtures did not adhere to the fuel after exposure to the gas flame. "The film was strong enough to buckle and lift itself from the wood. The coating with the expanded vermiculite alligatored with the heat but adhered well. The mixture of expanded vermiculite and bentonite caused a noticeable increase in the thickness of the mix, whereas with the ore and flake vermiculite the thickening was slight or nonexistent" (42).

Phillips and Miller (41) who in 1959 conducted thorough tests on bentonite for use as a fire retardant decided that bentonite because of its ability to hold large amounts of water can be classed as a good retardant. It is nontoxic to plants and animals, low in cost and the slurry is light in weight. The moisture-retention qualities of South Dakota bentonite are such that it remains invisible from the air for long periods after application. A coloring agent, Rhodamine B, 500 percent concentrate, pink aniline dye was added to the slurry which made it visible from the air when dropped on most types of vegetation. Other colors were also tested. According to the author, hard water reduces the swelling or water-holding capacity; the greater the hardness the less swelling. Use of dispersants such as sodium acid pyrophosphate and mineral lignin at the rate of 4 to 8 ounces per 100 pounds of dry bentonite were recommended for alkaline water. Dispersants have the peculiar effect of increasing viscosity if used in excess.

Johansen (31) reported that in tests conducted in 1959 at the Southeastern Forest Experimental Station, monoammonium phosphate ($NH_4H_2PO_4$) mixed at a 1-2/3 pounds per gallon of water stopped fast-moving head fires. The compound of 12 percent NH_4 and 61 percent P_2O_5 is not toxic to plants and is relatively light. The solution applied from a TBM equipped with a 400-gallon tank stopped the fires when sodium calcium borate and powdered asbestos failed. Corrosiveness was reduced by the addition of 220 parts of sodium silicofluoride and 20 parts of ammonium molybdate per million parts of retardant solution. The solution was colored in order to be visible from the air.

Present use of aerially applied forest fire retardants has tended to fall into two categories, the use of smaller, faster aircraft for initial attack and support tactics and very large aircraft for use only in support operations on large fires.

Utilization of helicopters for pinpoint drops of both chemical retardants and water has been tested in most western regions. This method of delivery has not been used to a great degree (5) because of the high delivery cost per gallon, except in California.

CHAPTER III

COLLOIDAL SUSPENSION AND CATION EXCHANGE

Since ion exchange, which is the tranfer and/or replacement of metallic ions, determines to a large degree the type of suspension which occurs in a colloidal system, this complex and contradictory phenonmenon certainly warrants discussion. One criteria of a good fire retardant is that it must easily enter a stable state of suspension and remain in this state for extended periods (38) (39). Most of the clay or clay-like materials used for fire retardants form one of three types of suspensions when mixed with water: dispersed, flocculated, or a thixotropic. According to Lyons and associates (33):

> The collodial state refers to a two-phase system in which one material (or materials) in a very fine state of aggregation, approaching but not attaining a molecular subdivision, is heterogeneously dispersed through a second.

One of the characteristics of a clay colloidal suspension is that all of the particles carry a net negative electric charge, the magnitude of which is known as the zeta potential. If the zeta potential of the particles in suspension is great enough, they will tend to repel each other, thus forming a dispersed system. If the zeta potential is small the particles will tend to attract each other and form a flocculated system (11). The thixotropic system is a state of gel which is not fully understood but can be illustrated simply as a state which is neither dispersed nor flocculated. It appears to occur when the zeta potential is not large enough for the particles to repel each other and not small enough for the particles to attract each other. Thus, a state of equilibrium between a dispersed and a flocculated system occurs. It must be noted, however, that a dispersed system which is changed to a flocculated system or vice versa, may or may not go through the thixotropic state. The state of thixotropy is most apparent in montmorillonite clays which carry the sodium ion in the dominant exchange position, although the presence of this ion is not wholly the determining factor (21). The American Borax and Chemical Corporation defines a thixotropic suspension as follows: (6)

> A thixotropic suspension is one that tends, when held without stirring, to become relatively thick, so that it is substantially completely stable against segregation of the various solid components or of the liquid and solid phases, and that becomes more fluid upon a moderate amount of agitation.

Calcium ions are generally regarded as being good flocculating agents while sodium ions are generally regarded as good dispersing agents although if used in excess, the sodium ions (and other dispersing ions) tend to act as flocculating agents. Hard water usually contains an excess of calcium. Thus, when it is used for mixing slurries a tendency to flocculate can be expected. Phillips and Miller (41) recommend the addition of dispersing agents to slurries in areas where hard water is used in the mixing operation. Ionic action also affects the viscosity of colloidal suspensions and their manner of drying. Grim (21) notes that the clay skin left by a dehydrated dispersed system is stronger than the clay skin left by a dehydrated flocculated system.

According to Baver (11), the colloidal clay particle is essentially a negatively charged particle with the charges congregated on the surface. Corresponding positive charges (cations) oscillate in a layer outside the negative charges. This outside layer of cations can be easily replaced by other cations having greater adsorptive energy. The basic principle of ion exchange is that the zeta potential varies inversely with the energy of adhesion and directly as the exchange capacity, which is defined as the quantity of ions replaced per unit of mass and which is usually expressed in milli-equivalents[*] of hydrogen per 100 grams of clay. The energy with which a cation is adsorbed varies inversely with the effective size of the cation. This occurs because an ion attracts water in a dipolar manner by means of its electric field intensity which increases directly with its charge and inversely with the square of the distance between the center of the ion and the center of the water molecule. Thus, small cations are more highly hydrated than large cations.

These highly hydrated cations are held at a relatively great distance from the negative charges due to the presence of the thick water hull. The force of adhesion and the distance of oscillation, varies inversely with the effective size of the cation, while the ease of cation replacement varies directly with the distance of oscillation. Thus, it can be seen that a highly hydrated cation promotes a high zeta potential.

The sodium ion which is a small, monovalent, highly hydrated cation is a good example of a dispersant. This cation is very loosely held, raising the zeta potential so that a dispersed or stable state is maintained. The addition of an excess of sodium ions causes a repression in the thickness of the double electric layer of the adsorbed sodium ions. This causes a decrease in the zeta potential and the colloidal material

---

[*] Baver (11) defines a milli-equivalent as one milligram of hydrogen or the amount of any other ion that will combine with or displace it.

becomes flocculated.

The addition of calcium ions to a dispersed system brings about immediate flocculation. This action is partially from ionic exchange and partially from the repression effect noted above. In general the adsorption of a calcium ion which is large, divalent and relatively unhydrated has the opposite effect (or at least reducing effect) on the zeta potential from that of the sodium ion.

CHAPTER IV

MATERIALS TESTED

The materials tested for use as fire retardants included ten which were mixed with water either alone or in combination with one or more of the others. The materials which are discussed separately below included three chemicals, one of which was used as a wetting agent, and seven types of clay or clay-like materials. Table III contains a partial cation exchange analysis of some of the samples while Table II shows the chemical analysis of only some of the materials.

Sodium Calcium Borate

Sodium calcium borate is a combination of calcium borate $Ca_2B_6O_{11}.5H_2$ sodium calcium borate, $NaCaB_5O_9.8H_2O$ and other additives (6). The particular material tested is manufactured by the United States Borax and Chemical Corporation of Los Angeles, California and is sold under the trade name of "Firebrake." It is a fine pinkish-white powder of -140 mesh size which can be easily dispersed in water. Aqueous mixtures of sodium calcium borate are stable suspensions or slurries with thixotropic properties (6).

Table III shows a partial cation analysis of sodium calcium borate while Table II includes the chemical analysis of sodium calcium borate as stated in (6).

South Dakota Bentonite

South Dakota bentonite is a highly colloidal clay mineral belonging to the montmorillinite expanding lattice group of clays possessing a 2:1

lattice structure and carrying the sodium ion in the dominant position. The general formula given by Grim (21) is $(OH)_4Si_3(Al_{3.34}Na_{.66})O_{20}$.

The material tested is sold under the name of "Volclay" and is mined by the American Colloid Company at Upton, Wyoming and Belle Fource, South Dakota. Two grades of material have been used for fire retardants: a particle size of -200 mesh which was used in these tests, and a particle size of -90 mesh. Essentially there is no difference in the colloidal properties of the two although the -90 mesh material is easier to mix and is relatively dust-free.

According to Ross and Shannon (44) bentonite is defined as a clay produced by the alteration of volcanic ash *in situ*. The clay micella consists of two silica tetrahedral sheets separated by a central alumina octahedral sheet. When exposed to water or other polar molecules, the structure can expand to a very great degree, in fact until almost complete separation of the individual layers occurs. Thixotropic gels of very pronounced nature are produced even when the amount of bentonite in relation to the amount of water is relatively small (21). Grim (21) states that only those montmorillonites which carry sodium as the dominant ion possess these high swelling characteristics, although the possession of this dominant ion is definitely not the only factor. Table III shows that the dominant exchangeable cation in bentonite is calcium and that the total exchange capacity for the cations tested is approximately 25 milli-equivalents per 100 grams of clay. Grim (21) states the total exchangeable cation capacity of these bentonite clays range from 80 to 150 milliequivalents per 100 grams of clay. Since the sodium ion was not tested, it is safe to say that the difference between the tested value and the quoted value is the quantity of exchangeable sodium ions. Grim (21) notes that the swelling bentonites are extremely sensitive to phosphate ions, their presence usually causing immediate flocculation. Table II shows the chemical analysis of South Dakota bentonite as taken from Grim (21).

O'Keefe Creek Bentonite

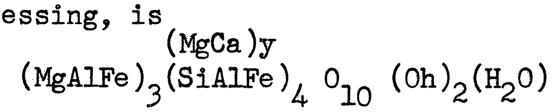
According to Grim (21), "The cause of the variation in properties fundamentally resides in the composition of the montmorillonite itself and in the character of the exchangeable ions." This material is almost the same in appearance as the South Dakota bentonite except it appears to contain a small amount of noncolloidal material. The sample was taken from a deposit found in the O'Keefe Creek drainage approximately 10 miles northwest of Missoula, Montana. No chemical analysis was readily available for this material but since it is a montmorillonite clay it may be safe to assume that the chemical analysis and plate structure are the same or nearly the same as that of the South Dakota bentonite. Only a slight difference is observed in the cation analysis contained in Table III.

One sample of clay was oven-dried before grinding in a ball mill and screened through a -140 mesh screen. Another sample of clay was treated in the same manner except that it was air-dried. It was found the oven-dried material would not swell and in order to produce a good suspension it had to be flocculated, using calcium chloride ($CaCl_2$) or an excess of sodium chloride ($NaCl$). The air-dried material mixed with water to form a thixotropic gel, although substantially larger quantities of clay were required than with the South Dakota bentonite. Since the difference in drying was the only difference in treating the two samples, it must be assumed that the crystal lattice of the clay was permanently collapsed to some degree. Grim (21) states that collapse of some montmorillonite clays occurs after heating from 105° C. to 125° C.

Vermiculite

The three forms of vermiculite used were furnished by the Zonolite Company of Libby, Montana. All three forms, exfoliated number 4, papermaker flake (PMF) and the micronized vermiculite will be briefly discussed after the general discussion of the vermiculite ore.

Vermiculite is a micaceous, odorless and tasteless mineral which exfoliates when subjected to heat or certain chemicals. The general structural formula for the ore, which remains relatively unchanged except for water content through processing, is



$$(\mathrm{MgAlFe})_3\overset{(\mathrm{MgCa})y}{(\mathrm{SiAlFe})_4}\,\mathrm{O}_{10}\,(\mathrm{Oh})_2(\mathrm{H_2O})\ x.$$ (8)

Vermiculite which is insoluble in water is a member of the montmorillonite expanding lattice group of clays possessing a 2:1 lattice structure (21). The structure consists of two silica tetrahedral sheets bonded to a central sheet of divalent ions mainly Mg++ in octahedral arrangement. The platelets carry net negative charges due to partial substitution of trivalent aluminum ions for tetravalent silicon ions in the tetrahedral sheets balanced by charged cations (Mg++ and Ca++) between the platelets (8), which are loosely held thus explaining the high cation exchange capacity of 100 to 150 milli-equivalents per 100 grams (21). Note that Table III states the total analyzed exchangeable cations of number 4 vermiculite as 14.3 milli-equivalents per 100 grams of material which agrees with other literature (8).

The vermiculite ore loses its water in three stages: 48 percent is lost just below 100° C. which is unbound water, 25 percent is lost from 250° C. to 400° C. and 27 percent is lost from 600° C. to 850° C. An endothermic peak accompanies the first water loss (50) as well as a contraction of the crystal lattice (10). Rehydration takes place almost instantly after cooling, if the heating process does not involve temperatures over 550° C. Ability to rehydrate is completely lost above 700° C. (50). When vermiculite is heated abruptly to 300° C. exfoliation occurs (8).

The principal difference between vermiculite and bentonite, which is also the montmorillonite group possessing many of the same properties, is that the lattice structure of vermiculite expands under the influence of water to accommodate only two layers of water molecules, while that of bentonite expands to accommodate many layers of water molecules. Table II shows the chemical analysis of the vermiculite as taken from the Zonolite Company's publication. (8).

Exfoliated vermiculite is manufactured by the rapid heating process mentioned and ground to the desired size. The number 4 variety has a bulk density of from 8 to 12 pounds per cubic foot and a particle size of -16 mesh. It has very good insulating qualities if a continuous sheet can be formed. The number 4 exfoliated vermiculite is used as a chemical carrying exfoliated vermiculite.

Paper makers flake vermiculite (PMF) has a mesh size of -80 and a bulk density of approximately 30 pounds per cubic foot. The material is light tan to gold in color. The PMF has a very high ability to form a strong cohesive bond.

The micronized vermiculite has an appearance much like PMF except that it is slightly darker in color and has a mesh size of -325. Bonding action by this material is not as strong as the PMF but appreciably stronger than the bonding qualities of the number 4 exfoliated variety.

Airport Clay

This material is actually a silty clay which was deposited on the bottom of Lake Missoula. The clay, as it is commonly but erroneously known occurs in deposits in depths up to 150 feet. The sample used was obtained in the immediate vicinity of the retardant mix plant at the U. S. Forest Service Aerial Fire Depot at Missoula, Montana. After air-drying the material was ground in a ball mill and screened through a -140 mesh screen. The powdered "clay" appeared reddish in color. Table III includes the partial cation analysis of the sample used for mixing.

Sodium Hexametaphosphate

This chemical was used as a wetting agent in order to test the effects of "wet water" mixed with sodium calcium borate and South Dakota bentonite. It is a fine, white, crystalline chemical which is soluble in water. "Calgon" is the trade name for sodium hexametaphosphate; which has the approximate formula of Na_3PO_4.

Monoammonium Phosphate

Monoammonium phosphate- $\underline{NH_4H_2PO_4}$, is a strong dehydrating agent widely used in agriculture as ammonium phosphate fertilizer. Only one ammonium radical is attached to the phosphate radical in the monoammonium variety. The particular material used consisted of 61 percent phosphate and 11 percent ammonium. This chemical is commonly known as M.A.P.

Diammonium Phosphate

Diammonium phosphate $(NH_4)2H_2PO_4$, is a dehydrating agent the same as monoammonium phosphate except that two ammonium radicals are attached to the phosphate radical. This chemical is relatively unstable compared to the monovalent variety. The commercial grades of both these chemicals are specifically manufactured for use as fire retardants.

CHAPTER V

TESTING EQUIPMENT AND PROCEDURES

The discussion of the equipment used and the procedures followed are covered in three categories: preliminary tests, water retention tests and burning tests. Preliminary tests included cation analysis, mixing characteristics, specific gravity, pH, viscosity and adherence-to-vegetation tests. The water-retention tests, which determined the water holding characterisitics of the slurries, was separated from the burning tests, although it was done in conjunction with the burning. The burning tests included time of ignition, resistance to burning and intensity of burn, all of which were essentially parts of one test and so are discussed in one section.

PRELIMINARY TESTS

Cation Analysis

A cation analysis of the dry retardants was conducted using the lumetron light transmittancy meter according to the procedures outlined by Holmes (27). The concentration in parts of calcium, magnesium, potassium, manganese and iron per million parts of solution were determined and converted to exchangeable cations in milli-equivalents per 100 grams of dry retardant which are shown on Table III. The presence of sodium was not included in the tests.

Mixing Characteristics

The materials were mixed approximately 4 hours prior to conducting the burning tests. The slurries were mixed in a 2,000-milliliter flask using a 2,000-revolutions-per-minute electric drill fitted with a 12-inch steel shaft, to the end of which was attached a 2¼-inch diameter three-bladed propeller. Prior to mixing, all materials were weighed and measured in the metric system in the proper proportion for 1/2 gallon of water. Materials which were to be used in combination were blended, prior to mixing with the water. All of the solutions were mixed for approximately 10 minutes. Objective measurements of the relative ease of mixing and tendency to lump were made for each mix. The expansion of the mixed slurries was also observed. The water used for mixing was obtained from the U. S. Forest Service Aerial Fire Depot, 6 miles west of Missoula. This particular water is pumped from a well and has a total hardness of 142 parts per million as of December 1, 1955 and is not chlorinated. Flocculation occurred much more readily in this water than when using Missoula city water which has a total hardness of only 27 parts per million and is chlorinated at the rate of 4.15 parts per million. Table I includes a complete chemical analysis of the Aerial Fire Depot water. All slurries were in such a state of viscosity that they could be pumped and dropped with ease at the time the burning tests were made.

Specific Gravity

The specific gravity of the slurries was determined by the use of a 1,000-milliliter volumetric flask of a predetermined weight. The weight of 1,000 milliliters of well-agitated slurry was determined and compared to a base weight of a 1,000 milliliters of water which weighed 1,000 grams giving a specific gravity of 1.000. No correction for temperature or pressure was made. The specific gravity of all the slurries was determined, from which the weight per gallon of slurry was calculated by multiplying the specific gravity of the slurry by 8.34 which is the weight of a gallon of water. This characteristic is very important, determining the logistics of the operation as well as having quite an effect on the manner of dispersion and canopy penetration.

pH

The pH of the slurries were determined by use of a Beckman electrode pH meter. Corrosive characteristics of a solution are indicated by the numercial variation indicated by the meter when a solution is compared to a neutral solution which has a pH of 7.

Viscosity

The viscosity of the slurry, which determines to a great extent the manner and amount of dispersion while dropping and also the manner of spread after striking the ground was tested. A 5-milliliter pipette having a 1/32-inch orifice and controlled by use of a rubber control valve was used for the test. The slurry was first agitated, 5 milliliters were then drawn into the pipette from a point 2 inches below the surface of the slurry. The time in minutes for the 5 milliliters of slurry to vacate the tube was clocked using a stopwatch graduated in minutes. This process was repeated 5 times the mean of which was converted to show the volume of flow in milliliters of slurry per minute. The viscosity of the slurries is shown on Table IV.

Adherence to Vegetation

Adherence to vegetation was visually tested as was the ease of mixing. Green, freshly cut coniferous branches and deciduous leaves were dipped in the slurries and allowed to dry. Tendency to crack and the type of coating upon drying was noted. It may be emphasized that the results of these objective tests depend only on individual judgment. Results of field drops may be markedly different due to the difference in method of application.

Water Retention Test

This test was carried out in conjunction with the burning tests but since it was a different test it will be described separately. Ponderosa pine (Pinus ponderosa) sapwood dowels, 7½ inches long by ½ inch in diameter with a screw-eye inserted in one end were used for this test. Four dowels were used to test the water retention ability of each slurry. The dowels were oven dried for 24 hours at 103° C. and weighed on a Mettler electric balance. The dowels were then dipped in the slurry, weighed and immediately put into an oven set at a temperature of 50° C. The dowels were removed after 5 hour intervals, allowed to cool to room temperature, weighed and returned to the oven. When the dowels had been removed after the fifth hour of drying and weighed, they were inserted in an oven at temperature of 103° C. for 19 hours after which they were removed and weighed for the last time. The dowels were considered to be oven-dried after this last drying period; therefore it was assumed that any additional weight consisted of solid material which the slurry had held. The percent weight of the slurry was calculated after each hour of drying up to the fifth hour and after the additional 19 hours of drying at 103° C.

BURNING TESTS

Ignition and Fire Intensity Tests

Some difficulty was experienced in finding a test which could give reliable and reproducible results when testing the ignition and fire intensity of burning dowels pretreated with each of the slurries. An open hood was first tried, the treated dowels were placed horizontally over a blue, Bunsen burner flame 6 inches high. Groups of 15 dowels were weighed and treated collectively but burned individually. Variable results were obtained because of the effect of even very small changes in room air currents, wood variation and changes in gas pressure. Another variation of the same test was tried in which the dowels were placed at a 45 degree angle and only one end exposed to a protected flame. Both of these tests produced very erratic and nonreproducible results.

It was concluded that the variations in results were due to the following:

1. Variation in dowel exposure to the gas flame, caused by wavering of the unprotected flame by room air currents.
2. Variation in wood density and pitch content which caused variation in the intensity of burning and variation in the amount of slurry adhering to the dowel when treated.
3. Variation in main line gas pressure.
4. Variation in amount of slurry picked up by the treated dowels and a smaller variation in the viscosity of the slurry picked up. A thickening effect seems to occur gradually in the slurry as more dowels are treated. It appears as if more water is absorbed and adsorbed in proportion to the amount of solid material which is

adsorbed and therefore, the slurry is gradually thickened.

By modifying the fire tube (47) (35) presently in use at the Forest Products Laboratory at Madison, and the tube used by Suggit and described by Markwardt (35) it was felt that the effect of the air currents in the room could be minimized. The fire tubes mentioned above were modified mainly by cutting the length of the tube to 18 inches, reducing the tube diameter to 1¼ inch, and omitting the balance arm. (See Plates 1 and 2 for detail.) The experimenter was reluctant to use a fire tube test because it was thought to be more desirous to expose the longitudinal treated surface of the dowel as occurs in the fire tube.

Variation of wood was eliminated to a great degree by having all of the dowels cut from only one Ponderosa pine sapwood plank.

The problem of gas variation was alleviated by placing a manometer in the gas line. The manometer was not a constant-flow type but merely an indicator type from which the gas pressure could be observed and thus corrected by adjustment of the main line valve.

The variation in the concentration of slurry was reduced to some degree by the use of a larger treating chamber. Initially a 100-milliliter graduated flask was used which was replaced by a 2000-milliliter flask. The diluting effect was still present but was substantially reduced in the greater volume.

A hygrothermograph (not shown in Plate 1) was calibrated and located adjacent to the fire-tube apparatus in order that variations in humidity and temperature could be observed. Temperature remained within the range of 70± 5° F. while the relative humidity remained within the range of 25± 5 percent.

The muffle furnace test for ignition as described in (3) was not thought to be a practical test for determining the ignition delay due to various treatments unless a pilot flame was used which was not available for these experiments. It was thought that a muffle furnace test would show only the resistance to ignition by radiation which although of some importance, this experimenter thought it to be of a secondary nature to ignition tests in the presence of a flame. Sources reported by Browne (12) state that the minimum rate of heating for ignition with the use of a pilot flame is approximately 0.3 calories per square centimeter per second while ignition without the use of a pilot flame requires a rate of heating of approximately 0.6 calories per square centimeter per second. The difficulties of free access of oxygen to the sample and temperature stabilization are likely to be encountered if the muffle furnace available was used.

The procedure followed in conducting the burning study was as follows: the ½-inch Ponderosa pine sapwood dowels were cut to a length of exactly 7½ inches using a prebuilt jig on a bandsaw. The dowels were then fitted with a No. 10 screen hook inserted so that 3/4 inch was exposed. Twenty-eight dowels were then oven-dried for 24 hours at a temperature of 103° C. The dowels were removed from the oven and allowed to cool to room temperature during which interval the slurry to be tested was agitated in order to obtain a more homogeneous dispersion of solids. Each dowel was then weighed (all weights being recorded to two decimal places), dipped quickly in the slurry and weighed again. All the dowels with the exception of four were placed in an oven and dried at a temperature of 50° C. The four dowels which were not placed in the oven were burned immediately in the fire tube. Four of the remaining 24 dowels were used for the water retention test and were treated as is described in that section. Four of the remaining 20 dowels were removed from the oven each hour, allowed to cool, weighed, and burned in the fire tube. This step was done 5 times so that relative rates of burning could be determined for dowels that were burned immediately after treating and for dowels that were burned 1 hour, 2 hours, 3 hours, 4 hours and 5 hours after treating. Each retardant was treated in this manner with the exception of the water-treated dowels which had a stabilized moisture content after drying 3 hours and the test was concluded.

The description of the apparatus and actual burning procedure is as follows: the fire tube consists of an 18-inch by 1½-inch steel tube open at both ends. A 1-7/8-inch pyrex tube was tried so that better observations could be made but the temperature differentiation between the top and bottom of the tube was too great and the tube shattered on the first trial. (Vicor tubing was recommended but was not readily available for these experiments.) Twelve 1/4-inch holes were drilled starting at a distance of 6 inches from the bottom and placed 1 inch apart, between centers. Holes were bored in each quadrant at the same level as the lowest hole. A 1/4-inch hole was also bored at the back of the tube 1/4 inch from the top. The thermocouple of porcelain-covered No. 16 wire was inserted into the hole in such a manner that the end of the thermocouple was located 1/2-inch from the wall of the tube. The heavy-duty model No. 324 pyrometer used in conjunction with the thermocouple was fastened to a stand adjacent to the tube. A stopwatch graduated in minutes was clamped immediately below the pyrometer. A Meker burner was placed in such a manner that its top was located 2 inches below the bottom of the tube. The underside of a 3-inch ring clamp was clamped 1/4 of an inch above the top of the burner. A valve was placed in the gasline immediately adjacent to the burner so that it could be cut off abruptly. A 4½-inch squirrel-cage fan turned by a 1/20-h.p. electric motor at 1600 revolutions per minute provided a more pronounced draft through the tube and served as a means of eliminating the smoke from the room. (See plates 1 and 2.) A dowel holder as shown in plate 2 was formed from No. 12 wire in such a manner that when hanging in the tube the bottom of the dowel was 9¼ inches from the top of the tube. When using the fire tube the temperature at the top of the tube was stabilized at a temperature of 300° C. by adjusting the needle valve at the bottom of the burner. When the temperature at the top of the tube was adjusted to 300° C., a blue-orange-tipped flame was barely visible at a point 6 inches from the bottom of the tube and approximately 3 inches below the bottom of the dowel. When these conditions were satisfied the temperature at the bottom of the dowel closely approximated 620° C.

When burning the dowels the burner was ignited, the stopwatch zeroed, and the temperature at the top of the tube stabilized at 300° C. The stopwatch was started at the instant the dowel was inserted in the tube. The time of ignition, observed through the holes in the tube, was recorded at the first appearance of yellow flame. Usually a small blue flame appeared first, but since it was thought that this was only the ignition of the combustible volatile materials expelled from the dowel and actually did not occur immediately near the surface of the dowel, the appearance of yellow flame was used as the criteria of ignition.

Temperatures registered on the pyrometer, were read and recorded at $\frac{1}{4}$-minute intervals from the time of dowel insertion in the fire tube until the highest temperature reached was noted. The dowel was allowed to burn in the tube for exactly 1 minute at which time the gas flame was extinguished by shutting the gas supply off. The pre-weighed glass cover dish was then placed on the ring clamp between the burner and the bottom of the tube in order that any flaked retardant and burned wood could be saved for weighing. The duration of burn is recorded as the total elapsed time from the initial insertion of the dowel in the fire tube until no flame is visible on the dowel.

The reader must realize that these tests were actually quite severe in nature. The intense heat, the furnace effect of the fire tube and the added draft supplied by the fan, all contributed to a test of fire intensity the severity of which would be only rarely duplicated in the field.

CHAPTER VI

PRESENTATION OF DATA

In order to facilitate graphical presentation of the data the treatments were divided into two equal classes. Class I retardants are classed as those retardants which prohibit the heat from a burning dowel from raising the temperature above 475° C. during exposure in the fire tube for $1\frac{1}{4}$ minutes. Class II retardants are classed as those retardants which allowed the heat from a burning dowel to raise the temperature above 475°C. after exposure in the fire tube for $1\frac{1}{4}$ minutes. This method of classification divided the 14 retardants into two groups of seven each. An exact definition of the two classes is given in the explanation of appendix.

Preliminary Tests

The results of the preliminary tests shown on tables III and IV are self explanatory except for the figures in the columns of table IV headed "Ease of mixing and adherence to vegetation" which were derived from observational measurements only. A scale of 0 to 10 was selected in each case so that the qualities could be compared. A small number denotes that mixing is relatively difficult or in the case of the adherence to vegetation column, a low number denotes poor adherence. High numbers in these columns indicate relative ease of mixing or good adherence to vegetation. The explanation of appendix includes the qualitative equivalents of the numbers.

Water Retention Test

The weight in grams of the treated dowels and the weight of slurry in percent of the weight of the dry dowel for each hour of drying was calculated. These values are shown in tables V and VI. Graphs 1 and 2 show the percent weight of slurry which adhered to the slurry when dipped and after each hour of drying. The last column of the tables shows the weight of solid material in grams carried by the slurry while the last point plotted on the graphs indicates the weight of solid material carried by the slurry in percent of dry wood weight.

Ignition Delay

The mean time of ignition of four dowels treated with each retardant and burned after different drying times is shown in table VII. Graph 3 and 4 contain the plotted values of the mean ignition time of class I and II retardants respectively. Note the wide range of values for each retardant and the wide range between the two classes at short drying times. As is to be expected the ignition delay varies inversely as the drying time and the values in both classes tend to be confined to a narrower range.

