PROBLEM ANALYSIS: PROBLEM 1 AND 2
IMPROVE THE EFFECTIVENESS AND EFFICIENCY OF CHEMICAL FIRE SUPPRESSION TECHNIQUES AND TACTICS (PROBLEM 1)
AND
TRANSFER RESULTS OF CHEMICAL AND MECHANICAL SUPPRESSION RESEARCH TO USER GROUPS (PROBLEM 2)

FIRE SUPPRESSION RESEARCH
Research Work Unit FS-INT-4402

Prepared by:

A D Blakely 6/1/86

A. Dave Blakely
Research Forester
Date

Gregg M. Johnson 6/12/86

Gregg M. Johnson
Physical Science Technician
Date

Cecilia W. Johnson 6/2/84

Cecilia W. Johnson
Chemist
Date

Charles W George 6/1/86

Charles W. George
Project Leader
Date

Recommended by:

Charles W George 6/1/86

Charles W. George
Project Leader

Approved by:

Richard G. Krebill 6/18/86

RICHARD G. KREBILL
Assistant Station Director Research-North
Date

USDA, Forest Service
Intermountain Research Station
Intermountain Fire Sciences Laboratory
P. O. Box 8089
Missoula, MT 59807

CONTENTS

INTRODUCTION

Forest Service expenditures for fire suppression increased exponentially during the last decade. These increasing expenditures have been attributed to rising costs of both presuppression and suppression. Annual expenditures during the last 5 years averaged 150 million dollars for presuppression and 65 million dollars (ranging from 29 to 106 million) for suppression. These increasing costs and a greater awareness of the role fire can play in many forest and grassland ecosystems created a need to reassess fire management policies and objectives as demonstrated by implementation of a revised fire policy: "to suppress wildfires at minimum cost consistent with land and resource management objectives and management direction." A combination of increasing suppression costs and the newly revised fire policy has required more intense fire management planning, and assessment of fire effects in relation to land management objectives. Real-time analysis, cost effective controllability, and risk factors of allowing escaped fires to burn are considered. The analysis should result in specific plans for initial action "to provide a reasonable probability of minimizing the sum of fire suppression costs plus resource damages, "For escaped fires, the analysis must in addition identify the most viable suppression alternatives including control strategies, forces needed, success probabilities, and estimates of control times, acreages, suppression costs, and resource damages.

The successful implementation of suppression alternatives (a specific mix or structure of control forces and activities) that indeed minimizes the sum of suppression costs plus resource damage is fundamentally dependent on knowledge of the effectiveness of each suppression activity and strategy in quantitative terms relative to situation variables. The lack of fire suppression effectiveness information is a major barrier in the analysis of suppression alternatives and identification of the mix of suppression forces and strategies necessary to meet stated resource management objectives. Hence, a problem identified for the fire suppression RWU was to conduct fundamental and applied research to improve effectiveness and efficiency in fire suppression techniques and tactics.

Suppression activities can be divided into two types: (1) mechanical, including the use of handtools, explosives, mechanical trenchers, light or heavy equipment such as plows and dozers, etc., used in the physical construction of fireline, and (2) chemical, including water, wetting agents, foams, short- or long-term retardant used to extinguish or reduce the intensity or spread of fire or indirectly to modify the flammability of the fuels.

Because mechanical and chemical fireline construction activities comprise the primary portion of suppression expenditures, it is somewhat a surprise that there is a general lack of definition of fireline requirements (width, continuity, etc.) relative to appropriate situation variables such as fire spread, intensity, spotting potential, and slope. Existing production rate data for specific activities are clearly inadequate due to changes in standards, technological advances, and organizational needs as well as most existing production rate data have been developed site-specific. It is easily demonstrated that slight changes in the suppression force structure or mix can have very significant impacts on the cost per unit of fireline (time base) due to the large range of activity production rates and costs for different methods.