Intensity of Burn

Tables VII and X and graphs 5 and 7 show a composite comparison of mean $\frac{1}{4}$-minute temperatures emitted from burning class I and class II retardant treated dowels respectively, immediately after treating. Tables IX and XI and graphs 6 and 8 show the temperature comparisons of the two classes of retardants when they are dry. The temperatures plotted for the wet curves were the mean of the four temperatures emitted by dowels which were burned immediately after treating. The temperatures plotted for the dry curves were the mean of all the temperature emitted by all the dowels in each treatment which were burned after the hourly intervals of drying during which less than 1 percent per hour weight difference was recorded. Again the outstanding factors were the wide range of curves between the two classes as well as between the individual treatments when wet and the extreme narrowing of the range when the slurries were dried.

Each of table XII to table XXV, inclusive and graphs 9 to 22 inclusive shows the mean $\frac{1}{4}$-minute temperature of dowels treated with each retardant tested. The difference between the maximum and the minimum of all the temperatures from which the plotted mean was determined, as well as the plotted mean are shown on the tables facing the graphs. From these graphs the difference of temperature profiles due to the effect of drying can be determined. Again in plotting these graphs the criteria of less than 1 percent moisture loss per hour of drying was used to classify a slurry as being dry. The dry curve is a mean of the temperatures obtained by burning the treated dowels which have been dried for the various times indicated on the temperature profile. These curves are indicative of the relative ability of the retardants to resist burning while exposed to the heat source and also their ability to retard burning after they have been ignited and the heat source removed. The temperature curves plotted up to the 1-minute point are indicative of resistance to burning while exposed to the heat. The part of the curve after the 1-minute point indicates the retarding ability of the slurry after burning has been established. It must be noted that these dowels were burning under very severe burning conditions, i.e., maximum fuel exposure, approximately a 5-mile-per-hour wind from the fan, and the furnace effect of the fire tube.

The drops in temperature at the 1-minute point are indicative of a good retarding effect while the initial drop in temperature indicates a good resistance to burning. For the purpose of this study, resistance to burning is defined as the effect of a slurry upon the ignition and rate of combustion of a sample while exposed to the heat source. The retarding ability is defined as the effect of a slurry upon the rate of combustion of a sample after the heat source has been removed. The explanation of appendix includes an explanation of the symbols and forms used in the graphs. The mean temperature values of burning untreated dowels are also shown on graphs 9 and 22. As stated in the section dealing with testing only the rise to peak temperature was recorded.

Resistance to Burning Index

Table XXVI shows the resistance to burning index of each retardant for each period of drying and for dry retardants. The index is calculated by planimetering the area under each curve shown in graphs 9 - 22, inclusive up to an exposure time of 1 minute. The dimension of the total area was considered to be from the 0-minute point to the 1-minute point on the X axis and from the 0-minute point up to 550° C. point on the Y axis, thus the total area was 12 square inches. The total area under the untreated curve was measured by use of a planimeter and found to be 8.2 square inches. The index is determined by use of the following formula:

$$I = \frac{\text{Area under untreated curve - area under treated curve}}{\text{Area under untreated curve}} \text{ X } 100$$

The values obtained by this equation are a measure of the resistance to burning of treated dowels calculated on the basis that untreated dowels have no resistance to burning, thus having an index value of 0. The range of values is from 0 - 100, with the higher values indicating the better resistance to burning.

The figures shown in tables XVII and XVIII appendix are the mean values of the results by the weighing procedure outlined in the section dealing with the burning tests. The dry weight is the weight of the dowels after being oven-dried, the preburn weight is the weight of the dowel plus the weight of slurry remaining on the dowel for each indicated time of drying.

The percentage weight of slurry is the weight of slurry in percent remaining on the dowels after drying for the indicated times, which is calculated as follows:

$$\frac{\text{Preburn weight - dry weight}}{\text{Dry weight}} \times 100$$

The percentage weight of water is the weight of only the water in the slurry at the indicated times of drying not including the weight of solid material and is calculated as follows:

$$\frac{\text{Preburn weight - (dry weight + weight of solid)}}{\text{dry weight}} \times 100$$

The percentage weight of wood lost while burning is calculated by determining the difference between the dry weight and the postburn weight of the dowels and the weight of solid material in the slurry as follows:

$$\frac{\text{Dry weight - (Postburn weight - weight of dry material in slurry)}}{\text{Dry weight}} \times 100$$

Duration of Burn

According to McNaughton and Van Kleek (35) a short duration of burn may result from either a specimen that is so combustible that it is consumed in a short time or from a specimen that is so thoroughly fire retarded that it simply will not burn. Interpretation of duration of burn must be done with caution. Retardant treatings which delay ignition for long periods may show a longer duration of burn than specimens which ignite readily.

The duration of burn was determined and recorded according to the procedure outlined in the section dealing with the burning tests. The reader must note that duration of burn is recorded as the elapsed time from when the dowel was first inserted in the fire tube until such time as no visible flame was apparent. This time was used instead of actual burning time because the wood loses weight when subjected to high temperatures even if ignition has not occurred, although at a much slower rate than after ignition has occurred.

There was very little difference in percent of wood lost while burning due to difference in drying times although a marked difference was observed when comparing the different retardants (see tables XXVII and XXVIII appendix). When a rate of percent of wood loss is calculated by dividing the calculated percent weight of wood lost by the time of exposure in the tube, a very noticeable difference is apparent. The rate of weight loss while burning is a fairly reliable measure of intensity of burn, and is more indicative than merely a measure of total loss in weight (49).

The percent of weight loss per minute as a function of drying time is shown on graph 23 appendix for class I retardant-treated dowels and on graph 25 for class II retardant treated dowels. Actual values are shown in tables XXVII and XXVIII, respectively. From these graphs it is apparent that quite a range in the rate of weight loss occurs when the period of drying is short, i.e., the dowels are wet. This difference decreases as the time of drying is increased and the lines tend to congregate in a narrow range. It is also apparent from these graphs that the difference in percent weight loss per minute for each hour of drying decreases as the time of drying increases, thus the curves tend to level off.

Analysis of Regression and Correlation

The dependence and association of the rate of weight loss in percent on the weight of slurry in percent is shown for the class I retardants on graphs 24 and for class II retardants on graph 26 appendix. By means of the least square method the regression coefficient and the correlation coefficient were calculated. The standard error of the estimate was also calculated in order to check the accuracy of the sampling.

The regression coefficient, "b", is a measure of the rate of change in the dependent or Y variable (percent weight of wood for a given change in the independent or X variable - percent weight of slurry). The numerical value of "b" which can range from 0 to a whole number is a mathematical expression of the slope of the line. As the steepness of the line increases the value of "b" also increases either in a positive or negative direction indicating a greater degree of negative or positive dependence of Y upon X. The following equation was used in order to calculate the regression coefficient:

$$b = \frac{\text{Sum } XY - \dfrac{\text{Sum } X \text{ Sum } Y}{n}}{\text{Sum } X^2 - \dfrac{(\text{Sum } X)^2}{n}}$$

The correlation coefficient, "r", is a measure of the degree of association between the X and Y variables. A wide scattering of points through which the line is plotted will show a low value for "r" while a close grouping of points along the plotted line will result in a high value of "r". The value of "r" which may be positive or negative showing either a positive or negative correlation is limited to a range of from +1 to -1 and is calculated by the following equation:

$$r = \frac{\dfrac{\text{Sum } XY - \dfrac{\text{Sum } X \text{ Sum } Y}{n}}{n}}{\sqrt{\dfrac{\text{Sum } X^2 - (\underline{\text{Sum } X})^2}{n} \qquad \dfrac{\text{Sum } Y^2 - \left(\dfrac{\text{Sum } Y}{n}\right)^2}{n}}}$$

The standard error of the estimate or SE_e is a measure of sampling accuracy and indicates the positive or negative fluctuation in units of Y, that can be expected by the plotted line. The value of SE_e is calculated from the following equation:

$$SF_e = \pm \sqrt{\left(\frac{\left[\text{Sum } Y^2 - \dfrac{(\text{Sum } Y)}{n} \right] \left[\dfrac{\text{Sum } XY - \text{Sum } XY}{\text{Sum } X^2 - \dfrac{(\text{Sum } X)}{n}} \right]^2}{n - 2} \right)}$$

These three values are shown for each slurry on graphs 24 and 26. The fire retarding qualities of any slurry can be determined by observing its particular regression line.

The value of X opposite the low end of the line indicates the percentage weight of slurry adhering to the dowel when treated, and the value of X opposite the high end of the line indicates the percentage weight of slurry adhering to the dowel after 5 hours of drying. The value of Y opposite each end of a line indicates the maximum and minimum ability of that slurry to reduce the intensity of burning. The slope of the line indicates the variation in burning intensity as effected by a change in percent weight of slurry. A steep line indicates that a slurry may substantially reduce burning intensity when wet but loses its effectiveness while drying, whereas a level or near level line indicates that drying has a relatively small effect on the difference in retarding qualities. The position of the line relative to the other lines indicates the relative ability of that slurry to reduce the burning intensity of treated dowels at the varying stages of dryness.

CHAPTER VII

DISCUSSION OF RESULTS

This discussion of the characteristics of the fire retardant deals primarily with the fire retardant qualities of the mixes tested. Since a discussion of this sort involved comparisons of the relative value of each retardant they will be dealt with in groups determined by the content of the mixes. The numbers preceding the mixes in each group accompany the particular slurry throughout the discussion. All suppositions and explanations included in this discussion are at present mostly conjective based upon observation of the test described. Further experimenting and testing are necessary in order for them to be stated as facts.

Sodium Calcium Borate

This retardant was used in three different slurries all of which were class II retardants. The following ratios in pounds of additives per gallon of water were used:

Class	Slurry No.	Description
Class II	1	Four pounds of sodium calcium borate plus 1/10 pound of Calgon (wet water).
Class II	2	Four pounds of sodium calcium borate.
Class II	9	Two pounds of sodium calcium borate plus 1/2 pound of South Dakota bentonite.

Slurry No. 1 is the same as slurry No. 2 except for the addition of 1/10 pound of Calgon which is a dispersing or wetting agent. Some use has been made of "wet water" mixing especially in areas where exceptionally hard water is used for mixing. The use of 1/10 of a pound of wetting agent per gallon of water is far above that amount which would normally be used but the intent was to emphasize any differences which may occur. This addition of Calgon made mixing just slightly easier. Although small areas of definitely flocculated, colloidal material were congregated around isolated particles of undissolved Calgon, these areas dispersed when blended into the slurry. This is in agreement with the literature (21) (41) which states that an excess of dispersant will cause flocculation. After sitting for 2 hours this slurry had settled, leaving approximately 3/4 inch of clear water on its surface. At this time it was also considerably less viscous than slurry No. 2. After a period of 2 weeks slurry No. 1 was fully dispersed and more viscous than slurry No. 2. This slurry had approximately 1/2 the water-holding capacity of slurry No. 2. The fire retardant properties of these two slurries will be discussed shortly.

Slurry No. 2 has been used extensively as a fire retardant in this ratio (3) (5) (37) (38). This retardant is very easily mixed, only a very slight tendency to lump was noticed which was easily dispersed by mixing. According to (6) this retardant forms a thixotropic suspension, although if such, in the opinion of this experimenter, it is a very weak thixotropic gel. Within 2 hours after mixing this slurry had settled leaving approximately 3/4 inch of clear water on the surface. This mix ratio of 4 pounds to a gallon of water makes approximately 1-2/10 gallons of slurry, the weight per gallon of which was found to be 9.78 pounds. This figure is not in agreement with the figure of 10.1 pounds per gallon stated in the literature (6) although it is noted in this publication (6) that discrepancies may occur. This slurry can generally be classed as having excellent mixing, dropping, dispersion, and vegetational-adhering characteristics, although it is relatively costly, abrasive, and toxic to plants as well as being rather ineffective as a retardant. This slurry has very poor water-adsorbing and holding qualities, the dowels were essentially dry after one hour of drying. Some cracking was noticed after prolonged drying.

Slurry No. 9 was tested mostly in order to satisfy a number of suggestions from interested people. It was hoped that the combination of the two retardants would complement the favorable properties of each. According to the tests it appeared as if the effect of the bentonite were almost completely nullified since the slurry showed nearly the same characteristics of sodium calcium borate mixed on a ratio of 3 pounds to the gallon. Water retention was poor although not as poor as slurry No. 1, mixing was relatively difficult but definitely easier than when mixing bentonite alone. The ignition delay afforded by this slurry was one of the longest of all the class II retardants while the resistance to burning index for this retardant was nearly average for this class. The burning intensity of dowels treated with this slurry was also nearly the average curve for a class II retardant. From the regression line shown on graph 26 and the regression coefficient this slurry was quite dependent on its moisture content for its fire retardant ability.

Slurry No. 1 was one of the poorest of the class II retardants. It had a high intensity of burn indicated by the steepness of the temperature curve on graph 9; it had a low resistance to burning index also shown on graph 9 by the abrupt rise in temperature from which the value of 38.41 shown on table XXVI is calculated. Water afforded a value of 34.75 for the resistance to burning index. Slurry No. 1 also showed the greatest change in burning intensity with a change in slurry moisture content. The excessively high peak temperatures shown by the temperature curves for dowels treated with the poorer retardants appear to be in error since the peak temperatures shown are higher than the peak temperatures shown for untreated dowels. This can be explained by a theory of controlled burning versus free burning. The untreated dowel is burned so rapidly, indicated by the almost vertical temperature gradient, that some portion of the combustible materials, mostly volatile in nature, are expelled from the dowel and out of the fire tube before their ignition can occur. Since these materials are not ignited their heat content is not contributed to the total heat and a peak temperature occurs which is lower than one would expect. A dowel coated with a poor retardant also burns very rapidly after the initial delay which, in some cases is very short. However, free egress of volatile materials from the dowel is impeded to some degree by even the poorest of retardants. Assuming this to be, it can readily be seen that more complete combustion of volatile materials can occur in the case of poorly retarded dowels, contributing more of the heat content of these volatile materials to the total amount of heat and a high peak temperature occurs.

The fire retarding ability of slurry No. 2 was in every test except the ignition test, better than that of slurry No. 1. Generally speaking this slurry was the better retardant of all the class II retardants and in some tests was better than some of the class I retardants. This slurry left almost double the weight of solids on the treated dowel which probably accounted for its good resistance to burning, according to table

XXVI, when wet the resistance to burning index was 75.00 and when dry it was 27.44. Once pyrolysis has commenced this slurry has very little retarding action as indicated by the profile on graph 10. This slurry caused a long ignition delay when wet (.59) minutes) which was reduced to .24 minutes after 1 hour of drying. A regression coefficient of .446 indicates relatively little dependence of retarding ability upon water content.

It seems odd that slurry No. 1 which initially picks up less water and carries less solids has a longer ignition delay than does slurry No. 1 after the 1-hour drying period. The possibility of error seems remote due to the consistency of the apparent reversal, although since four dowels were burned at each hour it is apparent that the difference of .02 minutes is certainly not significant. Three suppositions may be considered; that the Calgon is a fire retardant; that the water held by slurry No. 1 is held much tighter than the water held by slurry No. 2 and thus more heat is needed to expel it from the slurry; and that the manner of drying of the smaller quantity of material adhering to dowels treated with retardant No. 1 forms a coating which resists ignition better than the coating formed by slurry No. 2. The first supposition can be discarded for two reasons: it is doubtful that the concentration of Calgon was great enough to make a noticeable effect even if it is a fine retardant and also Calgon is a dehydrating agent and as such would shorten ignition time rather than increase it. The second supposition can also be discarded for two reasons: according to graph 2 and table VI the rate of water loss is approximately the same for the two mixes and since a wetting agent reduces surface tension "wet water" can be evaporated with less energy than is needed to evaporate plain water. This is due to the reduction in surface tension caused by dispersing or wetting agent. It can be argued that the more rapid evaporation would cool the surfaces to a greater degree thus causing the longer ignition delay. This can be repudiated mainly because again there is not a great enough quantity of water involved to make a noticeable difference. The third supposition may have some value. It is believed that the material left on the dowel by the "wet water" slurry deposited mostly smaller particles in opposition to the aggregate of large and small particles left by the plain water. The smaller uniform particles upon drying may have formed a more cohesive and gas-proof coating than the aggregate particles carried by the plain water. Ignition was thus delayed by the inhibition of the free egress of volatile materials from the dowel and the free access of oxygen. This effect was not noticed in the dowels which were burned immediately after treating due to the great difference in water content of the two slurries and also because a gas-proof coating cannot be formed when a slurry is dried by the rapid drying action of flame. This statement will be explained in the discussion of South Dakota bentonite.

One advantage of all the mixes containing sodium calcium borate was that since they dried so rapidly they would all be plainly visible from the air without the use of a coloring agent. For further details the reader is referred to the graphs and tables included in the appendix.

Sodium Trisilicate (Water Glass)

A 40 percent solution of sodium trisilicate made a very good fire retardant. A clear, hard, glossy coating adhered to the dowels upon drying which foamed profusely upon exposure to heat. This chemical was discarded primarily because of the extremely high cost and secondly, because of the difficulties involved in handling it. According to information furnished by a chemical supply firm in Missoula, this chemical can be purchased only in liquid form, in large metal barrels having at least restricted air circulation to prevent drying. The clear glass-like coating formed when dry is very hard and could be removed from aircraft surfaces only with great difficulty. A potential hazard involved with the use of aircraft in application of this chemical would be the rapid buildup, through continuous emergency use, of a thick layer of this glass-like material which could foul the control surfaces and cables in the tail of the aircraft. Serious consideration for use as a ground-applied fire retardant should be given this chemical.

<u>South Dakota Bentonite</u>

This retardant was used in seven different slurries, one of which has already been discussed, the other six will be discussed in this section. Listed below are the combinations used with this retardant and also the ratio of mix in pounds per gallon of water. The class in which each slurry belongs and its assigned number is given.

Class	Slurry No.	Description
Class I	4	Three quarters pound of South Dakota bentonite
Class I	5	Three quarters pound of South Dakota bentonite plus 1/100 pound of Calgon (wet water).
Class I	6	One-half pound of South Dakota bentonite plus one-half pound of No. 4 exfoliated vermiculite
Class I	7	One-half pound of South Dakota bentonite plus one-half pound of PMF vermiculite.

Class	Slurry No.	Description
Class I	8	One-half pound of South Dakota bentonite plus one-half pound of micronized vermiculite.
Class II	10	One-half pound of South Dakota bentonite plus two pounds of airport clay.

All of the combinations in which South Dakota bentonite was used made very good, easily handled slurries. Upon treatment, the dowels adsorbed from approximately 20 percent of their weight in slurry when treated with slurry No. 5 up to approximately 60 percent of the dowel weight when treated with slurry No. 4. Slurry No. 4 was the most difficult of all the slurries to mix. The strong tendency of the clay to swell when wetted caused the formation of globules of wet bentonite with dry powder in their centers. The use of Calgon in slurry No. 5 alleviated this situation only to a small degree. Slurries 6, 7, 8, 9 (discussed under sodium calcium borate) and 10 were all classed as being from a low easy value of 4 to a low very easy value of 7 according to the ease of mixing classification. The ease of mixing was greatly enhanced if the materials were preblended while still dry, this being especially true of the combinations using the varieties of vermiculite. All of the slurries entered a state of thixotropy in from 1/2 to 2 hours after being mixed except the slurries containing the vermiculites. These slurries, Nos. 6, 7, and 8 immediately formed a stable, fluid state that appeared almost like a dispersed state. This was especially true for the slurries mixed with micronized and PMF vermiculite. After standing for a period of 2 weeks, a small amount of separation was noted in these two slurries. Since the bentonite slurries lose their moisture at such a slow rate they must be colored in order to be visible from the air. According to previous unpublished results of burning tests, there was a definite improvement in the retarding qualities of a bentonite slurry which is in a thixotropic state when compared to a bentonite slurry which has not entered this state.

Various authors (41) and (43) report that upon drying the South Dakota bentonite had a tendency to crack and peel away from the fuel. This was noticed during the course of these studies also but it only occurred if the slurry dropped or was placed on a waterproof surface, thus no absorption into the material could occur. None of the treated dowels showed this cracking and peeling when dried. This may be explained by the fact that the dowels were oven dried and thus absorbed most of the moisture from the slurry immediately into the wood.

The dried coatings formed by slurries Nos. 7, 8, 4 and to a very slight degree 5, exhibited when subjected to burning, what this experimenter has called the "jet effect." This effect which became definitely apparent after the dowels had dried for a period of from 2 to 3 hours can best be attributed to the hard, impervious coating formed by these slurries. Upon exposure to the Meker burner flame, the volatile materials were expelled forcibly from the dowels. Unable to penetrate the impervious layer formed by the dried slurry these volatile materials developed a pressure which eventually fractured the coating. These fractures which developed as very fine hairline cracks emitted the volatile materials under pressure. Upon meeting the source of ignition the combustible constitutents of these volatile gases ignited forming a definite jet-like flame which was accompanied by a very audible noise not unlike the noise of a miniature jet engine. This effect was noticed to the greatest degree in slurry No. 7 and to a barely noticeable degree in slurry No. 5. The "jet effect" did not usually occur until after the treated dowels were dried at least 1 hour and was most apparent after drying for 2 or 3 hours. When the dowels which were burned immediately after treating were subjected to heat, the drying process was too rapid; thus the water which was present in the slurry was boiled away leaving a ruptured coating which was not impervious to the volatile materials. After drying for 4 and 5 hours the effect was noticed but was not so conspicuous as the effect portrayed after 2 or 3 hours of drying. The reduced intensity of the "jet effect" after the added drying period was thought to be due to a weakening of the skin caused by reduction of water content below the optimum amount needed to form a very impervious coating. Since there was a shorter period in which the volatile products could build up pressure while developing the cracks as was formerly the case, the volatile products were expelled under a lesser amount of pressure in the case of the weakened coating. The occurrence of the peak temperatures at the 1-minute mark for burning dowels treated with slurry No. 7 and shown on graph 14 coincides with the extinguishing of the gas flame. The peak occurs at this time because the coating afforded by this retardant was so effective in inhibiting the excess of combustible volatile materials from the dowel that only the external heat afforded by the gas flame was great enough to expel these gases. The duration of burn shown on table XVII for dowels treated with this slurry are also exceptionally low.

Powell and Perrine (42) of the Zonolite Company laboratory at Evanston, Illinois, state:

> In the burning tests, it was observed that the PMF and bentonite coating formed did not adhere to the wood after a short exposure to the gas flame. The film was strong enough to buckle and lift itself

from the wood. The coating with the expanded vermiculite [exfoliated] alligatored with the heat but adhered well.

According to the test results reported in this paper, the coatings formed by the slurry No. 4 (bentonite), slurry No. 8 (bentonite, plus micronized vermiculite) and especially slurry No. 7 (bentonite plus PMF) functioned in the opposite manner as stated by Powell and Perrine (42). Proof of the hardness and imperviousness of these coatings was observed during the burning tests. Rather than the retardant coating peeling from the wooden dowel it was the pyrolytic reduction in volume of the wood inside of the coating which separated the retardant coating from the wood. In several cases the wood was reduced to a thin shaft of charcoal which had ruptured itself after burning was complete, leaving a perfectly formed outer shell of dried slurry which was strong enough that it could be handled without sustaining damage. This occurence was observed mostly in case of slurry No. 7 but also in the case of slurries 4 and 8. Again this occurred only after drying for periods of 2 to 5 hours, this is not shown in picture 3 of plate 3. From the preceding discussion it can be seen that South Dakota bentonite when in a thixotropic gel or in combination with the micronized and PMF vermiculites will form a hard, and relatively impervious coating.

Three forms of temperature variation which should be explained are noted when observing the temperature profiles. The first form of temperature variation is the temperature "slump" portrayed by the majority of slurries containing South Dakota bentonite and which occurs at an exposure time of 1 minute. This "slump" corresponds to the time the Meker flame is extinguished. The "slump" occurs because even though the treated dowel has ignited, combustion is not rapid enough to sustain the temperature emitted by the gas flame and the burning dowel. This slump is only temporary but it does indicate that a retarding effect is being exerted on the process of pyrolysis. Only those slurries which carry a relatively large amount of water showed this effect and then only up to the second hour of drying.

The second form of temperature variation occurs immediately upon insertion of the treated wet dowel in the fire tube. All treated dowels and even the untreated dowels caused an immediate drop in temperature which was regained prior to the first temperature reading which was taken at an exposure time of 1/4 minute. This was obviously caused because of the immersion of the cold dowel into a chamber of stabilized temperature.

The third form of temperature variation also occurs immediately upon insertion of the treated wet dowel in the fire tube. Some of the dowels, however, caused a sustained drop in temperature which did not start to increase until active pyrolysis commences at which time the rise is usually very rapid until peak temperature is attained. This temperature variation appears to be associated with those slurries which release nearly all of their water during the first hour of drying, although slurry No. 8 is an exception to this generalization. The sustained immediate drop shown by slurry No. 12 is believed to be a combination of relatively easy water release along with the exceptionally large quantity (1.06 grams) of solid material which is carried by this slurry. Because of this temperature drop the resistance to burning index shown on table XXVI must be interpreted with care.

Generally speaking, slurries which contain a combination of vermiculites and South Dakota bentonite or the bentonite alone, if in a thixotropic gel, were the best of all the slurries tested. As shown by the tests, they have the capacity to carry relatively large quantities of water which is released comparatively slowly; they rank high according to the resistance to burning index; they promote long ignition delays; they have a good retardant effect on active pyrolysis and they have low regression coefficient values indicating that their ability to form a hard coating plays some part in the retarding of pyrolysis (note slurry No. 7 on graph 24).

The effect of mixing Calgon (wet water) with the bentonite was nearly the same as when Calgon was mixed with the sodium calcium borate slurry, a reduction in water retention, and all fire retardant qualities, including ignition delay occurred. In this case of the bentonite slurry mixed with wet water the difference in water content at each drying period was so great, when compared to the plain water mix that the water overshadowed any subtle effects that the Calgon may have had on ignition delay.

Slurry No. 10 rated high on the resistance to ignition index when burned immediately after treating but rated low when dry. This slurry, although not the poorest of the retardant tested does not warrant further consideration since the cost of processing the material is not thought to be justified by its retarding ability.

From these tests it is apparent that South Dakota bentonite is a very effective fire retardant either by itself, when in a state of thixotropic gel, or when used in combination with PMF vermiculite. The opinion of the experimenter is that this bentonite will ultimately be used chiefly as a carrying agent for other fire retardant chemicals which will not alter the ability of the bentonite to maintain a thixotropic gel.

Grim (21) mentioned the great influence exerted by even small amounts of the phosphate ion on the thixotropic properties of bentonite. Mr. D. W. Robinson of the Zonolite Company, Libby, Montana, also mentioned an attemp to combine phosphate-impregnated exfoliated vermiculite with South Dakota bentonite. All attempts in this endeavor failed unless the bentonite was allowed to attain a state of thixotropic gel, at which time the impregnated vermiculite could be added with no fear of flocculation occurring. In view of the time that would be involved in mixing this slurry it would be extremely undesirable for use as an aerially applied fire retardant. Pilot burning tests of dowels treated with slurries submitted by Mr. Robinson, contain chemical-impregnated vermiculites in combination with South Dakota bentonite were conducted, the results of which were encouraging enough to warrant further investigation.

Slurries of South Dakota bentonite generally have poor dispersion and canopy penetration properties due to their relative lightness and their viscous nature. Intensive field testing, including air drops with retardant No. 7 are recommended. The slickness of bentonite slurries presents a safety hazard both in the mixing operation and on the fireline. The addition of the vermiculites reduce this hazard considerably.

O'Keefe Creek Bentonite

The O'Keefe Creek bentonite was mixed in two different ratios, each of the slurries falling into one of the two classes of retardants. The ratios used per gallon of water are listed accompanied by this number and class.

Class	Slurry No.	Description
Class II	11	Three pounds of O'Keefe Creek bentonite.
Class I	12	Four pounds of O'Keefe Creek bentonite.

This bentonite is definitely a swelling variety but not to the extent of the South Dakota bentonite. This could be due to the non-colloidal impurities found in the O'Keefe Creek bentonite, although both of these slurries mixed fairly easily and produced a thixotropic gel. When the dowels were treated it was noted that adherence was good when the slurry was wet but upon drying, cracking and peeling was evident particularly where heavy concentration of slurry accumulated.

Slurry No. 11 showed a fair resistance to burning when wet but after drying its resistance was reduced considerably. It was generally a poor retardant either when wet or dry. Upon being exposed to the flame both slurries No. 11 and 12 lost nearly all of their coating due to rapid buckling and peeling. This occurred when dowels at all stages of dryness were burned.

Slurry No. 12 gave the best resistance to burning of all of the slurries. This is shown by the very pronounced sustained drop shown on graph 19. It is noted that when wet, the rise in temperature after the beginning of rapid pyrolysis was still rather slow. The sustained drop was probably caused mostly by the rapid release of water which partially explains the pronounced cracking and peeling and also by the large amount of solid material adhering to the dowel (1.06) grams). Resistance to ignition was also comparatively long in the case of slurry No. 12. Both of these slurries showed a high degree of dependence on the amount of moisture for their retarding ability, although these slurries retained their water up to 3 hours of drying. The regression coefficient of slurry No. 12 is relatively high showing its dependence on drying while slurry No. 11 has a low regression coefficient. This is mainly due to the fact that slurry No. 11 was poor to start with and thus the effect of change in moisture is not as pronounced as in the case of slurry No. 12. It was found that this clay material could be mixed immediately with the ammonium-phosphate-impregnated vermiculite without flocculating occurring. As was mentioned earlier, this was not possible using the South Dakota bentonite.