Use of various chemicals, including water, for fireline construction, hotspotting, etc., are activities that can be quite effective as well as costly. Of the numerous types and uses of chemicals in fire suppression, the application of long-term fire retardants from fixed-wing aircraft constitutes by far the most significant use. The aerial delivery program of the Forest Service alone, involves the delivery of near 12 million gallons of retardant annually at a cost of over 24 million dollars (Gale and Mauk 1983) - amounting to 10-15 percent of the annual Forest Service fire suppression budget. When added to the cost of other primary activities, using chemicals or water, such as the use of ground tankers or engines for direct or indirect fire attack, helitankers, and simple backpacks, chemical suppression activities are a major suppression expense. As in the case of mechanical suppression activities, the lack of knowledge regarding the effectiveness of these chemicals in fire suppression and the requirements for given fuel/fire situations, are barriers to selecting, allocating, and utilizing chemical alternatives in the most cost effective manner. As a result of the high costs involved in the delivery and application of chemicals (especially aerial delivered) substantial savings can be realized by knowledge of the effectiveness of the chemicals in appropriate terms, and in improving the delivery application, strategies, and tactics.

Besides acquiring knowledge of the requirements and effectiveness of mechanical and chemical suppression alternatives, a complementary effort to integrate combined results of chemical and mechanical suppression tactics for transfer of the technology to user groups was identified as a priority problem having a substantial payoff and contributing to the development of cost effective fire management programs that support resource management objectives. The application/technology transfer of suppression research has been identified as a second problem for the RWU RWU.

Since identification of the fire suppression research problem areas and completion and approval of the research work unit descriptions, severe budget cuts including a reduction in personnel have necessitated reducing and limiting research efforts. A reevaluation of suppression research financial priorities, consideration of the talent within the RWU and areas of outside support, resulted in identification of the chemical suppression research and related technology transfer as the primary problem area selected for research during the next several years. Therefore, this problem analysis will concentrate on the problem of improving the effectiveness and efficiency of chemical fire suppression techniques and tactics (problem 1) and tailoring research results for transfer of technology to users (problem 2). A less-indepth problem statement/analysis for the mechanical suppression research aspects, originally included as a part of both problems 1 and 2, has been prepared for future planning and reference and can be found in the appendix of this Problem Analysis.

PROBLEM 1 - FUNDAMENTAL CHEMICAL SUPPRESSION ACTIVITIES

Retardant Effectiveness

RESEARCH SUMMARY

Some of the first recorded studies to determine the feasibility of using chemical solutions to extinguish or retard wildland fire were conducted by Barrett (1931) and Truax (1939). Truax demonstrated that some chemical solutions were far superior to water for extinguishment under both laboratory and field situations. He found that retardant effectiveness depended on the type of chemical, its concentration, rate of application, fuel type and arrangement, weather conditions and fire characteristics. The most effective solutions evaluated were ammonium phosphates.

Tyner (1941) verified the Truax studies and showed that synergistic effects of combinations of chemicals were not significant. Numerous other studies (Fons 1950; Fry 1951; Miller and Wilson 1957; Phillips and Miller 1959; and Davis and others 1961) were performed with various retardant chemicals, some with altered physical properties that increased water retention and penetration. The treatments, however, did not improve the extinguishing or fire retarding ability of water as much as the addition of ammonium phosphate tested earlier.

During Operation Firestop (USDA Forest Service 1955a) ignition and combustion tests were conducted using retardant-treated dowels. When ammonium phosphate compounds caused faster ignition than water or sodium calcium borate, incomplete conclusions were made concerning the effectiveness of the phosphates as retardants. Subsequently, the operational use of ammonium phosphate compounds as forest fire retardants was delayed for several years. (In a study of the affect of ammonium sulfate and phosphate on the pyrolysis and combustion of cellulose, George and Susott (1971) explained that faster ignitions at lower temperatures did not necessarily mean that combustion would be sustained when external heat was reduced.)

Aidun (1960) conducted studies on the effects of water additives on the extinguishing efficiency of water. The studies demonstrated that viscous water was about four times more efficient than plain water in extinguishing certain types of laboratory fires. These results were verified during field tests and operational use of viscous water and algin gel on vehicle and brush fires (Davis and others 1962).

Laboratory tests using controlled open burning fires (Hardy and others 1962) demonstrated that thickened ammonium phosphates, ammonium sulfate, and sodium calcium borate were effective in reducing rate of flame spread, fire intensity, and convective column temperature. Rothermel and Hardy (1965) found that all the viscous retardants they tested had similar drying rates when applied to actual fuels in similar amounts, but those containing ammonium phosphate and sulfate were effective even after all the applied moisture had evaporated.