Ammonium Phosphates

Two varieties of this chemical were tested, one of which fell into each retardant class. Shown below are the retardant class, the number of the solution and the ratio of additive in pounds per gallon of water.

Class	Slurry No.	Description
Class I	13	One and two-thirds of monoammonium phosphate
Class II	14	One and two-thirds of diammonium phosphate.

As was expected dowels treated with both of these retardants ignited in a shorter time than the water-treated dowels. This was to be expected since both of these chemicals are dehydrating agents. The ammonium phosphates act as fire retardants in accordance with the gas theories and chemical theory. Upon heating these chemicals give off ammonia gas which tends to subdue flaming by the process of dilution. The phosphoric acid changes the course of reaction in the process of cellulose decomposition in a manner that discourages the formation of combustible gases and encourages the formation of charred material. It has been generally proven and accepted that the formation of charred phosphate is a better retardant than the monovalent variety, probably because of the ability to release double the amount of ammonia gas. According to these tests the monovalent variety, No. 13, was indicated to be the slightly better of the two retardants. Both of these solutions caused irritation and a burning sensation when they gained access to small cuts on this experimenter's hands.

When testing retardant No. 13 the temperature rise remained nearly the same after each period of drying except for those dowels which were burned immediately after treating. The difference in the two lines shown on graph 20 occurs in the lower extremity of the curve. This initial delay in temperature increase and subsequent higher resistance to burning index for this sample is due wholly to the water content of the freshly treated dowels. After this water content had evaporated by exposure to the flames, the temperature profiles nearly coincide. The ignition delay afforded by the monovalent variety also remained nearly constant except for those dowels which were burned immediately after treating. The ignition delay afforded by the divalent variety, No. 14, steadily decreased throughout the range of drying times and even promoted a longer ignition delay after the first hour of drying time than the water-treated dowels which by this time had nearly a stable moisture content. Since the divalent variety has an extra radical of ammonia which is relatively unstable and can be driven off by heat, it is apparent that this variety should delay ignition longer than the monovalent variety.

In the other three tests, resistance to burning, the index of which is shown on table XXVI, intensity of burn indicated by the steepness of the temperature profiles and by considering the total regression line, the monovalent variety is shown to be the better retardant. No explanation of this apparent contradiction of proven fact is attempted. Table XXIII and the accompanying graph show the temperature profile of the treated burning dowels after drying times. It can be seen that very little temperature fluctuation between the different hours of drying occurs except for the effect of the water already mentioned, although a slight drop is noted after the third hour of drying. The temperatures shown on table XXIV for the divalent variety fluctuated to a greater extent and also very definitely show a reduction after the third hour of drying. According to the regression line this decrease in burning intensity is also shown by the decrease in weight loss except for the one value of 34.75 for the divalent variety. The treated dowels that had been dried for the additional 19 hours at 103° C. were also burned for these two chemicals. The temperature profiles obtained from burning the monovalent phosphate treated dowels were comparably close to the 5-hour temperature profile shown. However, in the case of the divalent phosphate treated dowels, the temperature profile obtained was considerably lower than the 5-hour temperature profile and tended to approach the profiles of the monovalent phosphate treated dowels. According to the regression line of weight loss per minute the divalent variety is a better retardant when burned immediately after dipping and is nearly equal or just slightly better for each additional hour of drying except for the corrupting influence of the high value of 34.75. The experimenter is definitely convinced that the variation exhibited by the divalent variety is due wholly to the unstable character of the additional ammonium radical.

A definite ammonia aroma could be detected from the solution of the divalent variety indicating a loss of the ammonium radical. A greater loss probably occurred while drying in the oven at 50° C. and very definitely occurred while drying at 100° C. According to the regression coefficients the divalent variety is definitely affected by drying to a greater degree than is the monovalent variety. Both of these retardants are thought to have corrosive and irritating effects which may limit their use for aerially applied fire retardants. Limited testing on dowels saturated with either one of these chemicals showed that they are very effective fire retardants if applied in large concentrations.

Water

Dowels treated with water from the Aerial Fire Depot were also burned after different periods of drying. After 3 hours of drying the dowels still contained .88 percent moisture which could not be removed by further drying at 50° C.; therefore, the tests on the water-treated dowels were concluded. Graph 25 and table XXVIII show that the water-treated dowels lost a greater amount of wood per minute than the untreated dowels after drying for 1 hour. This is entirely possible since it is known that more complete combustion of wood occurs if a small amount of moisture is present than if the wood is oven dried, as were the untreated dowels. This occurs because during the pyrolysis of wood, some of the water present is driven off as water vapor but also some of it is broken down and the oxygen from the water is released and this contributes to burning (if this occurs the hydrogen also could possibly contribute to the process of burning). If a large amount of water is present the cooling action of the water overrides the contributory effect of the oxygen released, thus the rate of pyrolysis is reduced. If only a very small amount of water is present the contributory effect of the oxygen released masks the cooling action of the water. Cell rupture and subsequent more forceful expulsion of volatile materials is facilitated by the presence of small quantities of water.

As noted previously, the burning tests were conducted within a 10 degree temperature range and a 10 percent relative humidity range. These factors were not noted for each particular burning since the effects of these variables were assumed to be of such little consequence that their effects could not be measured with the equipment used, as long as their variation did not exceed the ten unit range. It can easily be imagined however, that in a case where two retardants which are nearly the same are being tested, a difference might be noticed if by chance the tests were conducted at the extreme opposite ends of the ten unit range. Atmospheric pressure, which is said to have some effect on burning, was not considered. These three factors may explain some of the apparent incongruities which the experimenter has tried to explain in other ways.

CHAPTER VIII

SUMMARY

Fourteen combinations of retardants were subjected to laboratory tests aimed at determining their comparative worth for use as aerially applied forest fire retardants. Slurries of sodium calcium borate, South Dakota bentonite by itself and in combination with the exfoliated variety of vermiculite, all of which have been used rather extensively as aerial applied fire retardants, were tested. Slurries mixed with "wet water" and undispersed water were also tested. Other materials tested included two other varieties of vermiculite in combination with South Dakota bentonite, two varieties of ammonium phosphate, sodium trisilicate and two locally found materials, one a silty clay and the other a bentonite clay which has many of the characteristics of South Dakota bentonite.

These retardants were subjected to preliminary tests, which attempted to evaluate ease of mixing, pH, viscosity, adhesion to vegetation and specific gravity; to water retention and drying tests; and to burning tests which determined the ignition delay, the resistance to burning and the intensity of burn of treated dowels.

The burning test results were based on observations of the burning characteristics of four dowels burned at six different stages of dryness for each slurry tested. The tests were conducted in a modified version of the fire tube used at the Forest Products Laboratory at Madison, Wisconsin. Treated dowels were subjected to a temperature of 620° C. for a period of 1-minute before being allowed to burn without an external heat source.

Temperature profiles plotted from readings recorded after each quarter-minute of dowel exposure in the fire tube were plotted. The 7½-inch by ½-inch dowels were oven-dried, then treated, weighed, dried, weighed, burned and weighed in that sequence. Duration of burn or exposure time in the fire was also recorded as the time in minutes from initial insertion of the dowel in the fire tube until no flaming was evident. Ignition delay was also recorded.

In plotting temperature profiles three peculiar temperature fluctuations were noted, two of which are important. An initial sustained drop in temperature indicates a slurry which loses water rapidly. When burned immediately after treating, dowels treated with these slurries usually showed a high to very high resistance to burning and a longer-than-average ignition delay. Slurries having this characteristic generally show very little retarding effect on burning intensity. A "slump" occurring at the 1-minute burning time was noticed with those retardants which have a high retarding effect on the intensity of burn. A temperature profile which reaches a low peak temperature at the 1-minute mark indicates a slurry which has a high retarding effect due to its impervious coating. These slurries caused a burning phenomenon which the experimenter has called the "jet effect."

The intensity of burn was noted by two methods, the steepness of the temperature profile after the initial delay had occurred and by calculation of a regression line showing percent of wood loss per minute plotted over percent weight of slurry.

Conclusions

From the results obtained during these tests it was concluded:

1. A combination of South Dakota bentonite with PMF vermiculite mixed well with water to form a stable, non-gelling slurry. This slurry exhibited better fire retarding qualities than all of the other retardants tested. Combinations of the bentonite and the other two forms of vermiculite, micronized and exfoliated number 4 also formed desirable slurries, although the latter was the least desirable of the three since it required a short time in which to gel which was not required by the other two vermiculite slurries.

2. Slurries which form colloidal suspension are chiefly dependent on the amount of water and the manner in which it is held by the colloidal particles, and the imperviousness of the coating upon drying for their fire-retardant properties.

3. The use of "wet water" for mixing slurries decreased their effectiveness by reducing the amount of solids and liquids adhering to the fuels, and by the reduction of the surface tension of the water present in the slurry which facilitates evaporation of that water.

4. The use of South Dakota bentonite as a carrying agent for chemical-impregnated vermiculite (especially the phosphate) is impractical due to the delay necessary while the bentonite attains a thixotropic gel, without which immediate flocculation of the bentonite occurs upon addition of the phosphate ion. When bentonite is mixed in such low concentrations the flocculated bentonite sinks to the bottom of the container leaving a clear liquid, thus no or little benefit

is derived from the bentonite.

5. Although both of the ammonium phosphates were irritating to small cuts on the experimenter's hands, this chemical is very effective when used in larger quantities; thus they may possibly be used as ground-applied retardants where concentrated amounts could be applied on a controlled stream to a confined area.

6. Sodium calcium borate definitely proved to be inferior as a fire retardant when compared to South Dakota bentonite and some of the combinations using South Dakota bentonite.

7. If combinations of South Dakota bentonite and vermiculite are to be used they should be purchased in a preblended form. This should not add a great deal to the price of the constituents and would make handling and storage easier and more economical.

Suggestions

Some suggestions and ideas are enumerated for further investigation into related fields.

1. Continued study of: foaming agents for ground and aerial attack; the use of bentonite as carrying agents for chemical-impregnated vermiculite, the use of bentonite in colloidal suspension with fire retardant hydro-carbon compounds, and the use of suspension of aluminum flakes for retardant coatings which would dissipate the heats rather than insulate the fuel.

2. Carefully designed combination field and laboratory studies conducted in order to correlate actual field dropping, dispersing and coating characteristics of slurries with easily duplicated laboratory tests. In conjunction with these tests the effects of aircraft

speed, altitude, and gate size and shape could be determined.

3. The design of new tests more closely simulating field conditions for means of evaluating fire retardants for both ground and aerial tanker application.

4. If the fire tube apparatus is used a more accurate temperature measuring device is recommended. Also, humidity cabinets should be used for drying.

5. An extensive investigation of forest fire retardants for ground tanker use should be conducted. This suggestion is meant to apply mainly to the use of chemicals which are good fire retardants but which are impractical or even hazardous for application by air tankers because of their corrosiveness, expense, or the difficulties involved in handling large quantities of these chemicals.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Anonymous
   1953. Aerial Delivery of Water Experiment. Los Angeles County Fire Department.
   (Reported in 2)

2. ________
   1955. Aerial Firefighting - Bulk Water Drop by Fixed Wing Aircraft. Progress Report No. 9, Operation Fire Stop.

3. ________
   1958. Chemical Fire Retardant Laboratory Tests. Operation Fire Stop.

4. ________
   1954. El Toro Air Drop, Informal District 6 Report, California Division of Forestry.
   (Reported in 2)

5. ________
   1954. Field Review. Progress Report No. 3, Operation Fire Stop.

6. ________
   1957. FIREBRAKE Chemical Forest Fire Retardant, Technical Bulletin FB/1, United States Borax and Chemical Corporation, Los Angeles, California.

7. ________
   1955. Fire Retardants - I. Progress Report No. 4, Operation Fire Stop.

8. ________
   1954. Vermiculite Chemical and Physical Properties (with supplements, 1959), Zonolite Company, Chicago, Illinois.

9. Banfield, W. O. and W. S. Peck
   1922. Effect of Chemicals on the Ignition Temperatures of Wood. Can. Chem. Met. 6, p. 172 - 176.
   (Reported in 12)

10. Barshad, I.
    1950. The Effect of Interlayer Cations on the Expansion of the Mica Type Crystal Lattice. Am. Mineral 35, p. 225 - 238.
    (Reported in 21)

11. Baver, L. D.
    1940. Soil Physics. Third Edition Wiley & Sons, New York.

12. Browne, F. L.
1958. Theories of the Combustion of Wood and Its Control. Report No. 2136, U. S. D. A. Forest Products Laboratory, Madison, Wisconsin.

13. Bruce, H. D. and V. P. Miniutti
1957. Small Tunnel Furnace Test for Measuring Surface Flammability. Report No. 2097, U. S. D. A. Forest Products Laboratory, Madison, Wisconsin.

14. Coppick, S.
1947. Mechanisms of Flameproofing. Chapter 3 in Flameproofing Textile Fabrics, Robert W. Little, Reinhold, New York. (Reported in 12)

15. Ellwood, B. L.
n.d. Notes on the Suppression of Bush-Fires from Aircraft. Australian Forestry, XII (2) p. 127 - 133. (Reported in 2).

16. Fons, Wallace L., R. S. McBride and E. E. Draves
1950. Unpublished Progress Report. California Forest and Range Experiment Station, Berkeley, California. (Reported in 7)

17. Garratt, George A.
1927. Fireproof Wood for Interior Construction. Am. Lumberman, No. 2713, p. 56 - 57, and No. 2714, p. 52 - 53. (Reported in 28)

18. Gay - Lussac, J. C.
1821. Note on the Property of Salts for Making Fabrics Incombustible. Ann. Chim. (2) 18: p. 211 - 217. (Reported in 12)

19. Gellius, Aulus
113-164. Noctes Atticae XV, 1. (Reported in 45)

20. Gooch, R. M., D. L. Kenaga and H. M. Tobey
1959. Fire Retardants for Wood Treated with Oil Type Preservatives. Forest Products Journal, Vol. IX, No. 10.

21. Grimm, R. E.
1953. Clay Mineralogy. Maple Press, York, P.A.

22. Grimshaw, J. E.
1956. Operation Cloudburst. Reprint from Timber of Canada, May 1956.

23. Hanson, P. D. and C. L. Tebbe
1947. Aerial Bombing of Forest Fires, A Progress Report of an Experiment. R-1 U. S. Forest Service, Missoula, Montana.

24. Harkom, J. F. and J. I. Dore
1933. Slow Combustion Test. Am. Wood Pres. Assoc. Proc. 1933, p. 87 - 106.

25. Hartman, Ernest F.
1933. Fire Retardant Treatments for Wood. Symposium on Wood Preservative, Am. Soc. Mech. Engr. Wood Industries Dept. (Reported in 28)

26. Herodotus.
484-431 B. C. Neu Bucher Geschichte. (ed Toldhagen) Vol. II, p. 172 - 180.
(Reported in 46)

27. Holmes, J. R. B.
1959. Analytical Procedure - Soil Chemistry. M. S. U. Forestry School Soils Laboratory, Missoula, Montana.

28. Hunt, George M. and George A. Garratt
1953. Wood Preservation. Second edition p. 371 - 392, Maple Press, York, P. A.

29. Hunt, George M., T. R. Truax and C. A. Harrison
1930. Fire Resistance of Wood Treated with Zinc Chloride and Diammonium Phosphate. Am. Wood Pres. Assoc. Proc. 1930, p. 130 - 164.

30. ________
1931. Additional Experiments in Fire Proofing Wood. Am. Wood Pres. Assoc. Proc. 1931, p. 104 - 142.

31. Johansen, R. W.
1959. Monoammonium Phosphate Shows Promise in Fire Retardant Trials. Research Note No. 137, Southeastern Forest and Range Experiment Station, Asheville, N. C.

32. Little, Robert W.
1947. Flameproofing Textile Fibers. Monograph No. 104, Am. Chem. Soc., Reinhold, New York.
(Reported in 12)

33. Lyon, T. L., H. O. Buckman and N. C. Brady
1950. The Nature and Properties of Soil, Fifth Edition, The Macmillan Company, New York.

34. Mackay, T. E.
1954. Aerial Water Bombing. Fireman, March 1954, p. 19 - 20.
(Reported in 2)

35. Markwardt, L. J., H. D. Bruce and A. D. Freas
1954. Brief Description of Some Fire-Test Methods Used for Wood and Wood-Base Materials. Report No. 1976, U.S.D.A. Forest Products Laboratory, Madison, Wisconsin.

36. McNaughton, C. G. and A. Van Kleek
1953. Fire-Test Methods Used in Research at the Forest Products Laboratory. Report No. 1443, U. S. D. A. Forest Products Laboratory, Madison, Wisconsin.

37. Miller, H. R., Jr.
1956. Chemical Fire Retardants for Wild Land Fire Control. Research Note 105, California Forest and Range Experiment Station. Berkeley, California.

38. Miller, H. R.,Jr. and C. B. Phillips
1958. Tests of Some New Fire Retardants. Research Note 140, California Forest and Range Experiment Station, Berkeley, California.

39. Miller, H. R., Jr. and C. C. Wilson
1957. A Chemical Fire Retardant. Technical Paper No. 15, California Forest and Range Experiment Station, Berkeley, California.

40. Moroney, M. J.
1956. Facts from Figures, Penguin Books, William Clowe & Sons, London, England.

41. Phillips, Clinton B. and H. R. Miller, Jr.
1959. Using Swelling Bentonite Clay as a Fire Retardant. Pacific Southwest Forest and Range Experiment Station, Berkeley, California.

42. Powell, F. E. and E. L. Perrine
1959. Forest Fire Retardant. Test Report No. 390 and Supplement, Zonolite Company Research Laboratory, Evanston, Illinois.

43. Robinson, D. W.
1959. Forest Fire Retardant. Research Project - Expanded Research Division. Zonolite Company. Libby. Montana.

44. Ross, C. S. and E. V. Shannon
1926. Minerals of Bentonite and Related Clays and Their Physical Properties. J. Am. Ceram. Soc. 9, p. 77 - 96. (Reported in 21)

45. Sandholzer, Marjorie W.
1946. Flameproofing of Textiles. Circular No. C455, National Bureau of Standards. (Reported in 12)

46. Schlegel, R.
1934. Investigations of the Scientific Basis of the Fireproofing of Wood. Verlag Chemie, G.m.b.H., Berlin Mathematical Formulation of the Mass Law in the Fire Protection of Wood. Korrosion U. Metallschutz 10: p. 195 - 196. (Reported in 12)

47. Truax, T. R. and C. R. Harrison
1929. A New Test for Measuring the Fire Resistance of Wood. Paper presented before Am. Soc. Testing Materials, June 1929.
(Reported in 29)

48. Truax, T. R., C. A. Harrison and R. H. Baechler
1933. Experiments in Fire Proofing Wood - Fourth Progress Report. Am. Wood, Pres. Assoc. Proc. 1933, p. 107 - 124.

49. Truax, T. R., G. M. Hunt and C. A. Harrison
1932. Experiments in Fire Proofing Wood - Third Progress Report. Am. Wood Pres. Assoc. Proc. 1932, p. 71 - 96.

50. Walker, G. F.
1951. Vermiculite and Some Related Mixed-Layer Minerals "X-Ray Identification and Structure of the Clay Mineral." Chap. VII, p. 199 - 223. Monograph, Miner Soc. of Great Britain.
(Reported in 21).

51. Wood, G. J. and T. C. Cooke
1957. Report on Water Dropping. Cochrane District, Ontario Department of Lands and Forests.

EXPLANATION OF APPENDIX

Definition of Retardant Classification - (Denoted by asterisk).

Class I Retardant - a retardant that will not allow the amount of heat emitted by a dowel burned immediately after treating to raise the temperature at the top of the tube in excess of 475°C. after a maximum exposure period of $1\frac{1}{4}$-minutes in the fire tube.

Class II Retardant - a retardant that allows the amount of heat emitted by a dowel burned immediately after treating to raise the temperature at the top of the tube in excess of 475°C. after a maximum exposure of $1\frac{1}{4}$-minutes in the tube.

Retardants are classed only according to the above definitions and remain in those classes for the duration of the tests.

Numbering of Curves on Graphs - 1 to 8 and 23 to 26.

The numbers accompanying the curves on these graphs denote the number that has been assigned to that retardant and correspond to the number and name of retardant found on the page facing the graph.

Denotation of Curves on Graphs 9 - 22

These notations apply to the hours of drying sustained by each treated dowel from which that temperature curve was plotted prior to burning.

Overhead Bars on All Graphs

Figures accompanied by overhead bars e.g. 8, denote the mean obtained from testing that number of dowels. All curves plotted show the results of tests using four dowels each unless so denoted. The curves accompanied by a series of hours which carry an overhead bar denote the periods of drying in which the retardants lost less than one percent of the dowel weight per hour Thus, the mean results of these dowels were plotted in one curve.

Delayed Peak Temperatures

Treated dowels which took more than 2.5 minutes in order to reach peak temperatures are noted as such, $\frac{675}{3.0}$. The top figure denotes the peak temperature attained and the bottom figure denotes the time in minutes taken to reach that peak temperature.

Temperature Shown in Tables V to XXVI

The temperatures shown in these tables are the mean temperatures resulting from treated dowels burned after each hour of drying. The top figure is the mean temperature, which is plotted and the bottom figure is the range of the figures to which the mean applies and from which it was calculated.

APPENDIX

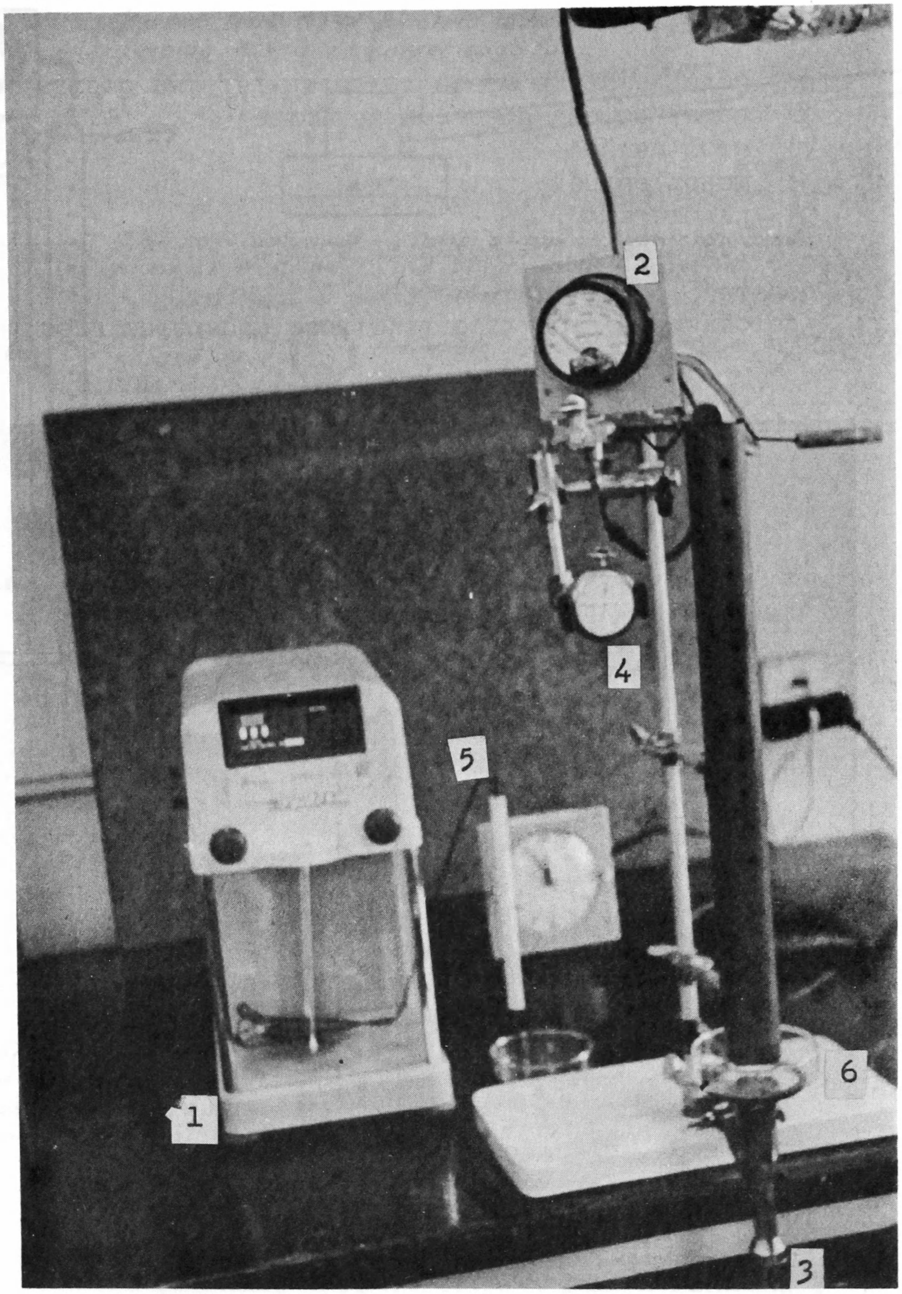
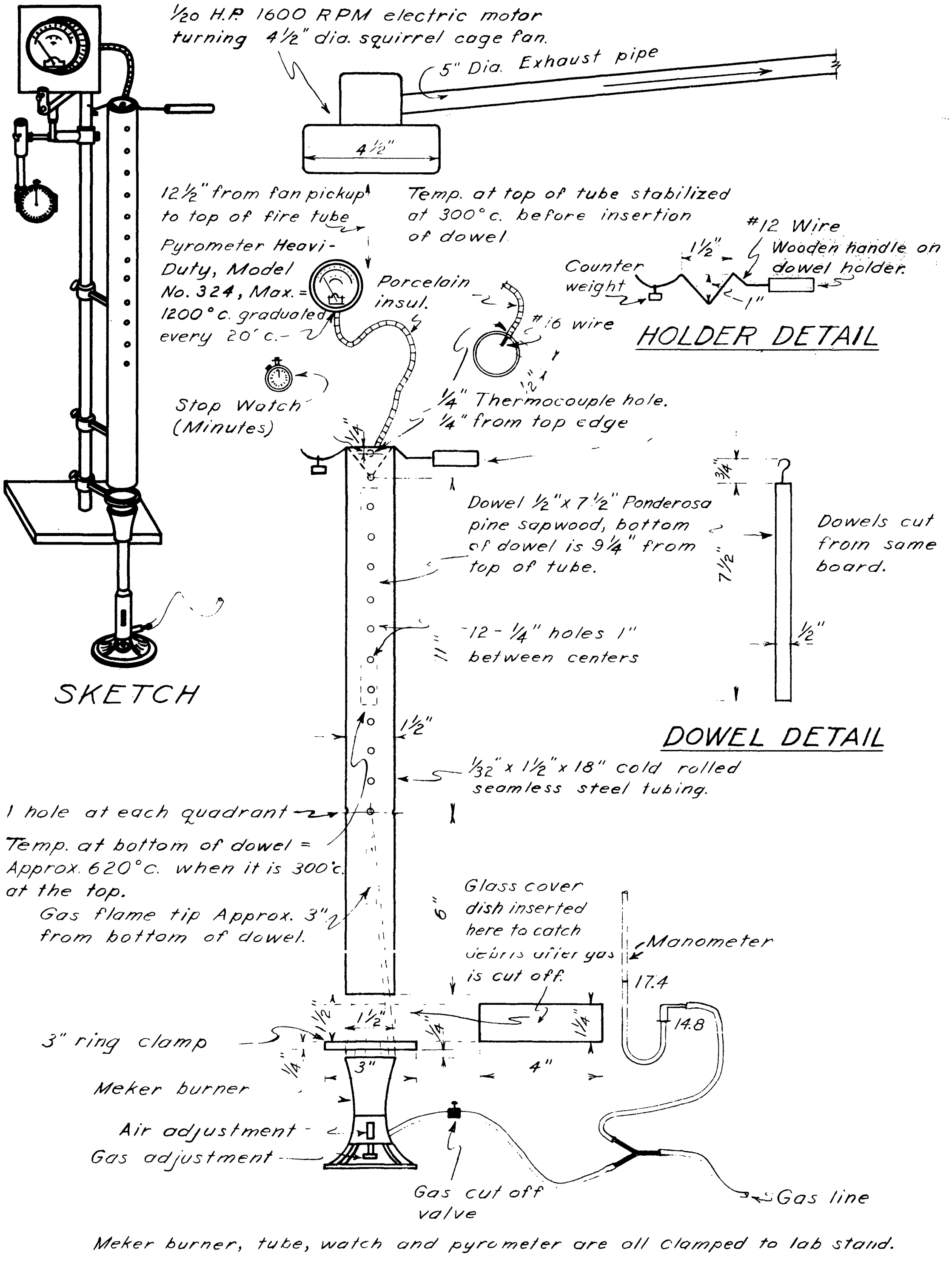


PLATE 1. Photograph of modified fire tube apparatus used for burning dowels.