George and Blakely (1970, 1972) evaluated various chemical fire retarding effects on pine needle and aspen excelsior mat-type fuel beds measuring energy release rate (weight loss) and flame spread rate. Their results showed that the effectiveness was related to the type of chemical applied and the distribution within the fuel bed. The increasing use of ammonium polyphosphate retardants prompted a study (George and others 1977) that indicated the fire retarding effectiveness of liquid phosphate based retardants is significantly affected by the amount of impurities they contain. Different liquid phosphate manufacturing processes cause significant product and fire retarding effectiveness differences. In recent years the cost of DAP has increased several times, and subsequently, monoammoniumn phosphate (MAP) or other active salts have replaced it in most retardant formulations. As a result a study was conducted (Blakely 1983) that indicated there were no signficant differences in fire retarding effectiveness of several varieties of white-acid MAP manufactured using different sources of raw material or processing plants.

Swanson and Helvig (1973, 1974) developed a vertical fuel coverage model based on forest hydrological and retardant dispersion studies (Grah and Wilson 1944, Leonard 1967, and Anderson 1974) that provides estimates of the vertical fuel distribution of required retardant amounts. The model was used to study the effect of various retardant characteristics including film thickness, salt content, fuel type, and the amount of retardant applied to the top of the fuel structure. Utilizing the model and the state-of-the-art in fuel descriptions (Deeming and others 1977), knowledge of rate-of-spread characteristics (Rothermel 1972) and determinations of retardant effectiveness (George & Blakely 1972, Rothermel and Philpot 1975), Swanson and Helvig made estimates of the amount of retardant required for several standard fuel situations.

Increasing costs for formulated products that contain fire retardant chemicals have caused renewed interest in use of thickened water for both ground and aerial application. Several new water thickeners have been operationally evaluated by the California Division of Forestry.[1/] A low cost foam, made from a by-product of the kraft paper manufacturing process and introduced by the Texas (State) Forest Service, is undergoing operational evaluation at numerous locations around the country. The low cost foam can be dispensed by simple and inexpensive ground applications equipment (Ebarb 1978).

Retardants have also been tested on different fuel types under laboratory and field conditions to determine how susceptible they are to removal from fuels by rain, dew, wind, etc. Results indicate that the materials adhere to rough surfaces and can remain effective after several inches of rainfall. Similar formulations are leached, however, from smooth, waxy surfaces and are ineffective.[2/]

[1/], [2/] Unpublished reports on file at Intermountain Fire Sciences Laboratory, Missoula, MT.

A recent study has examined the fire extinguishing effects of water and different chemical additives when applied to burning pine needle fuel beds (Blakely 1985). The study shows that water is the principal agent to reduce flaming combustion and the fire retarding chemicals slow or prevent the smoldering from causing flaming combustion to recover to its previous high intensities after water evaporation. Several different retardant salt combinations and concentrations have been tested to help develop less expensive formulations. Tests have shown that some liquid ammonium sulfates and combinations of ammonium sulfates and monoammonium phosphates are as effective as higher priced DAP based formulations.

A study has been conducted during two fire seasons in Southern California to determine the validity of estimated retardant coverage requirements by measuring the effectiveness of retardant aerial application on wildfires (George 1985). So far results from a limited number of fuel types and fire intensities have indicated that coverage level estimates need to be refined and incorporate fire intensity/-behavior as a factor influencing retardant requirements.

References

Aidun, A. R. Additives to improve the firefighting characteristics of water. Quarterly Progress Report 11-13. Syracuse University Research Institute. 1960.

Anderson, H. E. Forest fire retardant: transmissions through a tree crown. Research Paper INT-153. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory; 1974. 20 p.

Barrett, L. I. Possibilities of fire-extinghishing chemicals in fighting forest fires. Journal of Forestry 29:214; 1931.

Blakely, A. D. Monoammonium phosphate: effect on flammability of excelsior and pine needles. Research Paper INT-313. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 17 p.

Blakely, Aylmer D. Combustion recovery: a measurement of fire retardant extinguishment capability. Research Paper INT-352. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1985. 6 p.