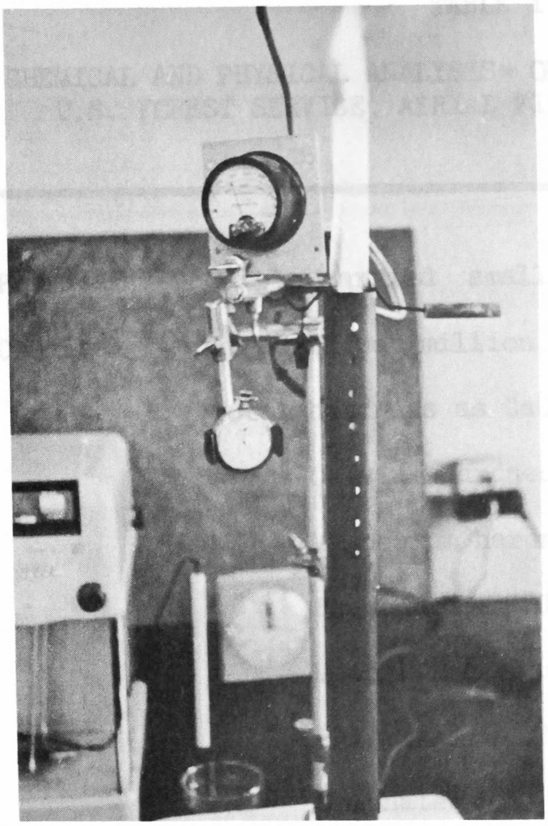
1. Scale used for weighing dowels.
2. Pyrometer.
3. Meker burner.
4. Stop watch.
5. Dowel holder used for weighing.
6. Cover dish in place to catch falling debris.



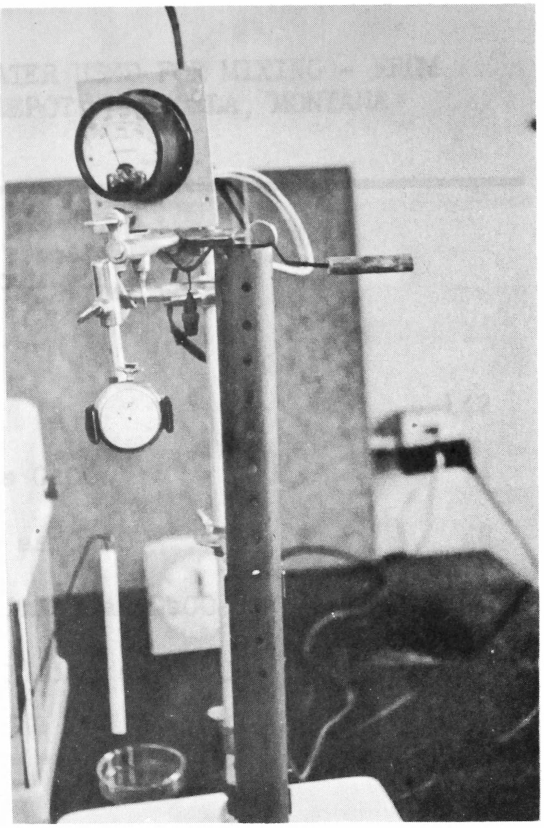
Meker burner, tube, watch and pyrometer are all clamped to lab stand.

Scale: 3/16" = 1"

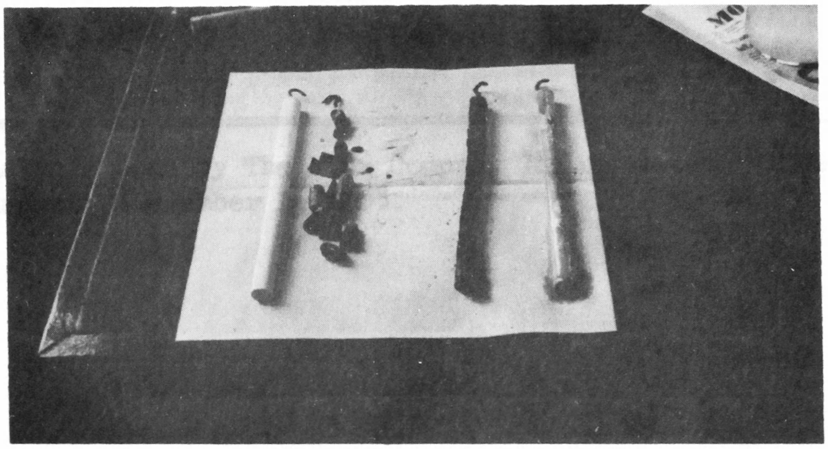
PLATE 2. FIRE TUBE APPARATUS FOR USE IN BURNING DOWELS



1.



2.



3.

PLATE 3. Picture 1 - Water treated dowel after burning 1.4 minutes.

Picture 2 - South Dakota bentonite + PMF vermiculite treated dowel after 1.4 minutes.

Picture 3 - (from left to right) Unburned water treated dowel, burned water treated dowel, burned South Dakota bentonite + PMF vermiculite treated dowel and unburned South Dakota bentonite + PMF vermiculite treated dowel. All dowels burned immediately after dipping.

TABLE I

CHEMICAL AND PHYSICAL ANALYSIS* OF WATER USED FOR MIXING - FROM U.S. FOREST SERVICE, AERIAL FIRE DEPOT, MISSOULA, MONTANA

Physical -	Sample carried small amount of sand.	
Chemical -	In parts per million.	
	Total hardness as $CaCO_3$	142
	Calcium hardness as $CaCO_3$	94
	Magnesium hardness as $CaCO_3$	48
	Phenophtalem Alkalinity as $CaCO_3$	0
	Methyl Orange Alkalinity as $CaCO_3$	144
	Chlorides as NaCl	10
	Sulphates as Na_2SO_4	13
	Silica as SiO_2	18
	Total pH	7.7

*Analysis done by The Flux Company Incorporated, Minneapolis 3, Minnesota, December 1, 1955.

TABLE II

CHEMICAL ANALYSIS OF SODIUM CALCIUM BORATE, VERMICULITE, SOUTH DAKOTA BENTONITE EXPRESSED IN PERCENT

	Retardant		
Compound	Sodium Calcium Borate (6)	Vermiculite (8)	South Dakota Bentonite (21)
SiO_2	9.5	38.64	55.44
MgO	3.5	22.68	2.49
Al_2O_3	1.1	14.94	20.14
Fe_2O_3	.3	9.29	3.67
K_2O		7.84	.60
CaO	15.9	1.23	.50
Ca_2O_3		.29	
Mn_3O_4		.11	
P_2O_5		Trace	
S		Trace	
Cl		.52	
H_2O	28.2	5.29	14.70
CO_2	3.2		
B_2O_3	33.0		
Na_2O	4.9		2.75
Undetermined	.4		

TABLE III

CATION EXCHANGE AND TOTAL ANALYZED EXCHANGEABLE CATIONS EXPRESSED IN MILLI-EQUIVALENTS PER 100 GRAMS OF DRY RETARDANT

Retardant	Ca++ in m.e./100 gr.	Mg++ in m.e./100 gr.	K+ in m.e./100 gr.	Mn++ in m.e./100 gr.	Fe++ in m.e./100 gr.	Total Exchangeable Cations in m.e./100 gr.
Sodium Calcium Borate	41.5	-	.3	.1	.8	42.7
Airport Clay	34.5	.2	.8	.7	.1	36.4
#4 Exfoliated Vermiculite	12.5	-	1.6	-	.2	14.3
South Dakota Bentonite	22.5	-	1.4	.1	.1	24.1*
O'Keefe Creek Bentonite	22.5	.1	1.9	-	-	24.5*

* Grim (21) states that the total exchange capacity of Na± bentonites is 80-150 m.e./100 grams. Since the laboratory analysis did not include Na+, it is assumed that the difference between the laboratory analysis and the figure cited by Grim is the quantity of exchangeable Na+.

TABLE IV

SOME PHYSICAL AND CHEMICAL CHARACTERISTICS OF RETARDANTS USED IN THE BURNING TESTS

Retardant		Mix lbs./gal. of H_2O	Volume Increase Percent	S.G. of Slurry	Wt./Gal. of Slurry lbs.	Viscosity mll/min.	pH	Ease of Mixing 0 - 10	*Adherence to* Vegetation	
No.	Name								Dec.	Con.
	Class I Retardants*									
4	S.D. Bentonite	.75	1.0	1.032	8.61	16.72	9.2	2	6	7
12	O'Keefe Cr. Bentonite 4 lbs./gal.	4.00	15.0	1.212	10.11	No Flow	7.6	3	4	5
7	S.D. Bentonite + PMF Vermiculite	.50 .50	3.0	1.055	8.80	45.50	9.5	7	7	8
8	S.D. Bentonite + Micronized Vermiculite	.50 .50	2.0	1.056	8.81	45.50	9.6	7	5	7
6	S.D. Bentonite + #4 Vermiculite	.50 .50	8.0	1.041	8.68	No Flow	9.6	6	3	4
5	S.D. Bentonite + Calgon (wet water)	.75 .01	1.0	1.032	8.61	50.00	9.1	4	4	3
13	$NH_4H_2PO_4$	1.66	-	1.091	9.10	166.66	4.6	10	-	-
	Class II Retardants*									
10	S.D. Bentonite + Airport Clay	.50 2.00	18.0	1.138	9.49	83.30	9.0	4	4	5
2	Sodium Calcium Borate	4.00	19.0	1.173	9.78	62.50	9.1	8	8	9
11	O'Keefe Cr. Bentonite 3 lbs./gal.	3.00	9.0	1.153	9.62	48.00	7.6	5	2	3
9	S.D. Bentonite + Sodium Calcium Borate	.50 2.00	18.0	1.121	9.35	83.40	9.4	6	4	4
1	Sodium Calcium Borate + Calgon (wet water)	4.00 .10	18.0	1.173	9.78	125.00	9.1	9	4	3
14	$(NH_4)2HPO_4$	1.66	-	1.091	9.10	166.66	7.9	10	-	-
15	Water	-	-	1.000	8.34	166.66	7.7	-	-	-

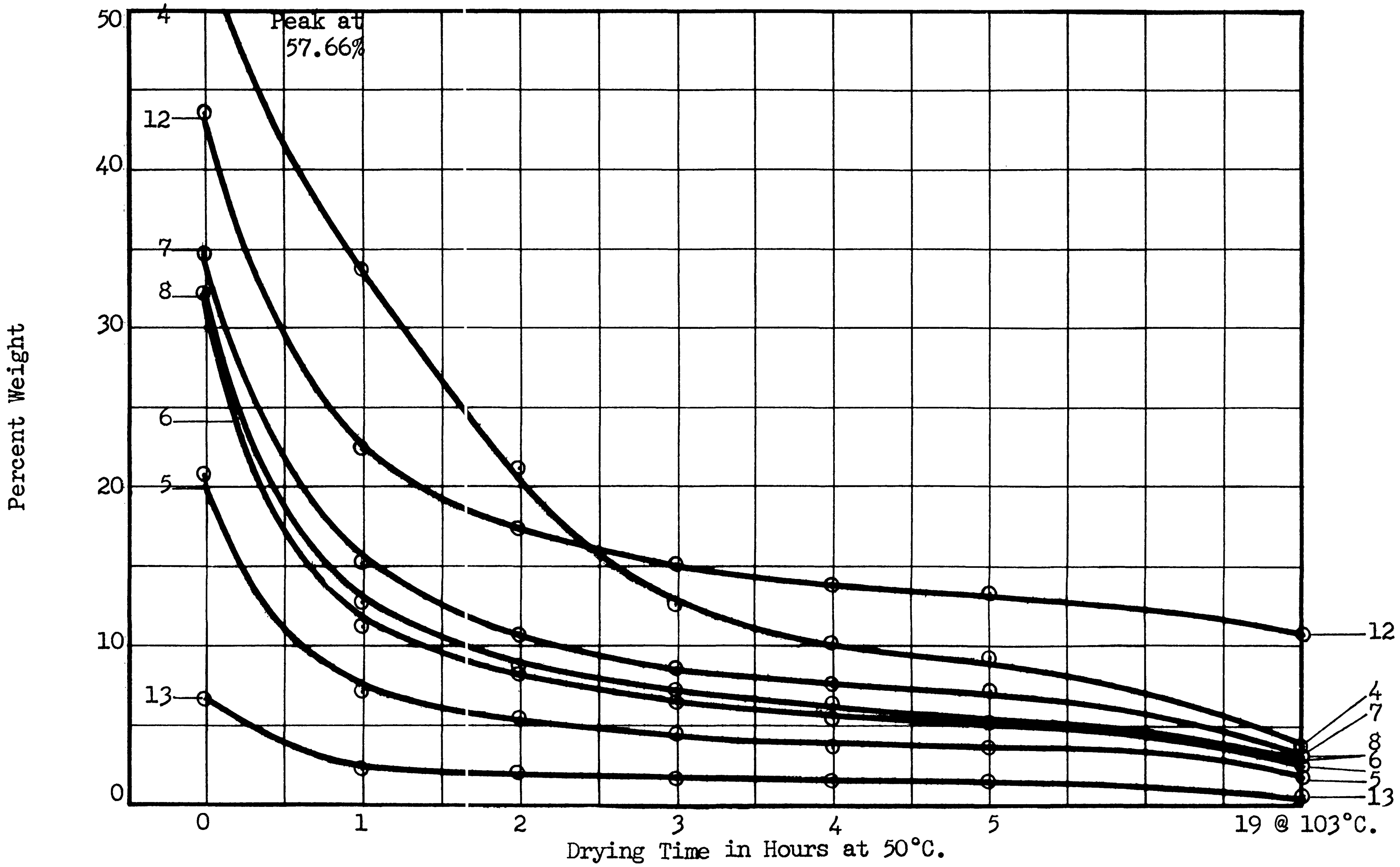
* See explanation of appendix.

TABLE V

MEAN WEIGHT IN GRAMS AND IN PERCENT OVER DRY WEIGHT OF DOWELS PRETREATED WITH CLASS I RETARDANTS* AT THE INDICATED DRYING TIMES AND TEMPERATURES

Retardant				Hourly Weight when Dried at 50°C.						Wt.after add'l. 19 hrs. @ 103°C.	Wt.of Solid Dry Mater.
No.	Name	Unit	Dry Weight	0 Hour	1 Hour	2 Hours	3 Hours	4 Hours	5 Hours		
4	S.D. Bentonite	Gr.	10.51	16.57	14.07	12.72	11.85	11.57	11.48	10.90	.41
		%	0	57.66	33.87	21.03	12.74	10.08	9.29	3.71	
12	O'Keefe Cr. Bentonite 4 lb./gal.	Gr.	9.86	14.15	12.07	11.57	11.34	11.23	11.18	10.92	1.06
		%	0	43.50	22.41	17.34	15.01	13.89	13.39	10.75	
7	S.D. Bentonite + PMF Verm.	Gr.	11.60	15.62	13.35	12.84	12.60	12.49	12.42	11.96	.36
		%	0	34.65	15.08	10.69	8.60	7.67	7.06	3.10	
8	S.D. Bentonite + Micronized Verm.	Gr.	11.26	14.97	12.70	12.24	12.07	11.99	11.94	11.59	.33
		%	0	32.95	12.79	8.70	7.19	6.48	6.04	2.93	
6	S.D. Bentonite + #4 Verm.	Gr.	11.98	15.82	13.32	12.97	12.75	12.65	12.59	12.26	.28
		%	0	32.05	11.18	8.26	6.43	5.59	5.09	2.34	
5	S.D. Bentonite + Calgon	Gr.	11.45	13.82	12.26	12.07	11.96	11.90	11.88	11.66	.22
		%	0	20.70	7.07	5.41	4.59	3.93	3.75	1.83	
13	$NH_4H_2PO_4$	Gr.	11.01	11.75	11.24	11.20	11.19	11.19	11.18	11.05	.04
		%	0	6.72	2.09	1.72	1.63	1.63	1.54	.36	

* See explanation of appendix.



Graph 1. Class I retardants*; hourly weight of treated dowels in percent over dry weight when dried for 5 hours at 50°C. and for 19 hours at 103°C. Refer to Table V for values in grams and percent.

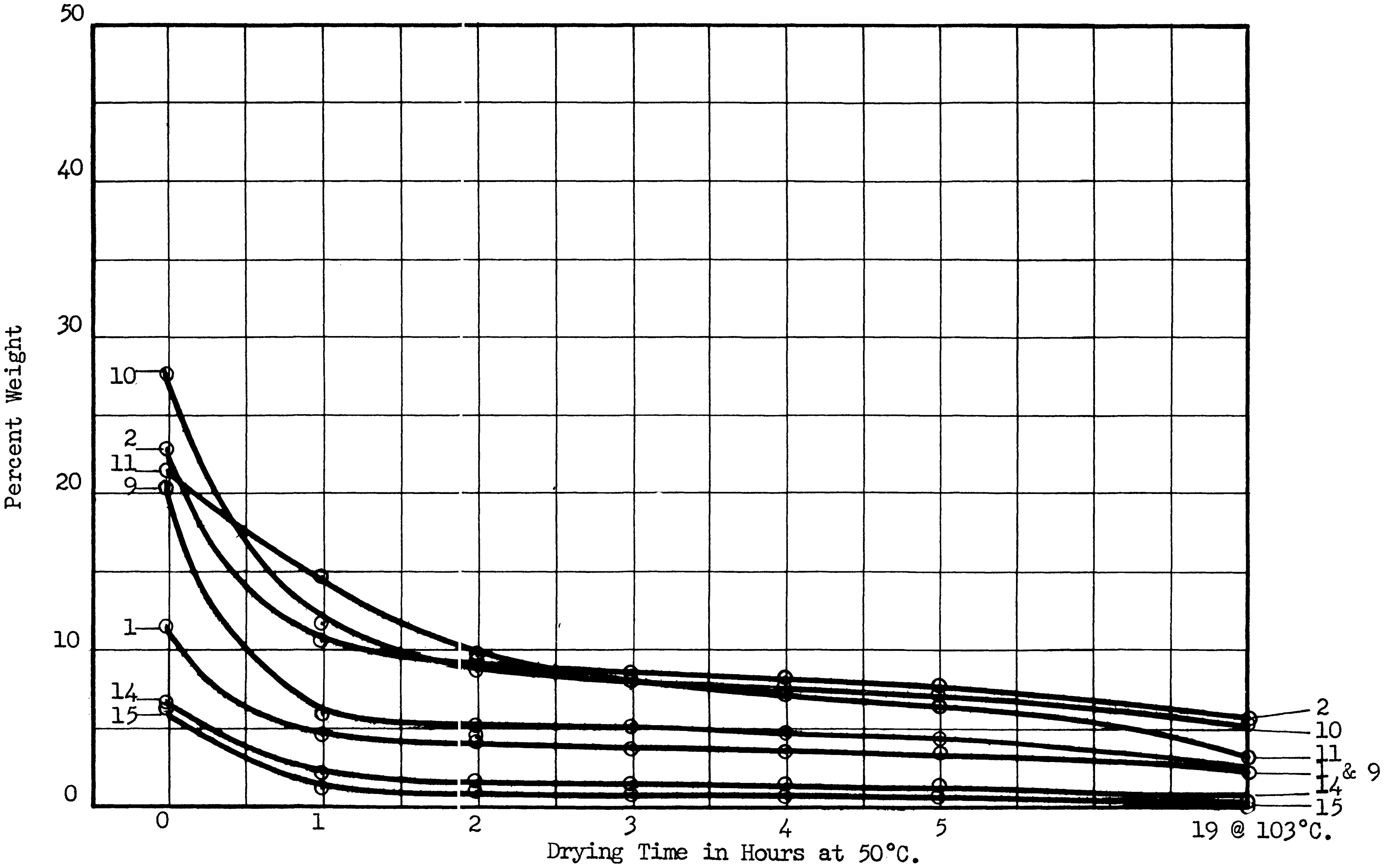
* See explanation of appendix.

TABLE VI

MEAN WEIGHT IN GRAMS AND IN PERCENT OVER DRY WEIGHT OF DOWELS PRETREATED WITH CLASS II RETARDANTS* AT THE INDICATED DRYING TIMES AND TEMPERATURES

Retardant				Hourly Weight when Dried at 50°C.						Wt. after add'l. 19 hrs. @ 103°C.	Wt. of Solid Dry Mater.
No.	Name	Unit	Dry Weight	0 Hour	1 Hour	2 Hours	3 Hours	4 Hours	5 Hours		
10	S.D. Bentonite + Airport Clay	Gr.	10.60	13.51	11.83	11.54	11.46	11.42	11.38	11.17	.57
		%	0	27.45	11.60	8.36	8.11	7.73	7.36	5.38	
2	Sodium Calcium Borate 4 lb./gal.	Gr.	11.49	14.13	12.70	12.56	12.48	12.43	12.40	12.16	.67
		%	0	22.97	10.53	9.31	8.62	8.18	7.92	5.83	
11	O'Keefe Cr. Bentonite 3 lb./gal.	Gr.	11.74	14.26	13.47	12.86	12.68	12.57	12.51	12.11	.37
		%	0	21.45	14.73	9.54	8.01	7.07	6.56	3.15	
9	S.D. Bentonite + Sodium Calcium Borate	Gr.	10.62	12.83	11.31	11.24	11.21	11.17	11.14	10.94	.27
		%	0	20.24	6.00	5.34	5.06	4.69	4.40	2.53	
1	Sodium Calcium Borate + Calgon	Gr.	11.82	13.17	12.37	12.30	12.28	12.26	12.25	12.07	.25
		%	0	11.42	4.65	4.06	3.89	3.72	3.64	2.11	
14	$(NH_4)2HPO_4$	Gr.	11.14	11.90	11.40	11.37	11.35	11.34	11.33	11.22	.05
		%	0	6.82	2.39	2.06	1.88	1.79	1.71	.72	
15	Water	Gr.	10.91	11.60	11.05	11.02	11.01	11.00	10.99	10.91	.00
		%	0	6.32	1.28	1.01	.92	.82	.73	0	

* See explanation of appendix.



Graph 2. Class II retardants*; hourly weight of treated dowels in percent over dry weight when dried for 5 hours at 50°C. and for 19 hours at 103°C. Refer to Table VI for values in grams and percent.

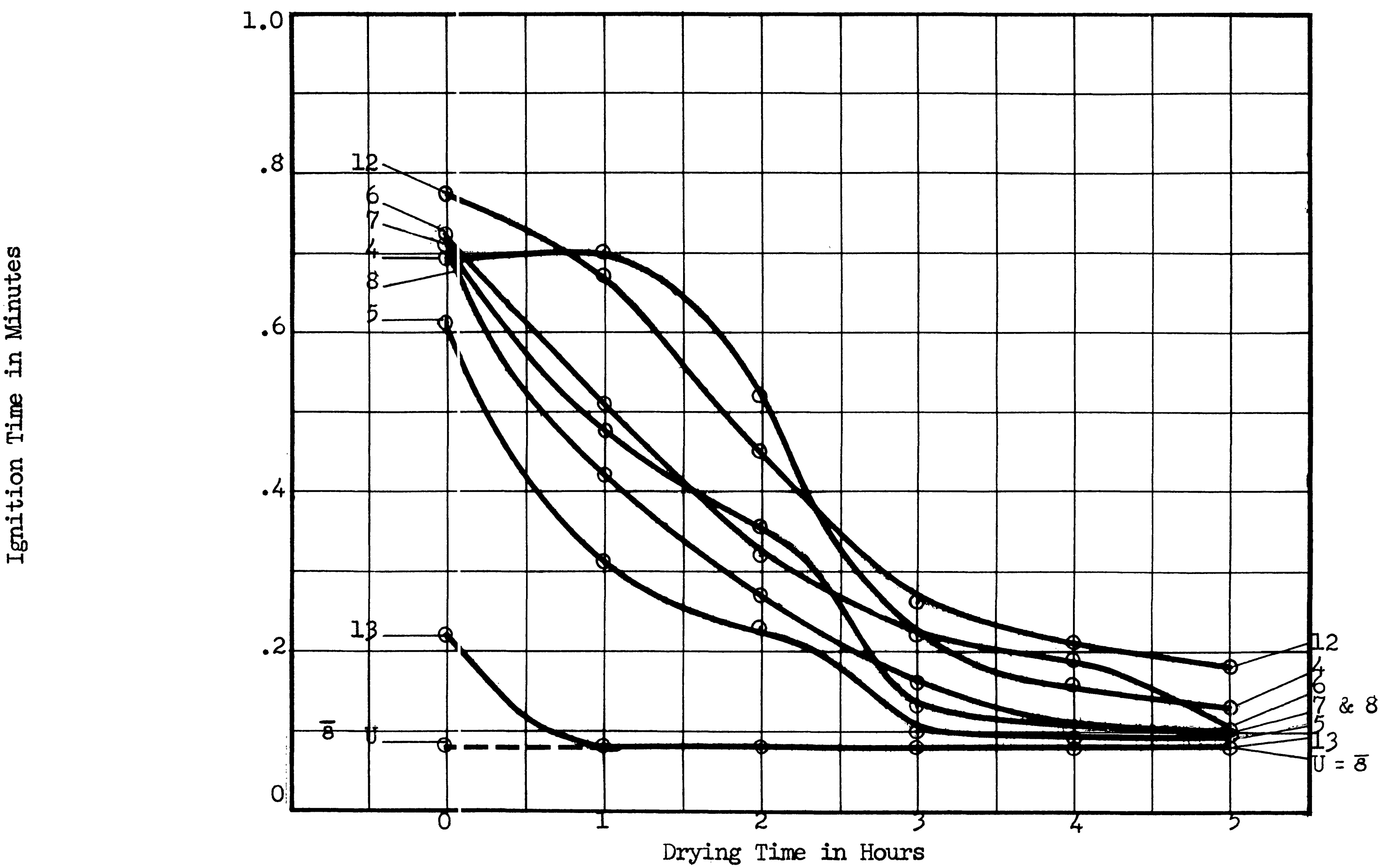
* See explanation of appendix.

TABLE VII

IGNITION TIME IN MINUTES OF TREATED AND UNTREATED DOWELS AFTER DIFFERENT DRYING TIMES

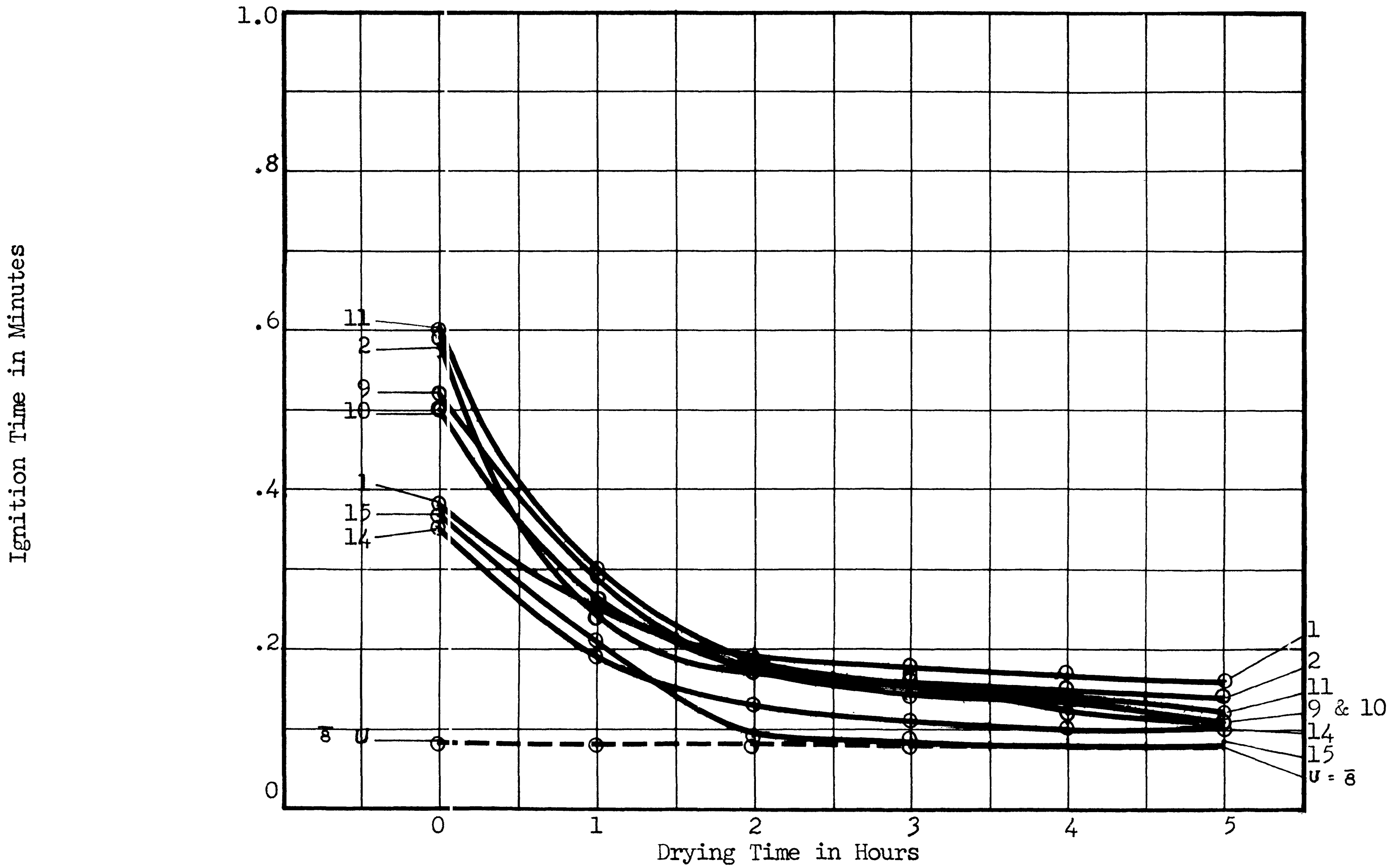
Retardant		Ignition after 0 hours drying	Ignition after 1 hour drying	Ignition after 2 hours drying	Ignition after 3 hours drying	Ignition after 4 hours drying	Ignition after 5 hours drying
No.	Name						
	Class I Retardants*						
4	S.D. Bentonite	.69	.70	.52	.22	.16	.13
12	O'Keefe Cr. Bentonite, 4 lbs./gal.	.77	.67	.45	.26	.21	.18
7	S.D. Bentonite + PMF Vermiculite	.71	.48	.36	.13	.11	.10
8	S.D Bentonite + Micronized Vermiculite	.71	.42	.27	.16	.11	.10
6	S.D. Bentonite + #4 Vermiculite	.72	.51	.26	.22	.19	.15
5	S.D. Bentonite + Calgon	.61	.31	.23	.15	.13	.13
13	$NH_4H_2PO_4$	.22	.08	.08	.08	.08	.08
	Class II Retardants*						
10	S.D. Bentonite + Airport Clay	.50	.26	.17	.14	.14	.11
2	Sodium Calcium Borate	.59	.24	.17	.16	.15	.14
11	O'Keefe Cr. Bentonite, 3 lbs./gal.	.60	.25	.18	.14	.13	.12
9	S.D. Bentonite + Sodium Calcium Borate	.52	.29	.17	.17	.16	.16
1	Sodium Calcium Borate + Calgon	.38	.25	.19	.18	.17	.16
14	$(NH_4)2HPO_4$	.35	.19	.13	.11	.10	.10
15	Water	.37	.11	.09	.08	-	-
	Untreated	.08	-	-	-	-	-

* See explanation of appendix.