Davis, J. B.; Dibble, Dean L.; Phillips, Clinton B. Firefighting chemicals--new weapons for the fire suppression crew. Miscellaneous Paper 57. Berkeley, CA: U. S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1961. 27 p.

Deeming, John E.; Burgan, Robert E.; Cohen, Jack D. The National Fire-Danger Rating System--1978. General Technical Report INT-39. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 17 p.

Ebarb, P. Texas Snow Job. Fire Management Notes 39(3):3-5; 1978.

Fons, W. L. Wet water for forest fire suppression. Research Note 71. Berkeley, CA: U. S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1950. 5 p.

Fry, J. F. The use of fire retardant chemicals and wetting agents in forest firefighting. Inst. Fire Engineering Journal; 1951. p. 1-7.

George, C. W.; Blakely, A. D. Energy release rates in fire retardant evaluation. Fire Technology 6(3):203-210. 1970.

George, C. W.; Blakely, A. D. Effects of ammonium sulfate and ammonium phosphate on flammability. Research Note INT-121. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1972. 26 p.

George, C. W.; Susott, R. A. Effects of ammonium phosphate and sulfate on the pyrolysis and combustion of cellulose. Research Note INT-90. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1971. 27 p.

George, C. W.; Blakely, A. D.; Johnson, G. M.; Simmerman, D. G.; Johnson, C. W. Evaluation of liquid ammonium polyphosphate fire retardants. General Technical Report INT-41. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, 1977. 54 p.

George, C. W. An operational retardant effectiveness study. Fire Management Notes 46(2):18-23; 1985.

Grah, R. F.; Wilson, C. C. Some components of rainfall interpretation. Journal of Forestry 42:890-898; 1944.

Hardy, C. E.; Rothermel, R. C.; Davis, J. B. Evaluation of forest fire retardants--a test of chemicals on laboratory fires. Research Paper INT-64. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1962. 33 p.

Leonard, R. E. Mathematical theory of interception. In: Forest Hydrology, W. E. Sopper and H. W. Lull (ed.), Pergamon Press, Oxford; 1967. p. 131-136.

Miller, H. R.; Wilson, C. C. A chemical fire retardant--results of field trials using sodium calcium borate on forest fires in 1956. Technical Paper PSW-15. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1957. 11 p.

Phillips, C. B.; Miller, H. R. Swelling bentonite clay--a new forest fire retardant. Technical Paper PSW-37. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1959. 30 p.

Rothermel, R. C. A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1972. 40 p.

Rothermel, R. C.; Hardy, C. E. Influence of moisture on effectiveness of fire retardants. Research Paper INT-18. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1965. 32 p.

Rothermel, R. C.; Philpot, C. W. Reducing fire spread in wildland fuels. Reprinted from: Experimental Methods in Fire Research. Proceedings of Meeting to Honor Clay Preston Butler, Stanford Research Institute May 9-10, 1974; 1975.

Swanson, D. H.; Helvig, T. N. High altitude drop mechanization study; final report. Honeywell Contract 26-2888 to Intermountain Forest and Range Experiment Station, Vol. I and II; 1973.

Swanson, D. H.; Helvig, T. N. Extended high altitude drop mechanization study: final report. Honeywell Contract 26-2888 to Intermountain Forest and Range Experiment Station; 1974. 151 p.

Truax, T. R. The use of chemicals in forest fire control. Report 1199. Madison, WI: U. S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1939. 11 p.

Tyner, H. D. Fire extinguishing effectiveness of chemicals in water solution. Industrial Engineering Chemicals 33(1):60-66; 1941.

U.S. Department of Agriculture, Forest Service, Progress Report No. 4, Retardants - I. Berkeley, CA: U. S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment AStation, Operation Firestop; 1955a. 12 p.