Graph 3. Class I retardants*; ignition time in minutes plotted over hours of drying at 50°C. after treatment. Refer to Table VII for values.

* See explanation of appendix.



Graph 4. Class II retardants*; ignition time in minutes plotted over hours of drying at 50°C. after treatment. Refer to Table VII for values.

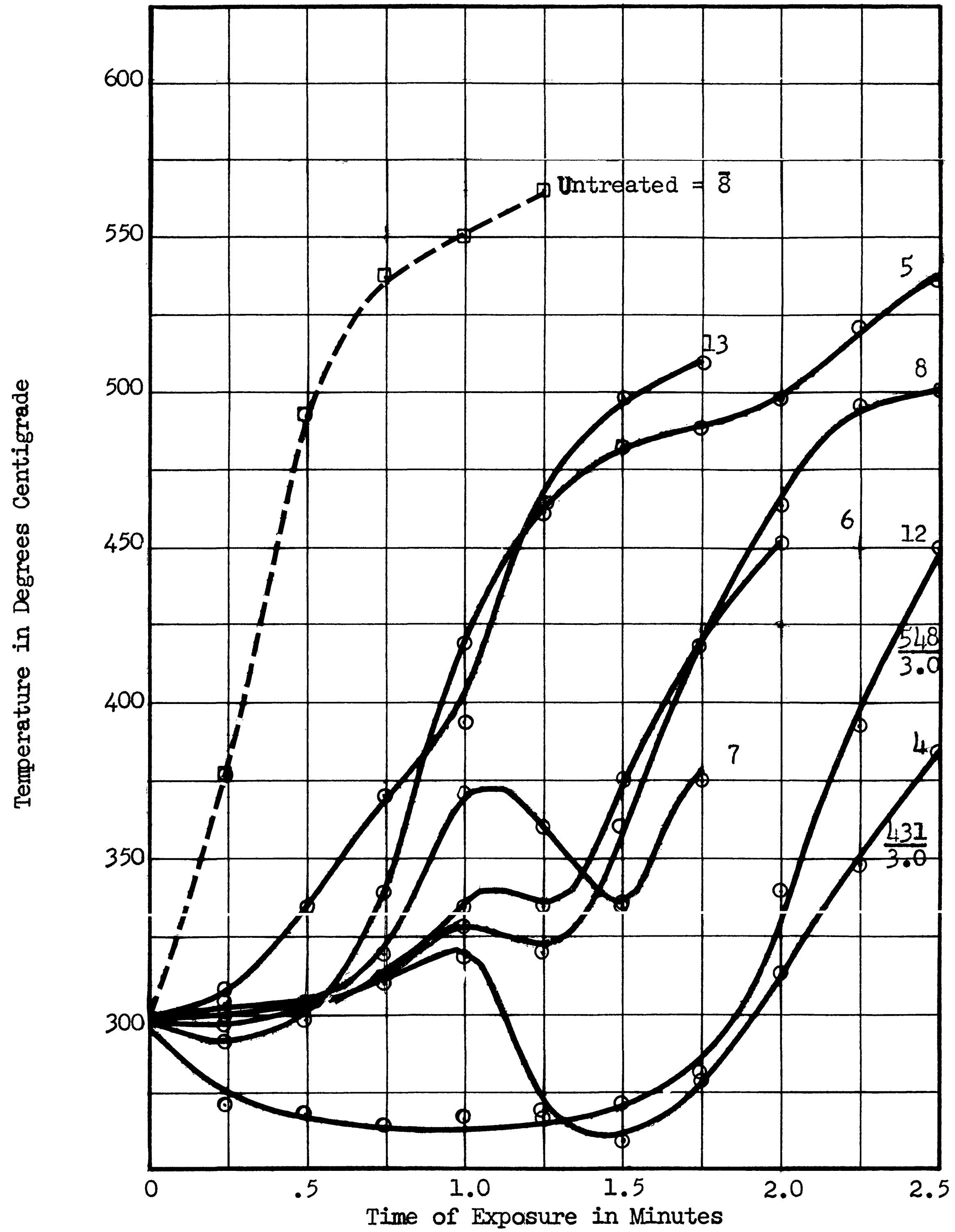
* See explanation of appendix.

TABLE VIII

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS PRETREATED WITH CLASS I RETARDANTS* - WET

Retardant No.	Retardant Name	°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	°C. at 2.0^m	°C. at 2.25^m	°C. at 2.5^m	°C. at 2.75^m	°C. at 3.0^m
4	S.D. Bentonite	300/0	300/40	305/10	311/30	319/60	267/60	260/140	280/190	314/235	349/275	385/270	412/250	431/245
12	O'Keefe Cr. Bentonite 4 lb./gal.	300/0	272/20	269/35	265/60	267/80	270/60	272/75	282/140	340/180	393/230	450/220	520/60	548/80
7	S.D. Bentonite + PMF Verm.	300/0	300/0	305/10	320/30	371/55	360/60	335/120	377/110					
8	S.D. Bentonite + Micronized Verm.	300/0	298/5	302/15	305/30	329/70	320/80	360/130	419/180	464/185	496/140	500/60		
6	S.D. Bentonite + #4 Verm.	300/0	304/25	305/30	311/35	335/40	335/40	375/100	424/95	451/115				
5	S.D. Bentonite + Calgon	300/0	292/50	299/60	340/80	420/40	462/110	483/130	489/125	499/95	521/75	537/30		
13	$NH_4H_2PO_4$	300/0	308/5	335/30	370/40	394/70	463/20	499/35	510/35					
	Untreated	300/0	377/40	493/30	537/20	550/25	565/35							

* See explanation of appendix.



Graph 5. Comparative mean temperature curves of wet, Class I retardant* treated dowels plus untreated dowels. Temperature plotted over every .25 minutes of exposure in the tube until peak temperature is reached. Refer to Table VIII for plotted values and ranges.

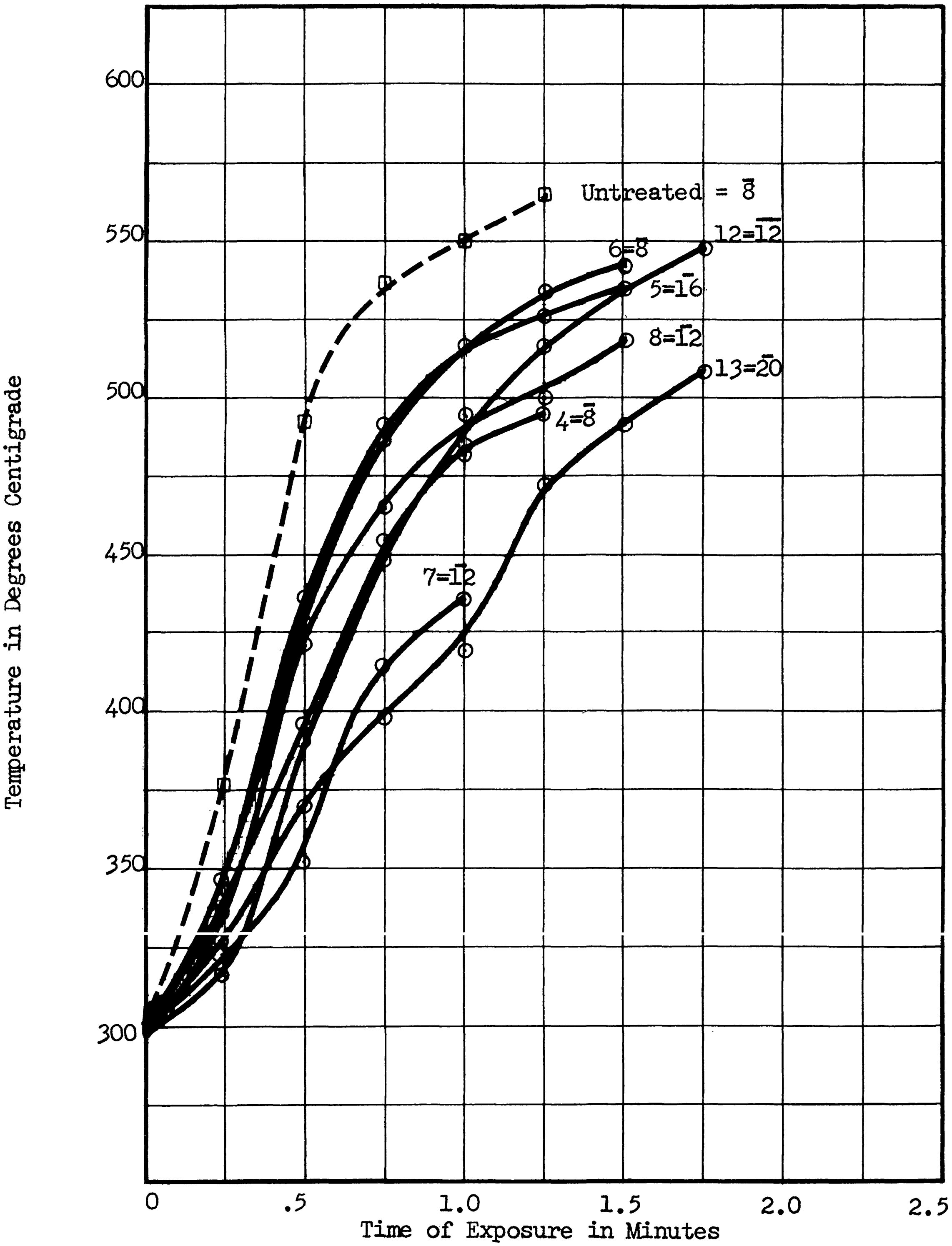
* See explanation of appendix.

TABLE IX

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS PRETREATED WITH CLASS I RETARDANTS* - DRY

Retardant		°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m
No.	Name								
4	S.D. Bentonite	300 0	340 65	396 110	454 130	485 130	495 60		
12	O'Keefe Cr. Bentonite 4 lb./gal.	300 0	317 40	391 40	449 70	482 70	517 70	535 85	548 75
7	S.D. Bentonite + PMF Verm.	300 0	320 30	352 55	415 90	436 85			
8	S.D. Bentonite + Micronized Verm.	300 0	346 55	421 85	465 90	494 90	500 100	519 30	
6	S.D. Bentonite + #4 Verm.	300 0	345 40	428 60	487 60	516 40	534 90	543 140	
5	S.D. Bentonite + Calgon	300 0	347 100	437 115	492 130	517 90	526 160	535 210	
13	$NH_4H_2PO_4$	300 0	327 40	370 60	399 80	420 85	473 90	492 100	509 75
	Untreated	300 0	377 40	493 30	537 20	550 25	565 35		

* See explanation of appendix.



Graph 6. Comparative mean temperature curves of dry, Class I retardant* treated dowels plus untreated dowels. Temperature plotted every .25 minutes of exposure in the tube until peak temperature is reached. Refer to Table IX for plotted values and ranges.

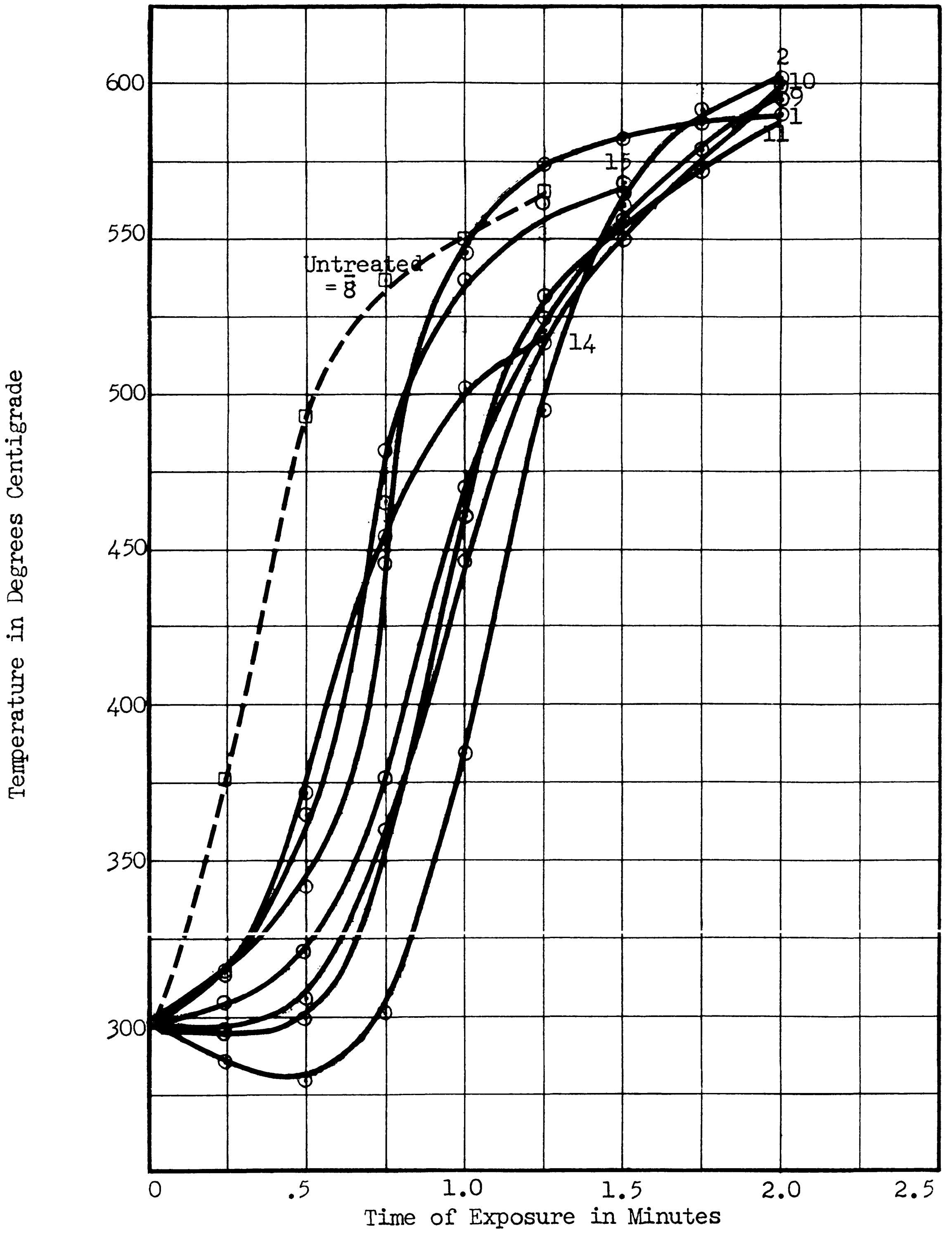
* See explanation of appendix.

TABLE X

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS PRETREATED WITH CLASS II RETARDANTS* - WET

Retardant No.	Name	°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	°C. at 2.0^m
10	S.D. Bentonite + Airport Clay	300/0	297/5	306/10	360/35	447/30	521/30	552/15	576/30	598/45
2	Sodium Calcium Borate	300/0	286/5	280/0	302/60	385/110	495/110	562/45	592/20	602/10
9	S.D. Bentonite + Sodium Calcium Borate	300/0	305/15	321/15	377/30	470/20	525/60	556/55	579/60	595/30
1	Sodium Calcium Borate + Calgon	300/0	315/10	342/50	466/35	546/20	574/30	582/30	587/40	590/80
11	O'Keefe Cr. Bentonite 3 lb./gal.	300/0	296/5	300/20	360/60	462/80	532/40	550/60	573/60	590/60
15	Water	300/0	314/10	365/60	482/40	537/20	562/50	564/70		
14	$(NH_4)2HPO_4$	300/0	315/15	372/60	454/55	502/30	517/60			
	Untreated	300/0	377/40	493/30	537/20	550/25	565/35			

* See explanation of appendix.



Graph 7. Comparative mean temperature curves of wet, Class II retardant* treated dowels plus untreated dowels. Temperature plotted every .25 minutes of exposure in the tube until peak temperature is reached. Refer to Table X for plotted values and ranges.

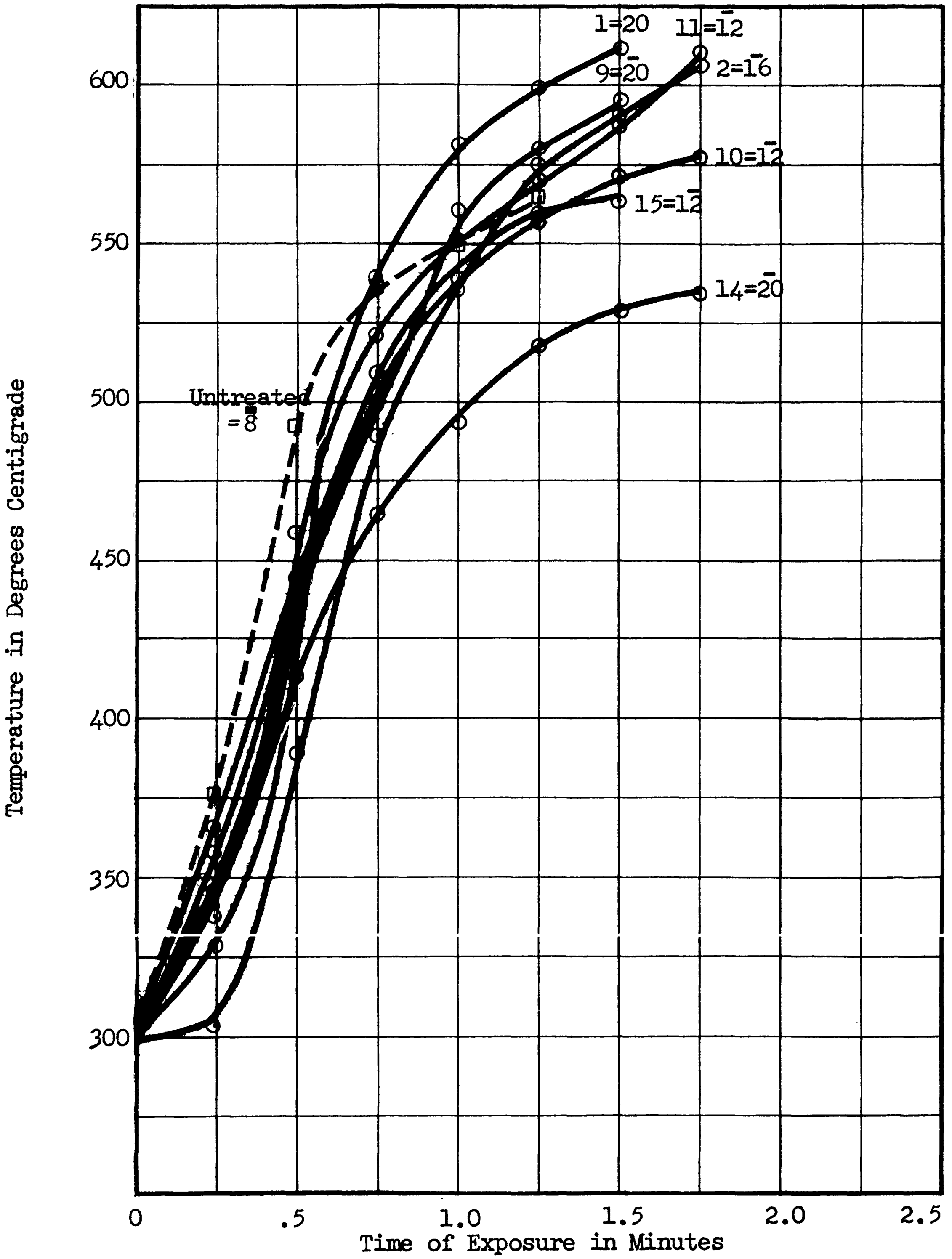
* See explanation of appendix.

TABLE XI

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS PRETREATED WITH CLASS II RETARDANTS* - DRY

Retardant No.	Name	°C. at 0m	°C. at .25m	°C. at .50m	°C. at .75m	°C. at 1.0m	°C. at 1.25m	°C. at 1.5m	°C. at 1.75m
10	S.D. Bentonite + Airport Clay	300/0	346/35	447/70	506/50	537/55	558/40	571/60	577/65
2	Sodium Calcium Borate	300/0	304/30	390/90	490/110	537/70	575/70	590/95	608/70
9	S.D. Bentonite + Sodium Calcium Borate	300/0	342/90	434/110	500/70	527/80	563/70	580/80	595/70
1	Sodium Calcium Borate + Calgon	300/0	329/80	447/120	539/140	581/75	599/80	611/60	
11	O'Keefe Cr. Bentonite 3 lb./gal.	300/0	358/50	459/40	522/40	552/40	570/80	587/90	610/40
15	Water	300/0	366/70	445/70	510/70	539/65	560/60		
14	$(NH_4)2HPO_4$	300/0	338/55	414/100	465/130	494/140	518/140	529/140	534/160
	Untreated	300/0	377/40	493/30	537/20	550/25	565/35		

* See explanation of appendix.



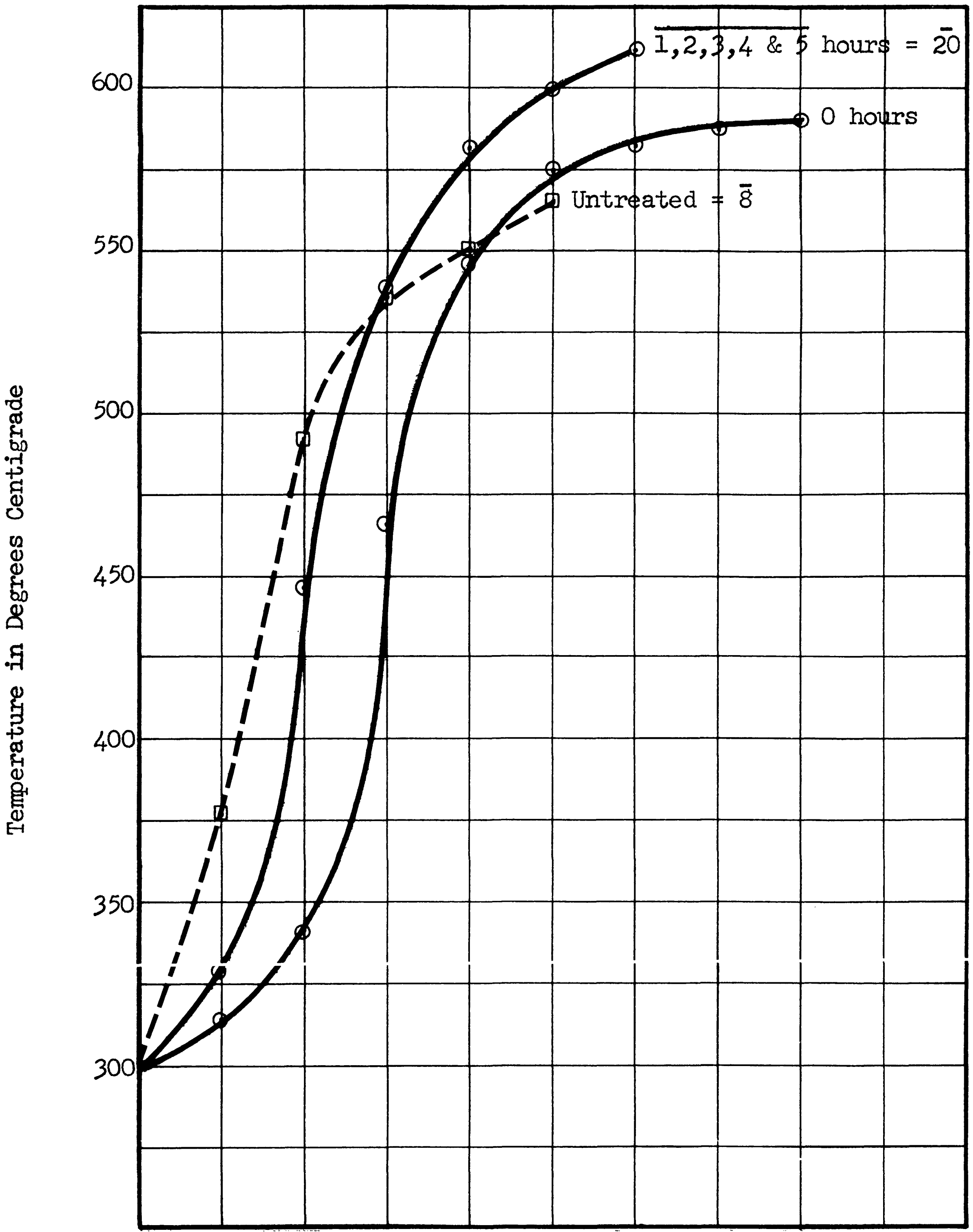
Graph 8. Comparative mean temperature curves of dry, Class II retardant* treated dowels plus untreated dowels. Temperature plotted every .25 minutes of exposure in the tube until peak temperature is reached. Refer to Table XI for plotted values and ranges.

* See explanation of appendix.

TABLE XII

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 1, SODIUM CALCIUM BORATE PLUS CALGON) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	°C. at 2.0^m	Duration of burn, minutes
0 Wet	300/0	315/10	342/30	466/35	546/20	574/30	582/30	587/40	590/80	2.70
1	300/0	325/75	427/120	507/115	579/45	601/55	610/50			2.36
2	300/0	327/20	430/35	540/60	570/55	590/25				2.19
3	300/0	330/30	440/40	544/70	579/60	595/50				2.19
4	300/0	331/20	469/20	548/20	582/20	602/40	610/55			2.20
5	300/0	331/60	470/80	559/70	594/60	609/70	614/35			2.16
Dry 1,2,3, 4,5	300/0	329/80	447/120	539/140	581/75	599/80	611/60			

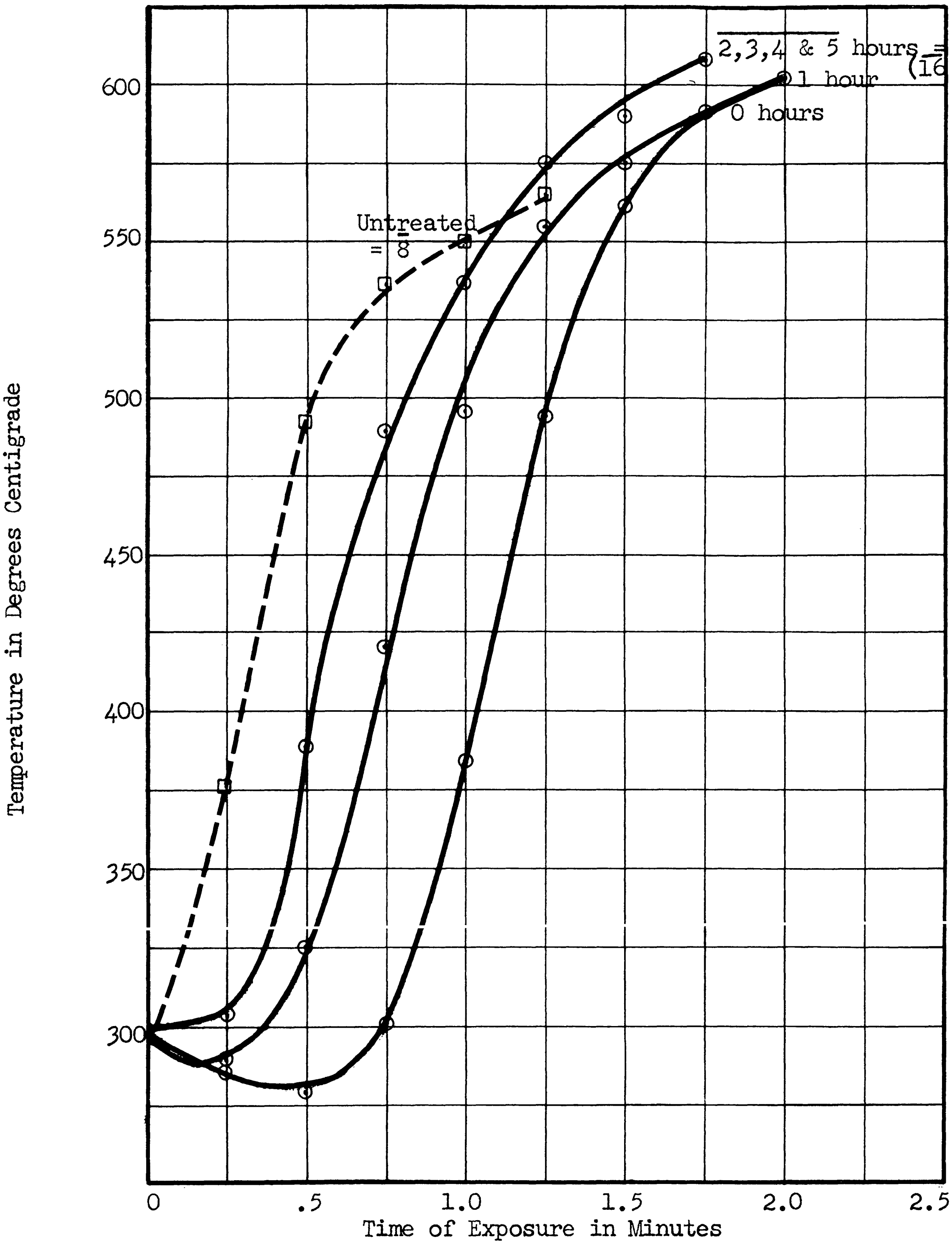


Graph 9. Comparative mean temperature curves of burning dowels pretreated with retardant #1, sodium calcium borate plus calgon after 0 and the mean of 1,2,3,4 & 5 hours of drying compared to untreated dowels. Refer to Table XII for plotted values and ranges.

TABLE XIII

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 2 SODIUM CALCIUM BORATE) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^m	°C. at .25^m	°C. at .50^m	°C. at .75^m	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	°C. at 2.0^m	Duration of burn, minutes
0 Wet	300 0	286 5	280 0	302 60	385 110	495 110	562 45	592 20	602 10	2.91
1	300 0	290 15	326 65	422 110	496 90	555 120	575 140	590 140	602 145	2.56
2	300 0	296 10	372 50	480 55	530 30	576 45	595 50			2.40
3	300 0	304 25	375 80	480 100	530 70	586 60	610 60	624 60		2.40
4	300 0	308 15	400 80	496 80	539 30	564 35	566 55			2.30
5	300 0	308 5	415 30	504 10	551 15	574 20	591 20	592 25		2.20
Dry 2,3,4, 5	300 0	304 30	390 90	490 110	537 70	575 70	590 95	608 70		

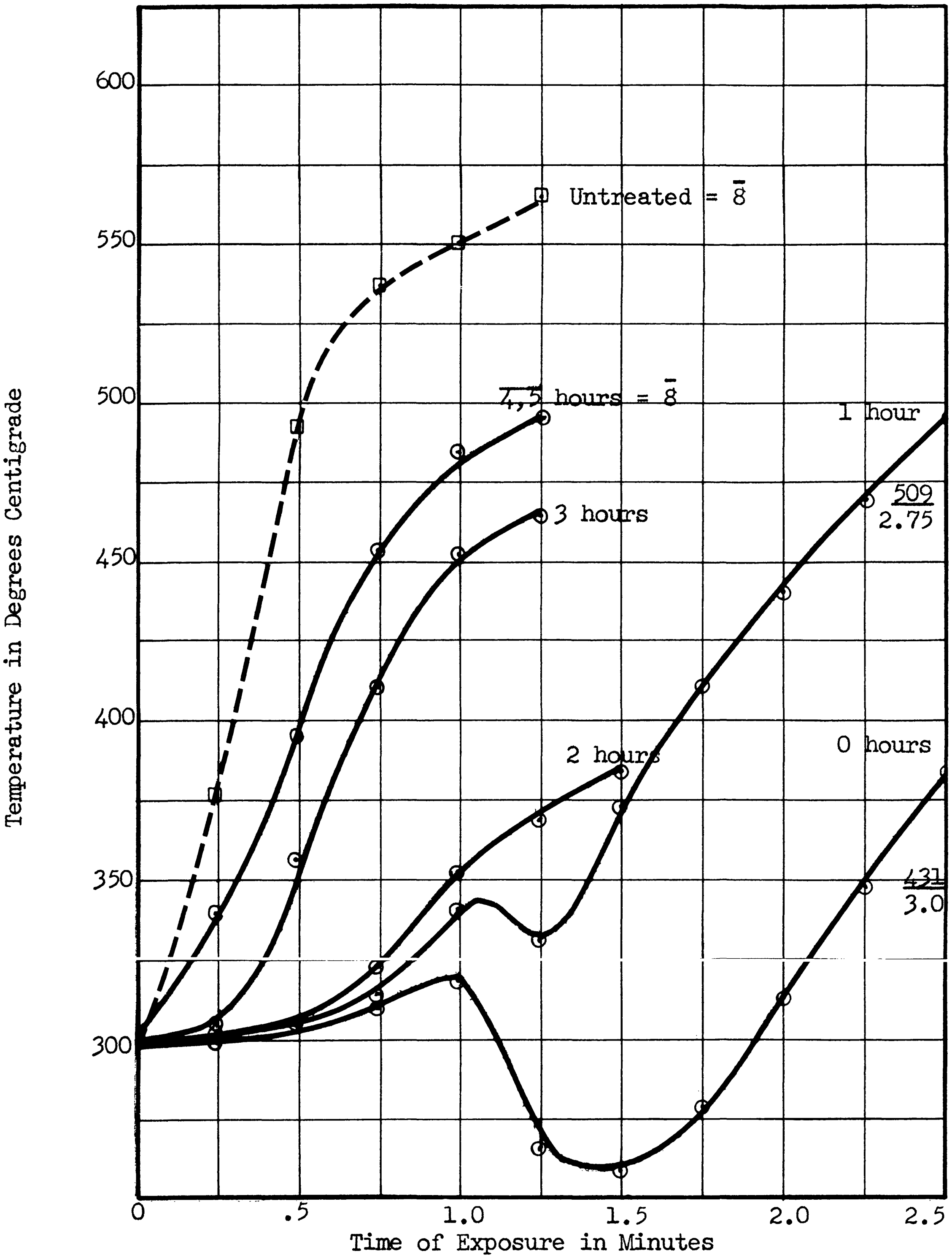


Graph 10. Comparative mean temperature curves of burning dowels pretreated with retardant #2, sodium calcium borate after 0, 1 and the mean of 2,3,4 & 5 hours of drying compared to untreated dowels. Refer to Table XIII for plotted values and ranges.

TABLE XIV

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 4 SOUTH DAKOTA BENTONITE) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^{m}	°C. at $.25^{m}$	°C. at $.50^{m}$	°C. at $.75^{m}$	°C. at 1.0^{m}	°C. at 1.25^{m}	°C. at 1.5^{m}	°C. at 1.75^{m}	°C. at 2.0^{m}	°C. at 2.25^{m}	°C. at 2.5^{m}	°C. at 2.75^{m}	°C. at 3.0^{m}	Duration of burn, minutes
0 Wet	300/0	300/40	305/10	311/30	319/60	267/60	260/140	280/190	314/235	349/275	385/270	412/250	431/245	4.75
1	300/0	302/5	306/15	315/20	342/60	332/60	374/45	412/90	441/95	470/130	496/155	509/135		3.87
2	300/0	302/5	306/35	323/90	353/105	370/130	385/195	385/190						2.90
3	300/0	306/10	357/100	411/105	452/110	465/35								2.40
4	300/0	325/20	387/100	451/125	487/120	495/60								2.31
5	300/0	355/40	405/70	457/35	484/45									2.21
Dry/4,5	300/0	340/65	396/110	454/130	485/130	495/60								

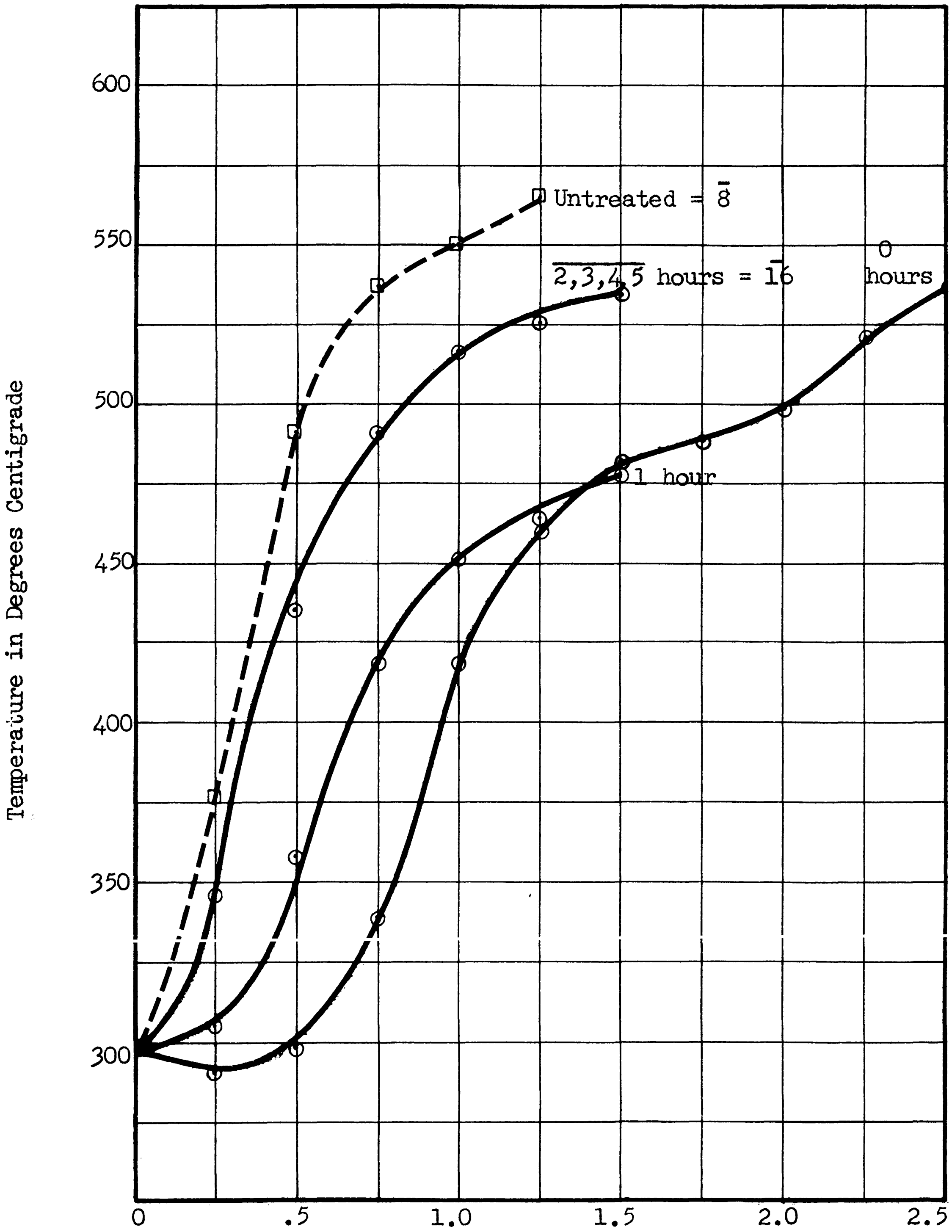


Graph 11. Comparative mean temperature curves of burning dowels pre-treated with retardant #4, South Dakota bentonite after 0, 1,2,3 and the mean of 4 & 5 hours of drying compared to untreated dowels. Refer to Table XIV for plotted values and ranges.

TABLE XV

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 5 SOUTH DAKOTA BENTONITE PLUS CALGON) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	°C. at 2.0^m	°C. at 2.25^m	°C. at 2.5^m	Duration of burn, minutes
0 Wet	300/0	292/50	299/60	340/80	420/40	462/110	483/130	489/125	499/95	521/75	537/30	2.71
1	300/0	306/20	359/50	420/70	452/80	465/75	477/90					2.26
2	300/0	323/40	392/70	462/70	485/80	455/160	458/200	477/140				2.24
3	300/0	347/70	429/110	484/55	516/80	540/30	555/40	560/20				2.10
4	300/0	356/40	461/25	520/30	537/50	559/40	561/50					2.05
5	300/0	362/30	465/50	514/40	530/40	550/70	565/100					2.10
Dry 2,3,4, 5	300/0	347/100	437/115	492/130	517/90	526/160	535/210					

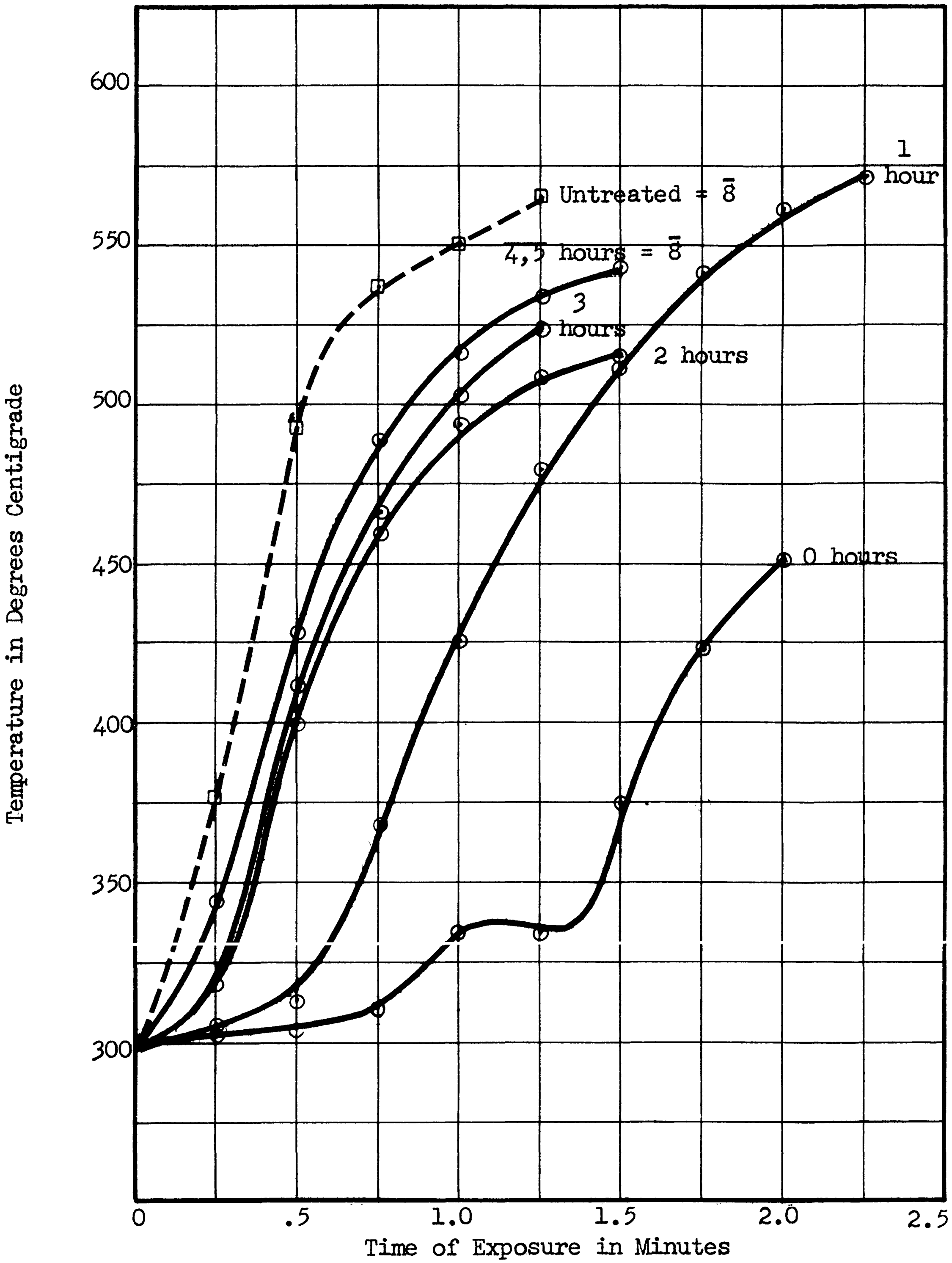


Graph 12. Comparative mean temperature curves of burning dowels pretreated with retardant #5, South Dakota bentonite + calgon after 0,1 and the mean of 2,3,4 & 5 hours of drying, compared to untreated dowels. Refer to Table XV for plotted values and ranges.

TABLE XVI

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 6 SOUTH DAKOTA BENTONITE PLUS NO. 4 EXFOLIATED VERMICULITE) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^{m}	°C. at $.25^{m}$	°C. at $.50^{m}$	°C. at $.75^{m}$	°C. at 1.0^{m}	°C. at 1.25^{m}	°C. at 1.5^{m}	°C. at 1.75^{m}	°C. at 2.0^{m}	°C. at 2.25^{m}	Duration of burn, minutes
0 Wet	300 0	304 25	305 30	311 35	335 40	336 40	375 100	424 95	451 115		3.29
1	300 0	306 10	314 25	369 45	427 80	480 90	516 90	541 90	562 100	572 100	2.97
2	300 0	319 25	400 40	460 10	494 20	509 35	511 35				2.36
3	300 0	317 10	412 40	466 40	503 90	525 70					2.34
4	300 0	342 40	422 40	485 40	518 40	534 90	543 140				2.33
5	300 0	347 10	435 40	488 50	514 40						2.30
Dry 4,5	300 0	345 40	428 60	487 60	516 40	534 90	543 140				

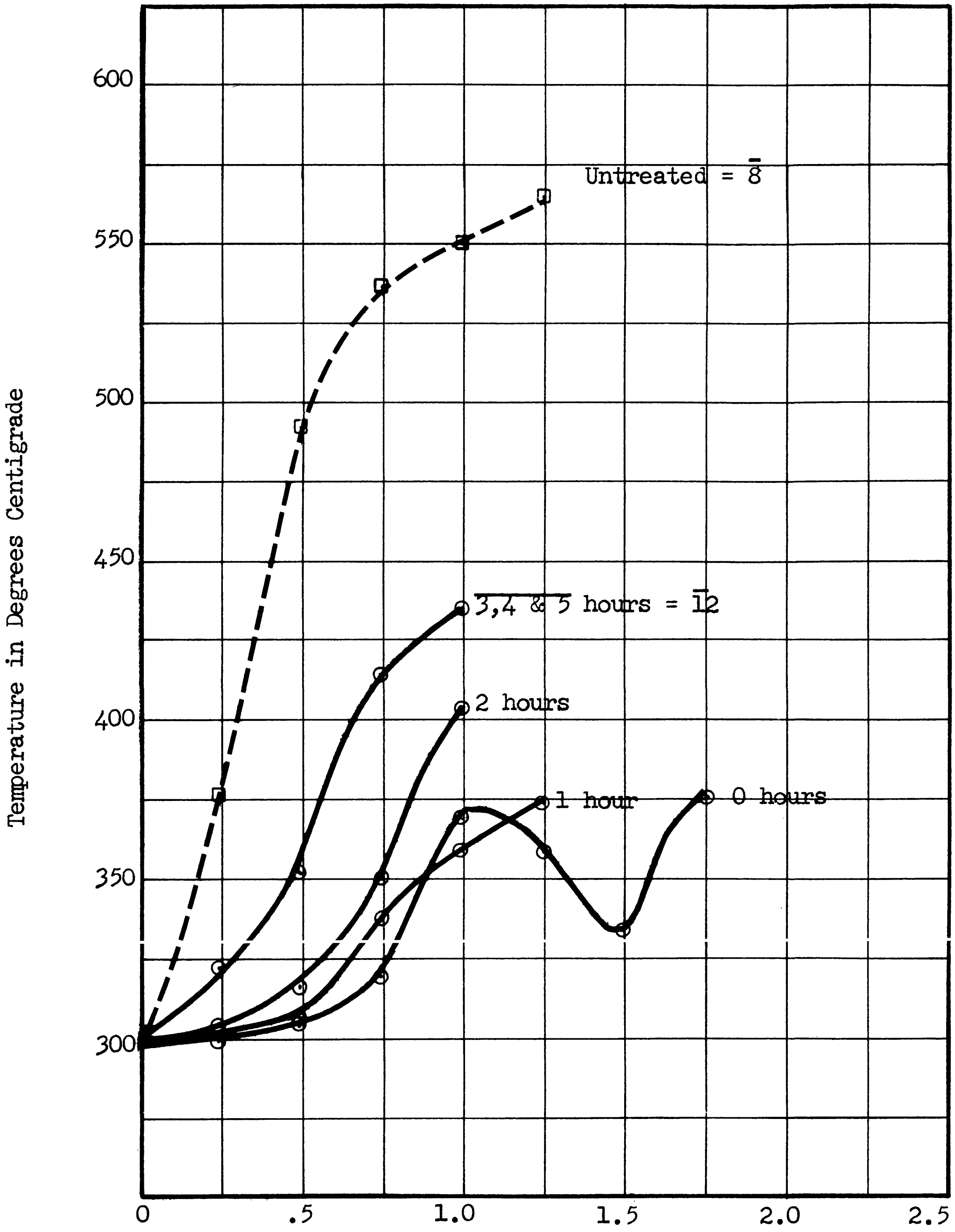


Graph 13. Comparative mean temperature curves of burning dowels pretreated with retardant #6, South Dakota bentonite plus #4 exfoliated vermiculite after 0,1,2,3 and the mean of 4 & 5 hours of drying compared to untreated dowels. Refer to Table XVI for plotted values and ranges.

TABLE XVII

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 7 SOUTH DAKOTA BENTONITE PLUS PMF VERMICULITE) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	Duration of burn, minutes
0 Wet	300/0	300/0	305/10	320/30	371/55	360/60	335/120	377/110	2.80
1	300/0	300/0	306/10	337/80	363/60	375/10			1.29
2	300/0	305/20	317/35	351/25	405/25				1.60
3	300/0	320/0	345/50	411/85	455/50				1.69
4	300/0	320/20	350/40	417/40	456/50				2.50
5	300/0	330/20	362/40	418/10					2.62
Dry/3,4,5	300/0	320/30	352/55	415/90	436/85				

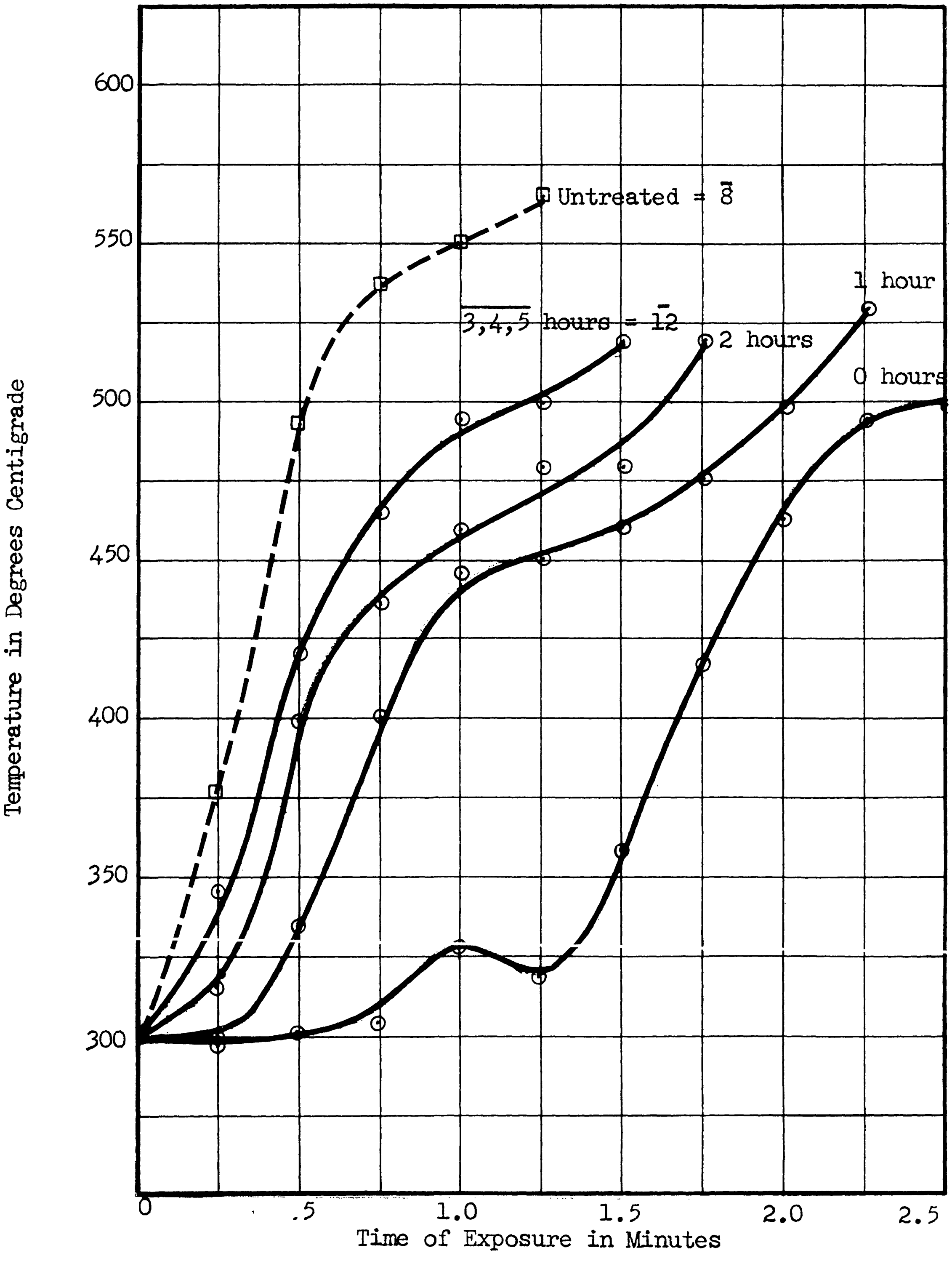


Graph 14. Comparative mean temperature curves of burning dowels pretreated with retardant #7, South Dakota bentonite plus PMF vermiculite after 0,1,2 and the mean of 3,4 & 5 hours of drying compared to untreated dowels. Refer to Table XVII for plotted values and ranges.

TABLE XVIII

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 8 SOUTH DAKOTA BENTONITE PLUS MICRONIZED VERMICULITE) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^{m}	°C. at $.25^{m}$	°C. at $.50^{m}$	°C. at $.75^{m}$	°C. at 1.0^{m}	°C. at 1.25^{m}	°C. at 1.5^{m}	°C. at 1.75^{m}	°C. at 2.0^{m}	°C. at 2.25^{m}	°C. at 2.5^{m}	Duration of burn, minutes
0 Wet	300/0	298/5	302/15	305/30	329/70	320/80	360/130	419/180	464/185	496/140	500/60	3.46
1	300/0	300/10	336/85	402/150	447/170	451/185	462/175	477/160	499/145	530/70	557/50	2.81
2	300/0	316/10	400/70	437/140	460/100	480/130	480/90	520/140				2.31
3	300/0	346/55	424/40	478/80	515/50							2.15
4	300/0	345/40	440/80	449/35	462/40	480/60	533/10					2.14
5	300/0	346/20	420/30	469/35	505/35	519/40	515/30					2.13
Dry/3,4,5	300/0	346/55	421/85	465/90	494/90	500/100	519/30					

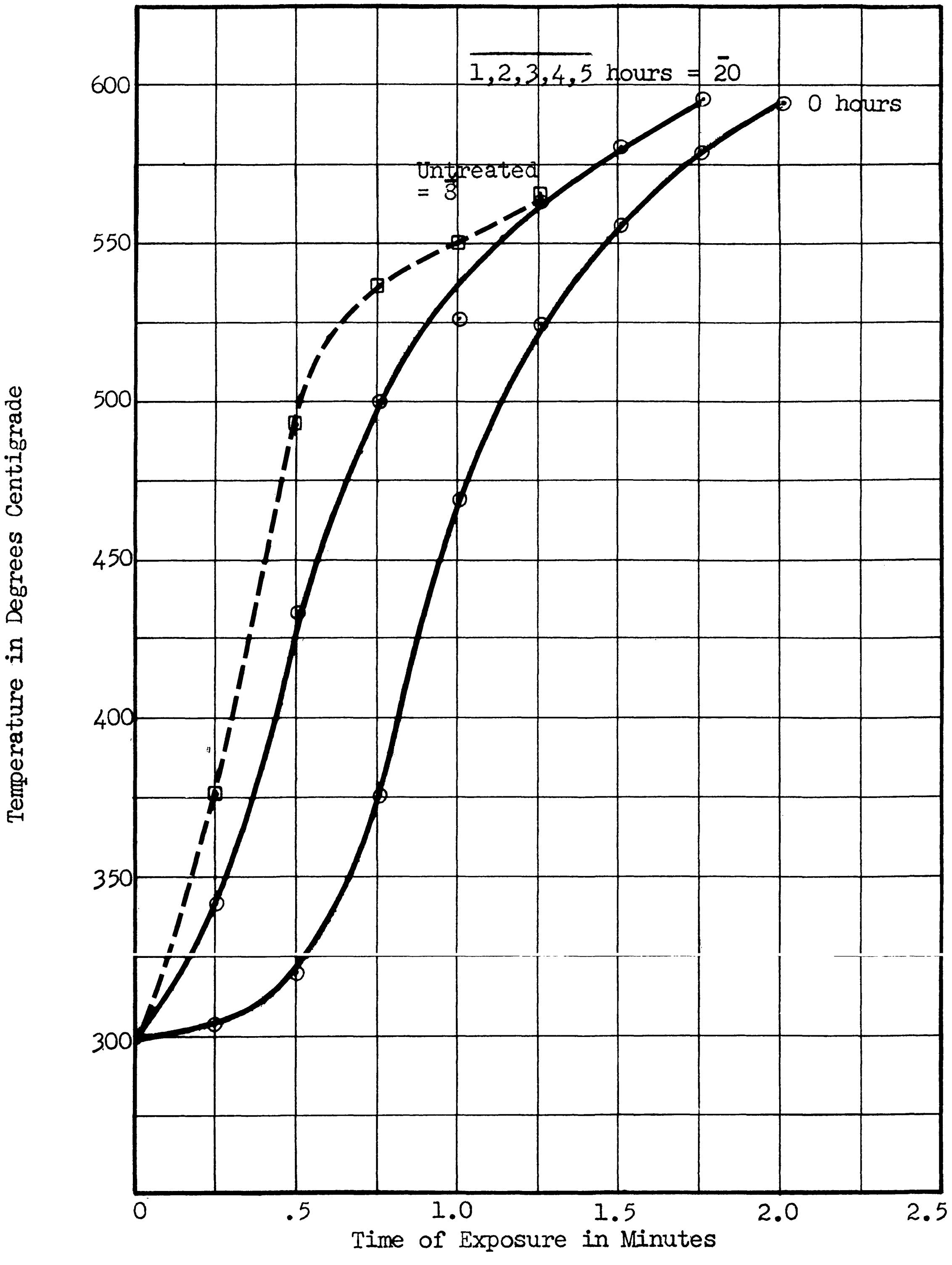


Graph 15. Comparative mean temperature curves of burning dowels pretreated with retardant #8, South Dakota bentonite plus micronized vermiculite after 0,1,2,3 and the mean of 4 & 5 hours of drying compared to untreated dowels. Refer to Table XVIII for plotted values and ranges.

TABLE XIX

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 9 SOUTH DAKOTA BENTONITE PLUS SODIUM CALCIUM BORATE) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C.° at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	°C. at 2.0^m	Duration of burn, minutes
0 Wet	300 0	305 15	321 15	377 30	470 20	525 60	556 55	579 60	594 55	2.91
1	300 0	305 10	382 30	475 30	522 25	561 15	572 20	584 30	595 30	2.56
2	300 0	331 45	435 40	496 40	518 65	560 65	578 65	596 60		2.25
3	300 0	352 50	444 65	501 70	522 40	557 60	567 80			2.11
4	300 0	352 30	457 10	519 35	545 30	579 15	594 25	606 20		2.11
5	300 0	370 50	452 60	510 30	529 30	558 35	590 0			2.06
Dry 1,2,3, 4,5	300 0	342 90	434 110	500 70	527 80	563 70	580 80	595 70		

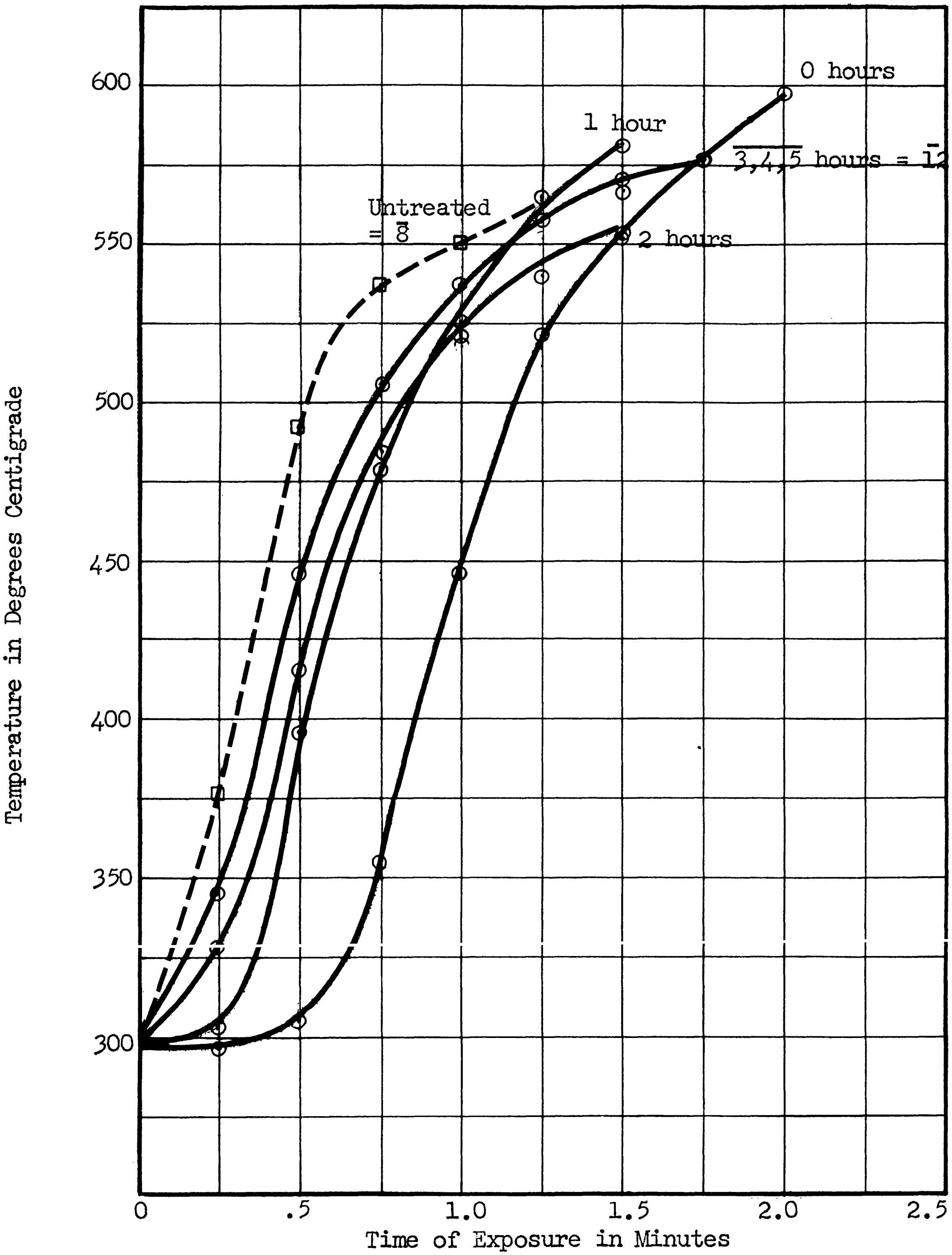


Graph 16. Comparative mean temperature curves of burning dowels pretreated with retardant #9, South Dakota bentonite plus sodium calcium borate after 0 and the mean of 1,2,3,4 & 5 hours of drying compared to untreated dowels. Refer to Table XIX for plotted values and ranges.

TABLE XX

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 10 SOUTH DAKOTA BENTONITE PLUS AIRPORT CLAY) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	°C. at 2.0^m	Duration of burn, minutes
0 Wet	300 0	297 5	306 10	360 35	447 30	521 30	552 15	576 30	598 45	2.90
1	300 0	304 5	397 35	480 70	520 50	565 20	582 30			2.37
2	300 0	329 20	417 35	485 15	525 40	540 40	554 19			2.18
3	300 0	340 0	432 50	495 40	530 35	546 10	564 15	565 35		2.15
4	300 0	342 30	444 30	505 20	539 35	565 30	581 25	590 40		2.10
5	300 0	356 25	466 20	519 20	541 25	562 30	567 60			2.06
Dry 3,4,5	300 0	346 35	447 70	506 50	537 55	558 40	571 60	577 65		

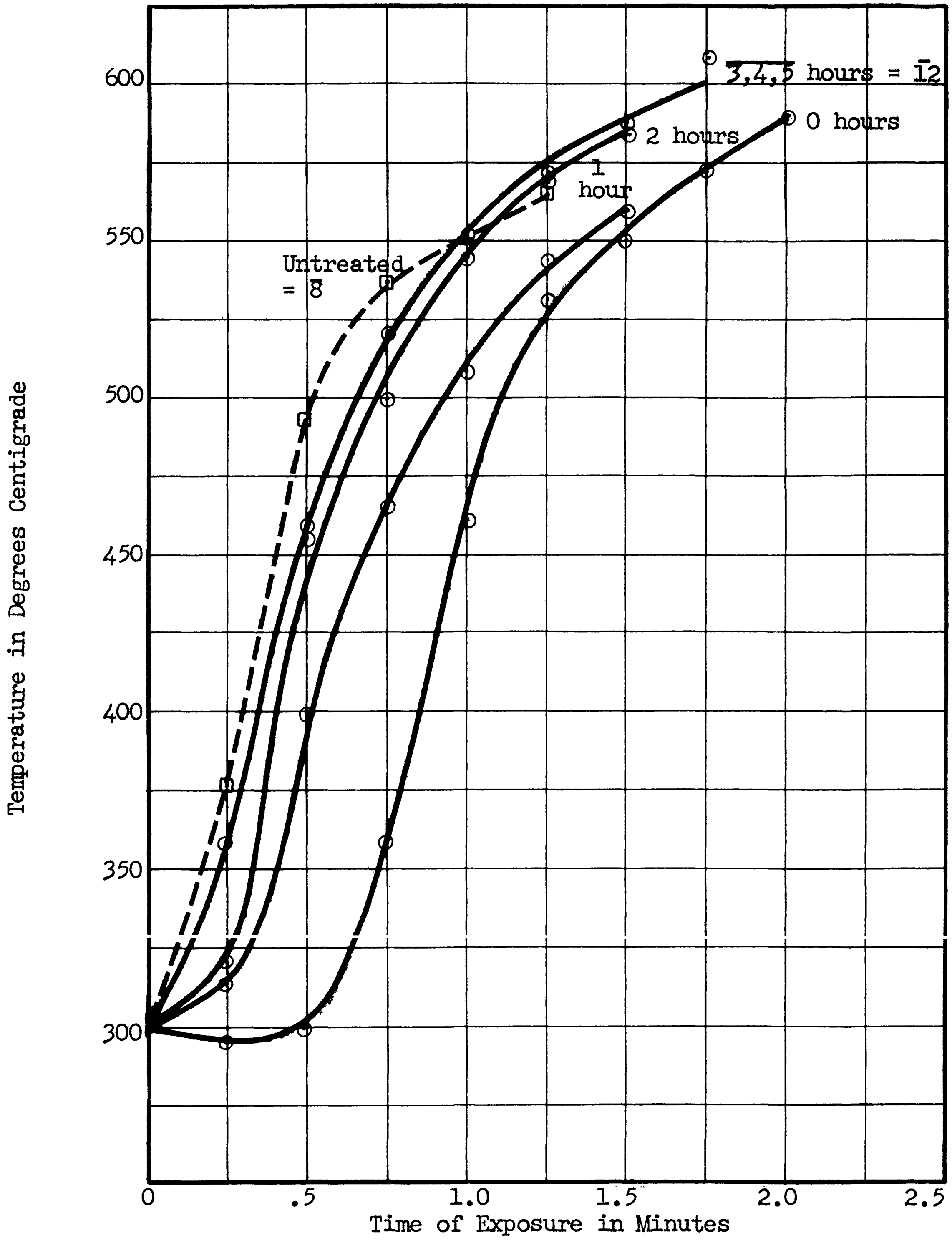


Graph 17. Comparative mean temperature curves of burning dowels pretreated with retardant #10, South Dakota bentonite plus airport clay after 0,1,2 and the mean of 3,4 & 5 hours of drying compared to untreated dowels. Refer to Table XX for plotted values and ranges.

TABLE XXI

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 11 O'KEEFE CREEK BENTONITE 3 POUNDS/GALLON) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	°C. at 2.0^m	Duration of burn, minutes
0 Wet	300 0	296 5	300 20	360 60	462 80	532 40	550 60	573 60	590 60	2.46
1	300 0	314 40	400 90	467 90	509 70	544 85	560 70			2.30
2	300 0	322 30	417 60	500 45	545 45	571 40	585 60			2.29
3	300 0	357 30	457 30	514 25	545 30	571 50	585 40			2.18
4	300 0	357 30	460 40	524 40	555 30	570 80	590 70	610 20		2.15
5	300 0	360 50	460 20	527 30	557 30	570 20	590 20			2.13
Dry 3,4,5	300 0	358 50	459 40	522 40	552 40	570 80	587 90	610 40		

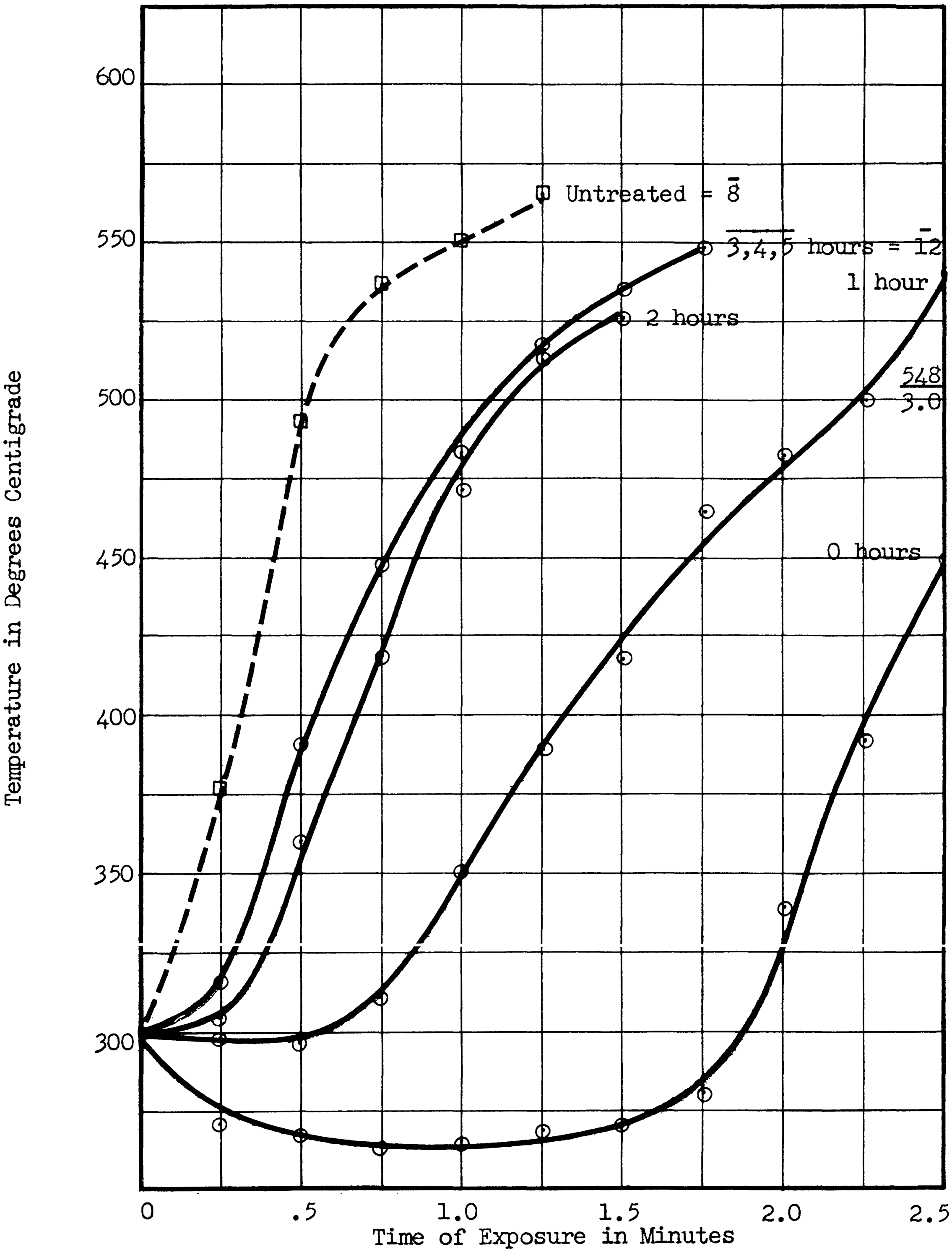


Graph 18. Comparative mean temperature curves of burning dowels pretreated with retardant #11, O'Keefe Creek bentonite (3 lbs./gal.) after 0,1,2 and the mean of 3,4, & 5 hours of drying compared to untreated dowels. Refer to Table XXI for plotted values and ranges.

TABLE XXII

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 12 O'KEEFE CREEK BENTONITE 4 POUNDS/GALLON) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^{m}	°C. at $.25^{m}$	°C. at $.50^{m}$	°C. at $.75^{m}$	°C. at 1.0^{m}	°C. at 1.25^{m}	°C. at 1.5^{m}	°C. at 1.75^{m}	°C. at 2.0^{m}	°C. at 2.25^{m}	°C. at 2.5^{m}	°C. at 2.75^{m}	°C. at 3.0^{m}	Duration of burn, minutes
0 Wet	300 0	272 20	269 35	265 60	267 80	270 60	272 75	282 140	340 180	393 230	450 220	520 60	548 80	3.04
1	300 0	299 5	297 10	312 20	351 75	390 70	428 50	465 55	483 70	500 70	540 40			2.72
2	300 0	305 10	361 60	420 40	472 50	515 60	526 85							2.51
3	300 0	312 20	385 20	430 40	470 50	507 70	526 70	531 20						2.52
4	300 0	317 20	391 20	461 45	496 40	536 45	551 60	565 55						2.30
5	300 0	322 30	397 10	457 30	480 20	508 40	530 60							2.36
Dry 3,4,5	300 0	317 40	391 40	449 70	482 70	517 70	535 85	548 75						

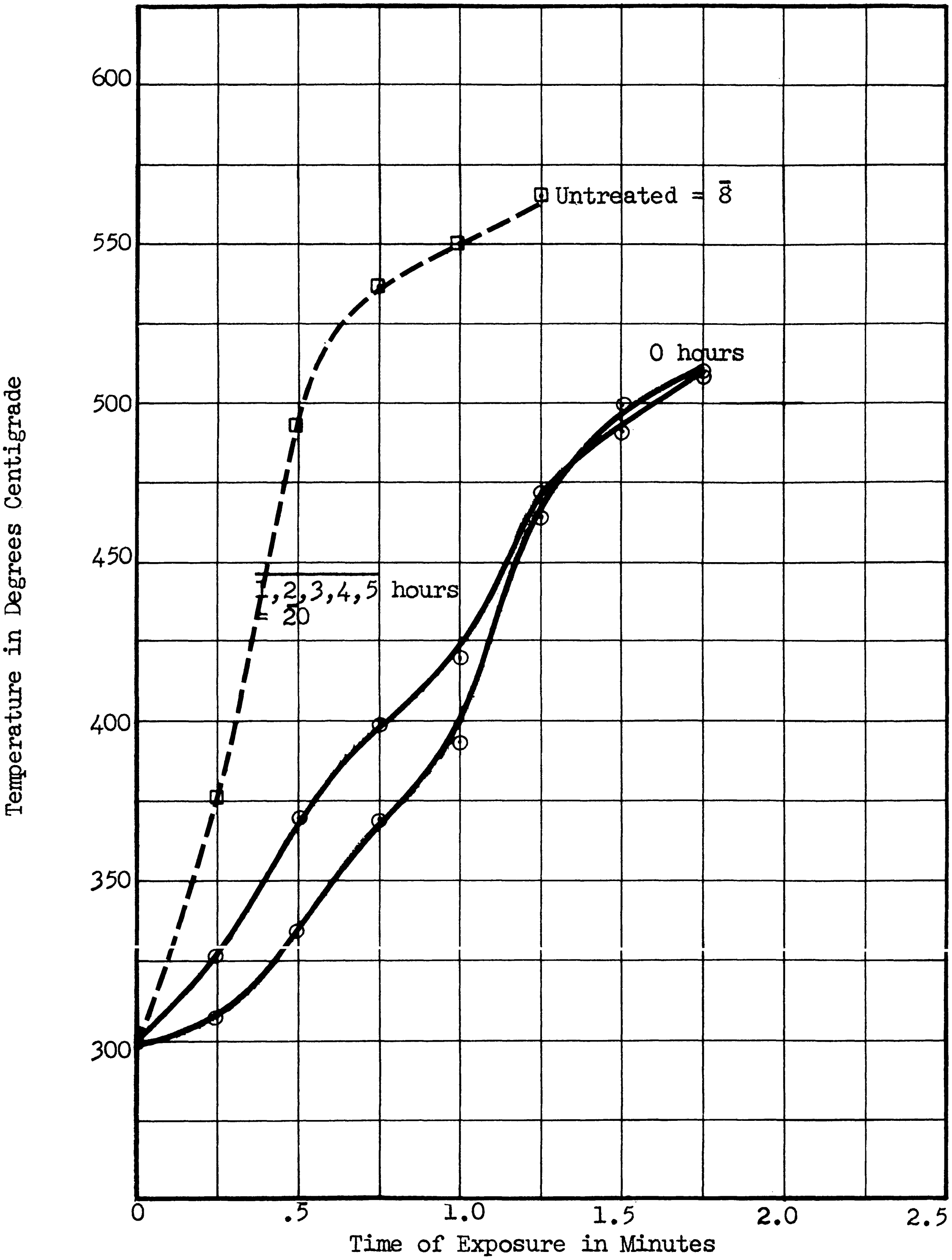


Graph 19. Comparative mean temperature curves of burning dowels pretreated with retardant #12, O'Keefe Creek bentonite (4 lbs./gal.) after 0,1,2 and the mean of 3,4 & 5 hours of drying compared to untreated dowels. Refer to Table XXII for plotted values and ranges.

TABLE XXIII

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 13 MONOAMMONIUM PHOSPHATE $NH_4H_2PO_4$) AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0m	°C. at .25m	°C. at .50m	°C. at .75m	°C. at 1.0m	°C. at 1.25m	°C. at 1.5m	°C. at 1.75m	Duration of burn, minutes
0 Wet	300/0	308/5	335/30	370/40	394/70	463/20	499/35	510/35	2.27
1	300/0	337/10	366/25	392/20	411/20	475/20	494/50		2.16
2	300/0	330/20	381/30	415/30	444/35	490/40	522/35		2.10
3	300/0	328/20	369/20	396/25	415/40	479/45	501/65	512/75	2.13
4	300/0	320/30	372/50	400/80	419/80	469/75	479/70	505/0	2.20
5	300/0	321/10	364/55	392/65	411/85	455/80	466/85		2.27
Dry 1,2,3,4,5	300/0	327/40	370/60	399/80	420/85	473/90	492/100	509/75	

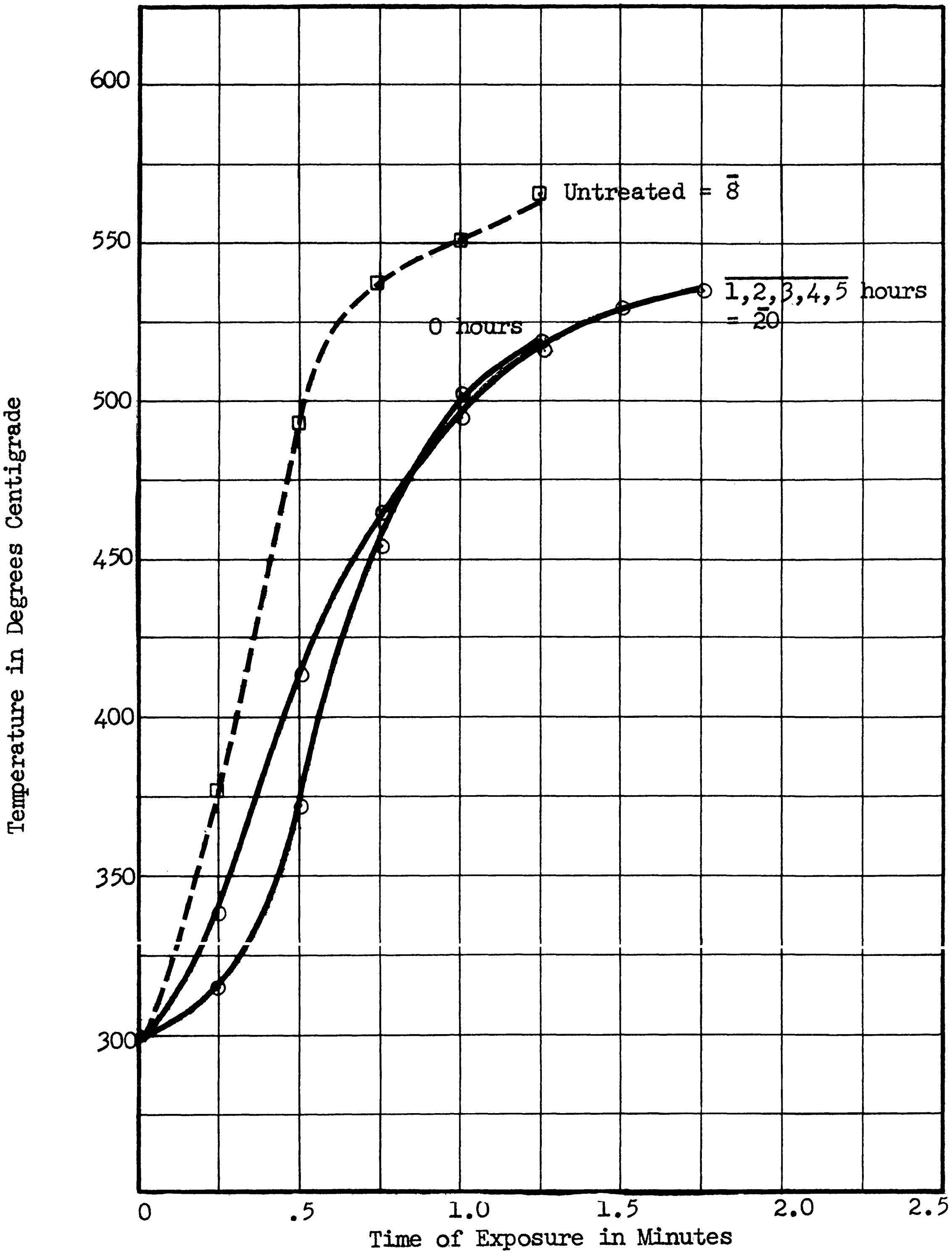


Graph 20. Comparative mean temperature curves of burning dowels pretreated with retardant #13, monoammonium phosphate after 0 and the mean of 1,2,3,4 & 5 hours of drying compared to untreated dowels. Refer to Table XXIII for plotted values and ranges.

TABLE XXIV

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 14 DIAMMONIUM PHOSPHATE $(NH_4)2HPO_4)$ AFTER DIFFERENT DRYING TIMES

Drying time, hours	°C. at 0^m	°C. at $.25^m$	°C. at $.50^m$	°C. at $.75^m$	°C. at 1.0^m	°C. at 1.25^m	°C. at 1.5^m	°C. at 1.75^m	Duration of burn, minutes
0 Wet	300 0	315 15	372 60	454 55	502 30	517 60			2.34
1	300 0	340 55	425 40	475 40	507 35	531 60	547 65	575 30	2.14
2	300 0	341 20	427 40	490 70	527 60	548 50	567 40		2.16
3	300 0	341 5	427 40	488 50	510 70	535 50	538 80	560 40	2.25
4	300 0	340 40	422 60	471 55	505 60	531 25	535 60		2.15
5	300 0	329 20	371 20	405 30	421 35	446 50	460 60	466 70	2.05
Dry 1,2,3 4,5	300 0	338 55	414 100	465 130	494 140	518 140	529 140	534 160	

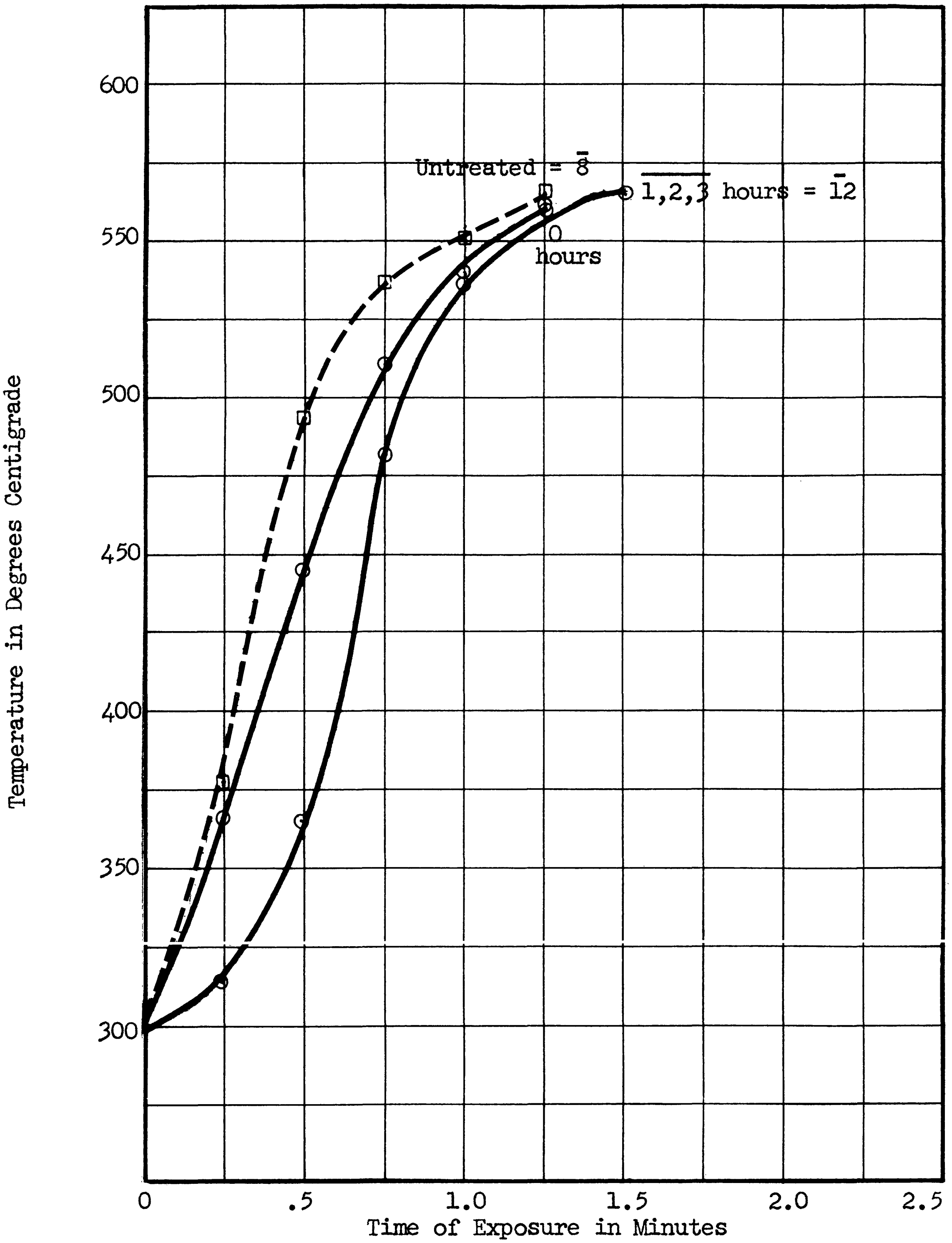


Graph 21. Comparative mean temperature curves of burning dowels pretreated with retardant #14, diammonium phosphate after 0 and the mean of 1,2,3,4 & 5 hours of drying compared to untreated dowels. Refer to Table XXIV for plotted values and ranges.

TABLE XXV

MEAN QUARTER-MINUTE TEMPERATURE/RANGE IN °C. OF BURNING DOWELS (PRETREATED WITH RETARDANT NO. 15 WATER) AFTER DIFFERENT DRYING TIMES - ALSO UNTREATED DOWELS

Drying time, hours	°C. at 0^{m}	°C. at $.25^{m}$	°C. at $.50^{m}$	°C. at $.75^{m}$	°C. at 1.0^{m}	°C. at 1.25^{m}	°C. at 1.5^{m}	Duration of burn, minutes
0 Wet	300 0	314 10	365 60	482 40	537 20	562 50	564 90	2.11
1	300 0	366 10	469 20	521 40	532 35	548 25		1.91
2	300 0	380 40	471 55	517 50	530 60	567 50		1.94
3	300 0	405 70	476 60	522 60	557 45	565 55		1.97
Dry 1,2,3	300 0	366 70	445 70	510 70	539 65	560 60		
Un-treated	300 0	377 40	493 30	537 20	550 25	565 35		1.96



Graph 22. Comparative mean temperature curves of burning dowels pretreated with retardant #15, (water) after 0 and the mean of 1,2 & 3 hours of drying compared to untreated dowels. Refer to Table XXV for plotted values and ranges.

TABLE XXVI

RESISTANCE TO BURNING INDEX OF THE VARIOUS RETARDANTS COMPUTED FROM THE TEMPERATURE CURVES SHOWN ON GRAPHS 9 - 22, INCLUSIVE

Retardant		Index at Given Times				
No.	Name	Wet 0 hours	1 hour	2 hours	3 hours	Dry
	Class I Retardants*					
4	S.D. Bentonite	73.41	72.07	68.90	48.17	29.27
12	O'Keefe Cr. Bentonite 4 lbs./gal.	90.00	71.95	45.73		33.90
7	S.D. Bentonite + PMF Vermiculite	67.68	65.85	57.93		45.12
8	S.D. Bentonite + Micronized Vermiculite	73.54	51.09	36.59		25.00
6	S.D. Bentonite + #4 Vermiculite	71.95	58.41	30.36	26.71	18.41
5	S.D. Bentonite + Calgon	65.85	45.73			17.07
13	Monoammonium Phosphate $NH_4H_2PO_4$	56.71				44.51
	Class II Retardants*					
10	S.D. Bentonite + Airport Clay	74.39	34.27	22.56		14.02
2	Sodium Calcium Borate	75.00	48.78			27.44
11	O'Keefe Cr. Bentonite 3 lbs./gal.	71.95	32.93	19.27		7.93
9	S.D. Bentonite + Sodium Calcium Borate	52.44				15.24
1	Sodium Calcium Borate + Calgon	38.41				9.76
14	Diammonium Phosphate $(NH_4)2HPO_4$	37.19				23.78
15	Water	34.75				12.80

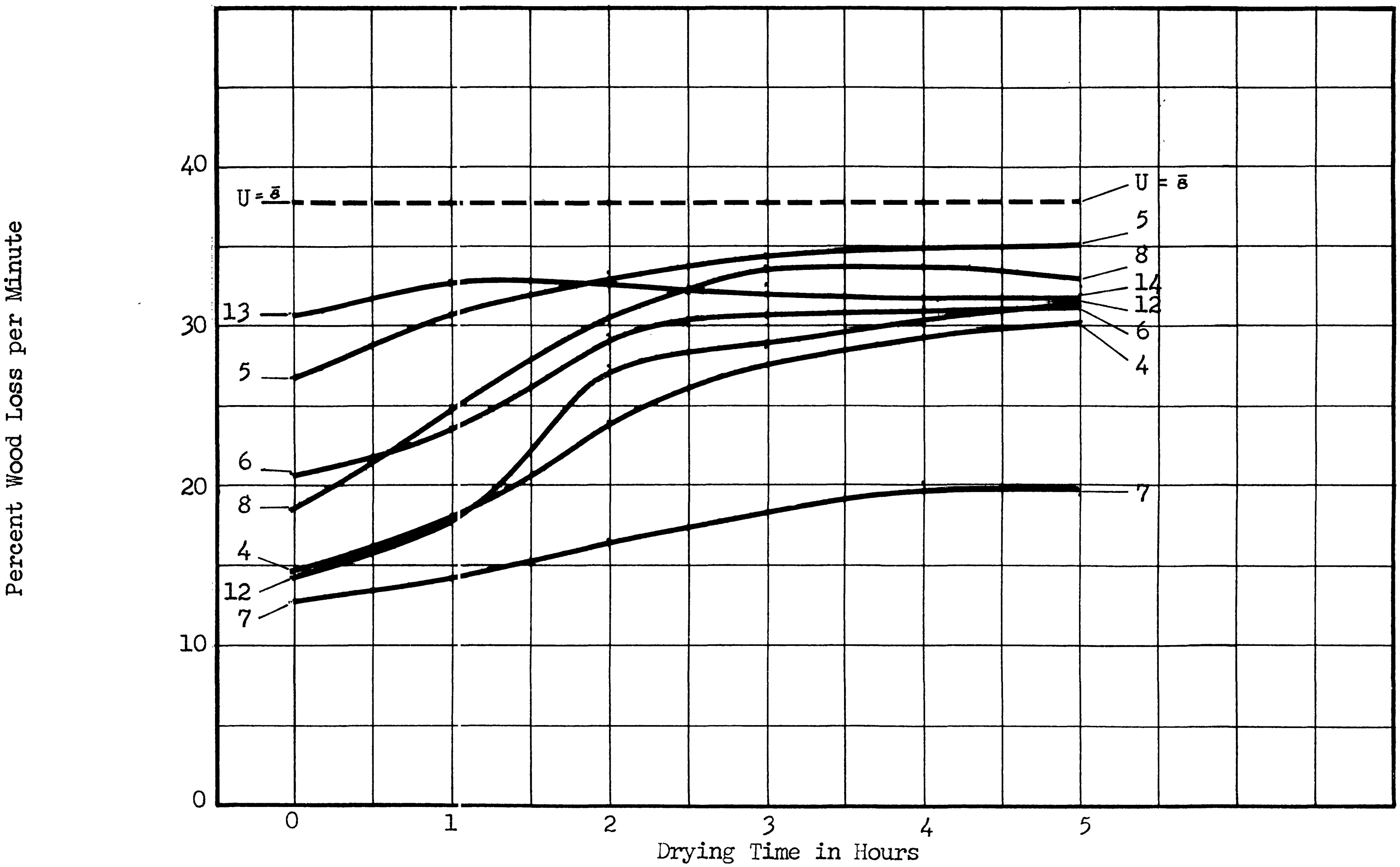
* See explanation of appendix.

TABLE XXVII

MEAN WEIGHT SUMMARY OF CLASS I RETARDANT* TREATED DOWELS

Retardant No.	Retardant Name	Drying Time in Hours	Dry Weight in Grams	Pre-burn Wt. in Grams	% Wt. of Slurry	% Wt. of Water	% Wt. of Wood Loss	Duration of Burn in Minutes	% Wt. of Wood Lost/Min.
4	South Dakota Bentonite	0	10.92	17.15	57.05	53.30	70.51	4.75	14.84
		1	10.72	15.38	43.47	39.65	69.87	3.87	18.05
		2	11.77	14.87	26.34	22.85	69.75	2.90	24.05
		3	10.49	12.13	15.63	11.72	66.44	2.40	27.68
		4	10.63	11.79	10.91	7.05	67.92	2.31	29.40
		5	10.56	11.65	10.32	6.44	66.29	2.21	30.13
5	South Dakota Bentonite + Calgon	0	11.60	13.69	18.02	16.12	72.90	2.71	26.99
		1	10.86	11.51	5.98	3.96	67.95	2.26	30.70
		2	11.60	12.15	4.74	2.84	73.02	2.24	32.58
		3	10.56	11.00	4.17	2.08	72.15	2.10	34.36
		4	10.23	10.64	4.01	1.86	72.14	2.05	35.19
		5	11.62	11.95	2.84	.95	72.89	2.10	34.71
6	South Dakota Bentonite + #4 Exfoliated Vermiculite	0	10.87	14.91	37.16	34.59	68.81	3.29	20.91
		1	10.96	13.91	26.92	24.36	70.62	2.97	23.78
		2	10.19	11.21	10.00	6.78	69.87	2.36	29.60
		3	11.25	12.03	6.93	4.44	71.82	2.34	30.69
		4	12.23	12.91	5.56	3.27	72.12	2.32	31.09
		5	11.64	12.31	5.76	3.35	71.30	2.30	31.00

* See explanation of appendix.

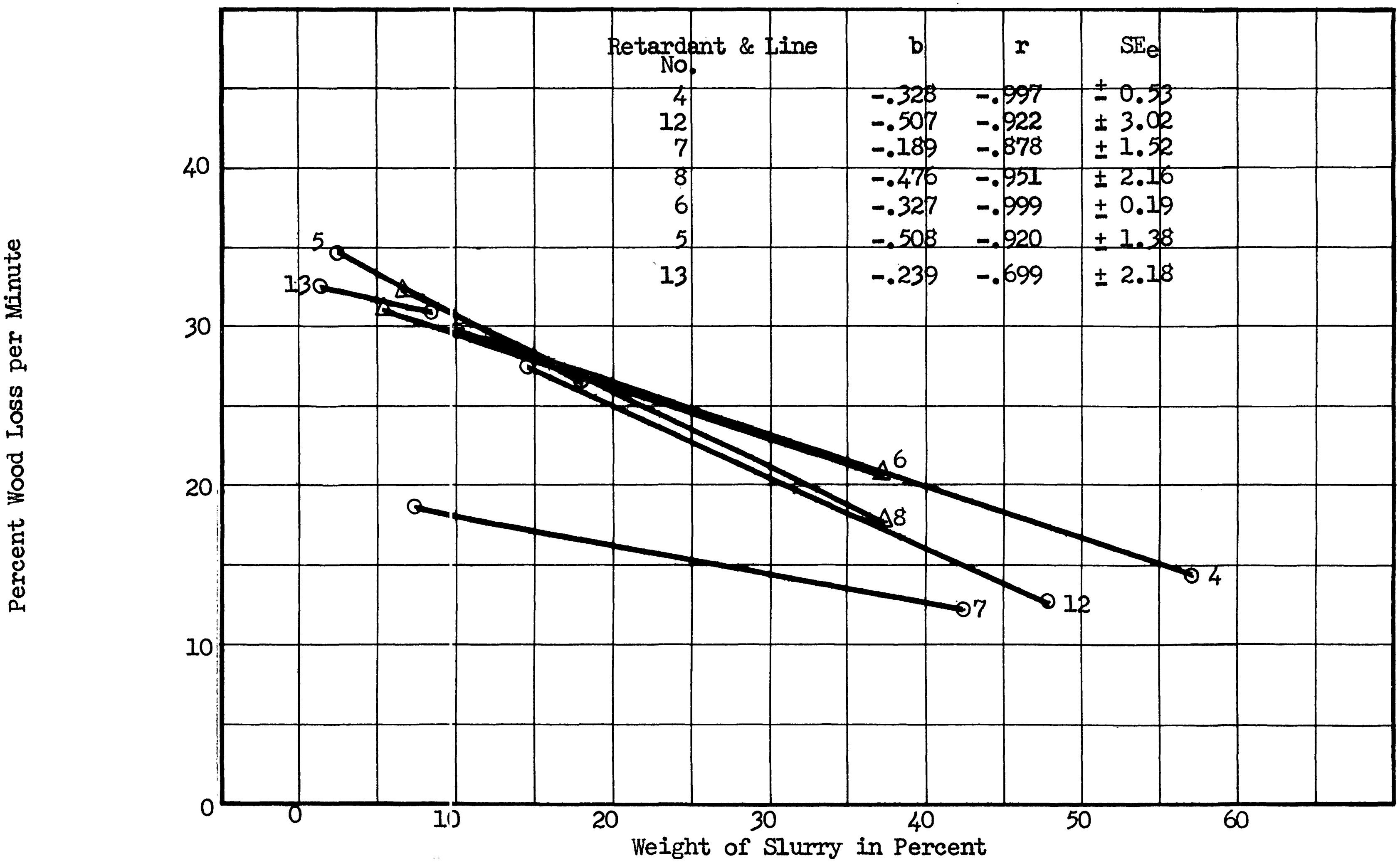


Graph 23. Class I retardants* - percent wood loss per minute plotted as a function of drying time in hours. Refer to Table XXVII for determination of values.

* See explanation of appendix.

TABLE XXVII (Continued)

Retardant		Drying Time in Hours	Dry Weight in Grams	Pre-burn Wt. in Grams	% Wt. of Slurry	% Wt. of Water	% Wt. of Wood Loss	Duration of Burn in Minutes	% Wt. of Wood Lost/Min.
No.	Name								
7	South Dakota Bentonite + PMF Vermiculite	0	10.65	15.13	42.42	38.68	35.96	2.80	12.84
		1	11.40	13.54	18.77	15.61	18.33	1.29	14.21
		2	10.73	12.17	13.42	10.06	26.84	1.60	16.75
		3	11.11	12.18	9.63	6.39	30.96	1.69	18.31
		4	11.94	12.91	8.12	5.11	50.33	2.50	20.13
		5	10.54	11.34	7.59	4.17	50.01	2.62	19.06
8	South Dakota Bentonite + Micronized Vermiculite	0	10.47	14.40	37.53	34.38	64.56	3.46	18.66
		1	10.96	12.68	15.69	12.68	69.79	2.81	24.84
		2	10.71	11.62	8.50	5.42	70.58	2.31	30.55
		3	10.75	11.57	7.63	4.56	72.74	2.15	33.83
		4	11.83	12.64	6.85	4.06	70.64	2.14	33.91
		5	10.52	11.23	6.74	3.61	68.53	2.13	32.17
12	O'Keefe Creek Bentonite 4 lbs./gal.	0	10.49	16.46	47.86	37.76	44.61	3.04	14.67
		1	10.95	15.57	27.19	17.51	48.77	2.72	17.93
		2	10.40	12.97	19.71	9.62	69.13	2.51	27.54
		3	11.67	13.96	16.02	6.02	72.49	2.52	28.76
		4	10.73	12.45	15.09	5.24	71.11	2.30	30.92
		5	11.13	12.77	14.57	4.47	73.41	2.36	31.10
13	Monoammonium Phosphate $NH_4H_2PO_4$	0	10.81	11.72	8.42	7.95	69.93	2.27	30.81
		1	10.85	11.05	2.84	2.38	70.78	2.16	32.77
		2	10.56	10.76	1.89	1.42	69.89	2.10	33.28
		3	10.68	10.93	2.34	1.87	69.38	2.13	32.57
		4	11.06	11.26	1.81	1.37	69.80	2.20	31.73
		5	11.62	11.82	1.72	1.29	72.46	2.27	31.92



Retardant & Line No.	b	r	SE_e
4	-.328	-.997	± 0.53
12	-.507	-.922	± 3.02
7	-.189	-.878	± 1.52
8	-.476	-.951	± 2.16
6	-.327	-.999	± 0.19
5	-.508	-.920	± 1.38
13	-.239	-.699	± 2.18

Graph 24. Class I retardants* - regression line showing the average percent wood loss per minute of burn as a function of weight of slurry in percent of dry weight. Refer to Table XXVII for determination of values.

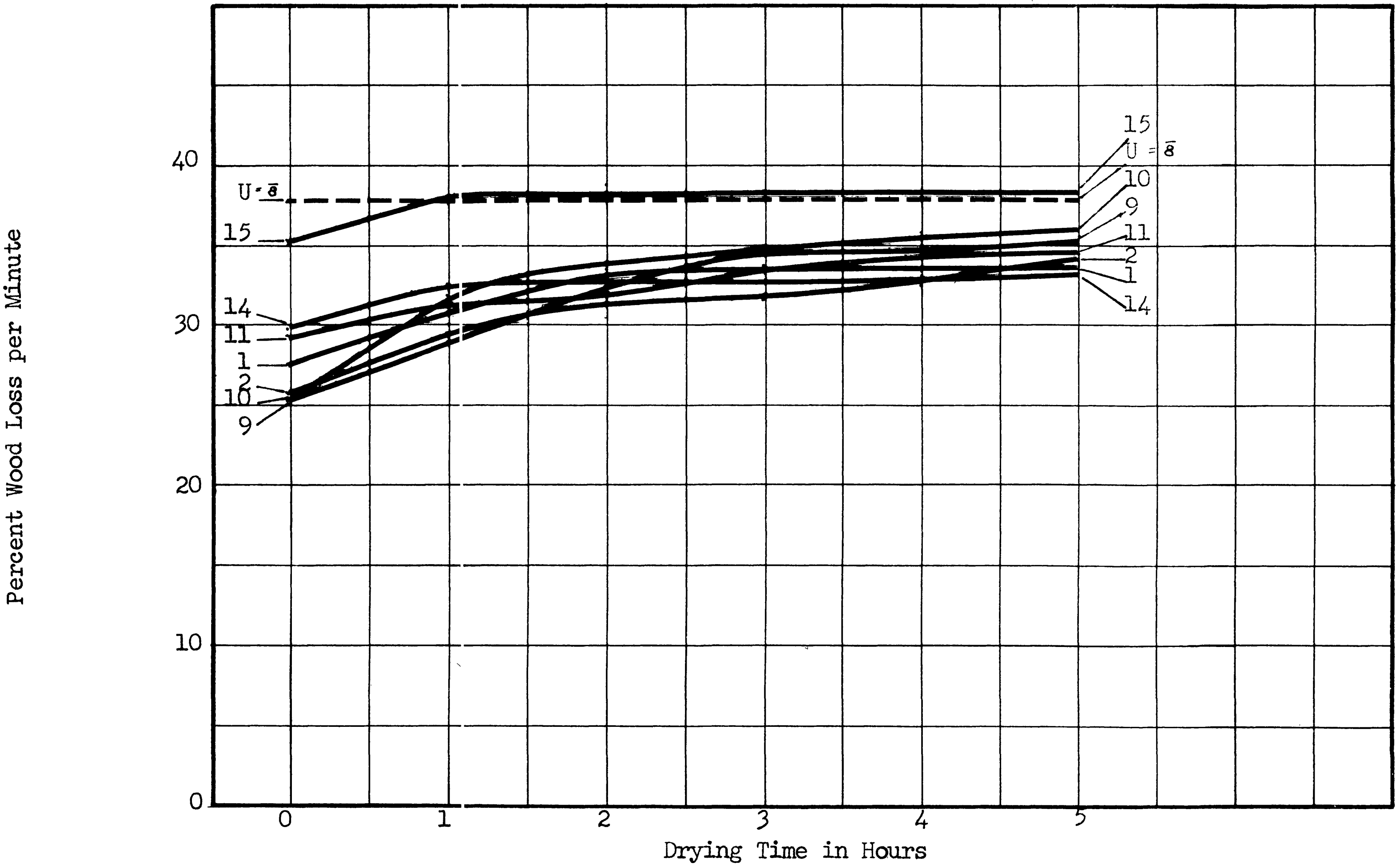
* See explanation of appendix.

TABLE XXVIII

MEAN WEIGHT SUMMARY OF CLASS II RETARDANT* TREATED DOWELS

Retardant		Drying Time in Hours	Dry Weight in Grams	Pre-burn Wt. in Grams	% Wt. of Slurry	% Wt. of Water	% Wt. of Wood Loss	Duration of Burn in Minutes	% Wt. of Wood Lost/Min.
No.	Name								
1	Sodium Calcium Borate + Calgon	0	12.43	13.75	10.62	8.61	74.25	2.70	27.50
		1	12.06	12.56	4.15	2.07	72.39	2.36	30.67
		2	10.78	11.16	3.52	1.21	73.47	2.19	33.55
		3	10.42	10.78	3.45	1.05	72.55	2.19	33.13
		4	11.06	11.44	3.44	1.17	73.06	2.20	33.21
		5	10.56	11.00	4.17	1.80	72.25	2.16	33.40
2	Sodium Calcium Borate	0	11.30	13.84	22.48	16.54	75.30	2.91	25.87
		1	11.52	12.61	9.46	3.64	75.43	2.56	29.46
		2	10.92	11.91	9.06	2.93	74.91	2.40	31.21
		3	12.29	13.27	7.97	2.52	75.51	2.40	31.46
		4	10.21	11.13	9.01	2.45	75.80	2.30	32.96
		5	10.99	11.87	8.01	1.91	74.98	2.20	34.08
9	South Dakota Bentonite + Sodium Calcium Borate	0	11.95	14.00	17.15	14.89	73.72	2.91	25.33
		1	12.94	14.37	11.05	8.96	73.57	2.56	28.74
		2	10.43	11.03	5.75	3.16	72.87	2.25	32.39
		3	10.58	11.09	4.82	2.27	72.87	2.11	34.53
		4	10.40	10.92	5.00	2.40	72.69	2.11	34.45
		5	10.70	11.15	4.21	1.68	72.99	2.06	35.43

* See explanation of appendix.

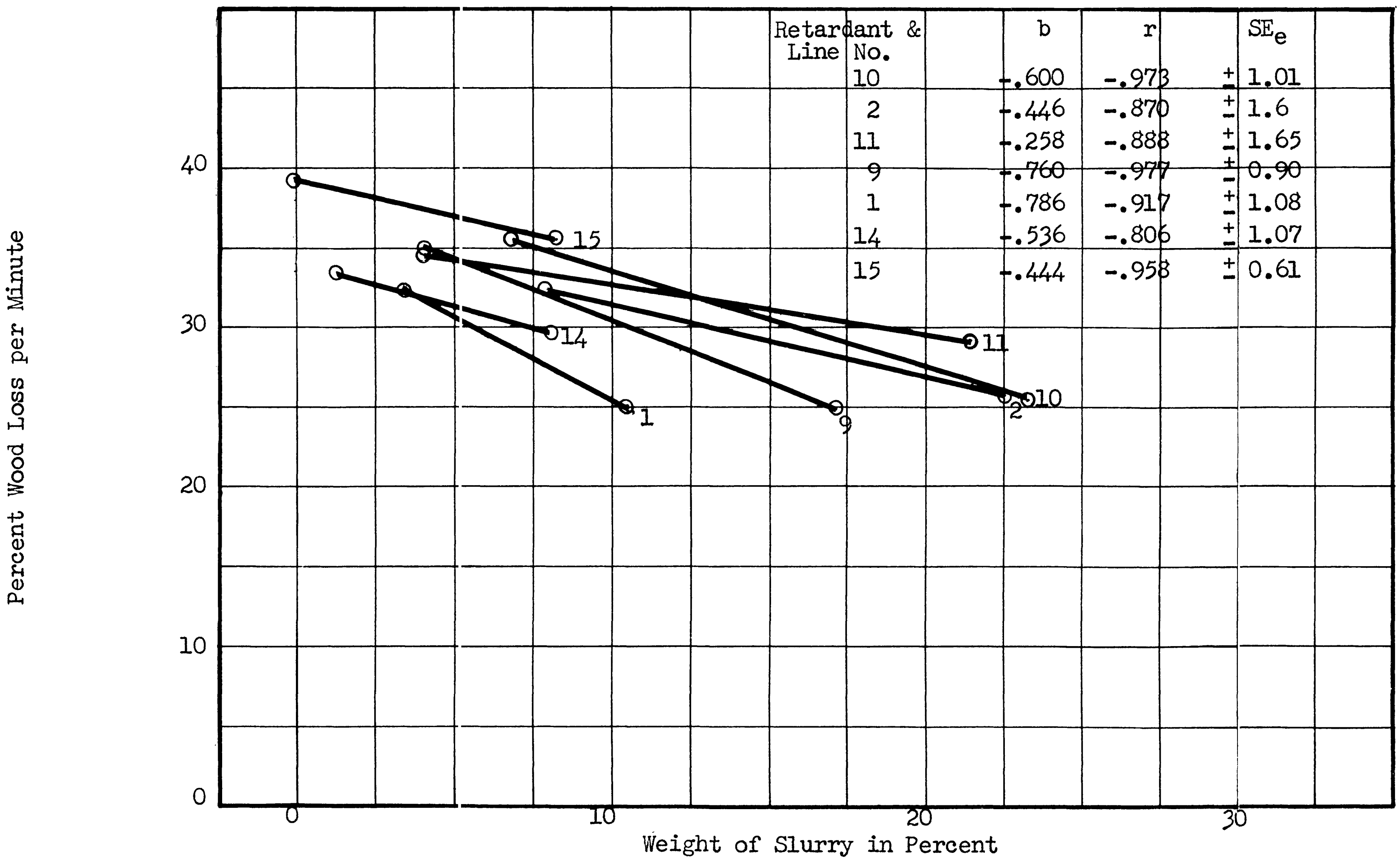


Graph 25. Class II retardants* - percent wood loss per minute of burn plotted as a function of drying time in hours. Refer to Table XXVIII for determination of values.

* See explanation of appendix.

TABLE XXVIII (Continued)

Retardant No.	Retardant Name	Drying Time in Hours	Dry Weight in Grams	Pre-burn Wt. in Grams	% Wt. of Slurry	% Wt. of Water	% Wt. of Wood Loss	Duration of Burn in Minutes	% Wt. of Wood Lost/Min.
10	South Dakota Bentonite + Airport Clay	0	11.68	14.39	23.20	18.32	74.23	2.90	25.60
		1	11.25	12.37	9.95	4.89	75.38	2.37	31.80
		2	10.38	11.31	8.96	3.47	73.60	2.18	33.76
		3	10.77	11.62	7.89	2.60	73.26	2.15	34.07
		4	11.71	12.59	7.51	2.65	75.32	2.10	35.87
		5	10.71	11.44	6.82	1.49	73.58	2.06	35.77
11	O'Keefe Creek Bentonite 3 lbs./gal.	0	9.98	12.13	21.54	17.83	72.24	2.46	29.36
		1	10.53	11.38	8.07	4.56	72.08	2.30	31.34
		2	12.01	12.77	6.33	3.25	73.02	2.29	31.89
		3	11.60	12.16	4.83	1.64	73.36	2.18	33.65
		4	11.41	12.00	5.17	1.93	73.44	2.15	34.16
		5	11.07	11.53	4.15	.08	72.81	2.13	34.18
14	Diammonium Phosphate $(NH_4)2HPO_4$	0	10.71	11.57	8.03	7.66	69.65	2.34	29.76
		1	10.47	10.80	3.15	2.77	69.63	2.14	32.54
		2	10.81	11.06	2.31	1.94	69.93	2.16	32.37
		3	12.12	12.36	1.98	1.65	71.03	2.25	31.57
		4	10.66	10.40	2.25	1.88	69.79	2.15	32.46
		5	11.14	11.31	1.53	1.16	71.24	2.05	34.75
15	Water	0	10.19	11.03	8.24	8.24	74.19	2.11	35.16
		1	10.79	11.16	3.43	3.43	75.62	1.91	38.00
		2	10.67	10.77	.94	.94	75.35	1.94	38.84
		3	10.20	10.29	.88	.88	74.90	1.97	38.02
	Untreated		10.54	10.54	–	–	74.19	1.96	37.85



Retardant & Line No.	b	r	SE$_e$
10	-.600	-.973	± 1.01
2	-.446	-.870	± 1.6
11	-.258	-.888	± 1.65
9	-.760	-.977	± 0.90
1	-.786	-.917	± 1.08
14	-.536	-.806	± 1.07
15	-.444	-.958	± 0.61

Graph 26. Class II retardants* - regression line showing the average percent wood loss per minute of burn as a function of weight of slurry in percent of dry weight. Refer to Table XXVIII for determination of values.

* See explanation of appendix.