PLANNED RESEARCH

In past studies the relative effectiveness of many different fire retardant chemicals has been quantified under controlled conditions in the laboratory and under field conditions. Although the studies produced invaluable data, in most cases they were limited to specific fuels and fire intensities. Some of these studies have been used as a basis to derive recommended retardant coverage levels for various fuels as described in the National Fire Danger-Rating System, but those coverage levels do not adequately consider fuel conditions and fire intensity or consider the retardant other than in a fully dry condition. Retardant requirements are needed for all fuel types and fuel conditions, under different fire severity situations when applied indirectly or directly on the fire front (thus in various states of dryness). The resulting data will assist in determining retardant requirements under the variety of tactical conditions as well as in different fuel/fire conditions and will help define the conditions for which retardant will most efficiently meet management needs.

In laboratory studies of effectiveness, retardants have been applied using various means (e.g., spraying, dipping, cascading, impregnation, etc.) to achieve different levels of chemical treatment. These studies have not shown, however, the most effective placement of the retardant on the surface of individual fuel elements or on which area or areas of the total fuel complex. (The area needing treatment is a function of the type of fire and/or the involved fuel.)

Thus, we continue to be faced with the problem of judging which retardants, if any, to use and how to apply them to the greatest advantage. There are several areas that should be examined more thoroughly in the laboratory to pinpoint which retardant-fuel coverage relationships are most important. Field studies are needed to identify various fire/fuel characteristics and the retardant coverage required to produce desired fire intensity reductions.

The following studies will help in determining the retardant requirements for any fire/fuel situation and management objective:

A. Determine retardant effectiveness in terms of the amount and type of retardant chemical applied, its distribution within the fuel complex, its placement on individual fuel elements, and the relative area that it covers.

B. Determine effectiveness of retardant pattern width and coverage levels relative to fire intensity and flame length.

C. Determine retardant coverage level requirements for a cross section of different fuel/fire intensity situations throughout the United States.

D. Identify the retardant coverage levels necessary to control fire intensities for prescription burns (in cooperation with fire effects research and objectives).

E. Quantify effects of retardant applied as an extinguishing agent (direct attack) as compared to application in advance of the fire front as a "retardant."

F. Define fire retardant effectiveness in common terms of realistic capabilities and inline with the objectives of fire managers.

Operational application of retardant aerial delivery was emphasized as an area of concern in the winter 1985 Fire Chief's Meeting. Application problems, including accuracy, was also noted as a cause of ineffectiveness and inefficiency in operational retardant effectiveness studies. Studies are needed to define retardant breakup parameters and mechanisms, including fall and drift rates relative to wind vectors, aircraft tank and gate system parameters, and drop and environmental parameters such as airtanker airspeed and drop height. Close cooperation with Aviation and Fire Management, airtanker operators, retardant and equipment manufacturers, systems can be developed to improve delivery, accuracy, and provide more economical use of retardant.

Retardant Extinguishing Capabilities (2107-02-08)

Need:

Fire retardants are applied to wildfires by either air or ground tankers, but the majority of retardant used each year is applied by airtankers. Much of the retardant is applied directly onto the flaming fuels in an attempt to totally extinguish flaming combustion and control the fire's advance. Few studies have been made to quantify the fire-extinguishing abilities of currently used fire retardant formulations (long-term or short-term), although considerable information is available on their "retardant ability," (effectiveness after all original moisture is lost).

Summary:

Testing the effectiveness of fire retardants as extinguishing agents in direct fire suppression has been limited, especially under controlled conditions. Unthickened water solutions containing several different fire retardant chemicals were evaluated in the late thirties for their effectiveness in reducing flaming and glowing combustion. Studies including thickening agents were conducted in later years; however, the interaction between long-term chemicals, thickening agents that alter droplet size, and the extinguishing and retarding actions have not been determined quantitatively. Knowledge of these relationships is essential in assessing the value of altering retardant formulations, determining the most effective tactical use, and application conditions. Recent research has resulted in a laboratory method for quantifying the fire-extinguishing capabilities of different water/chemical combinations commonly used to suppress fires. Measured application rates, and their affect on energy release rate and duration (combustion recovery) demonstrated the ability to use "combustion recovery" as a measure of fire retardant extinguishment capability (Blakely 1985). The method will provide a basis to evaluate the interactions of active chemicals, rheological properties (droplet size), application rates, fuel/fire characteristics and thus tactical alternatives and formulation options.

Objectives:

The objectives of this study are to (1) quantify the retardant required to extinguish flaming and glowing combustion in different fuels and fire intensities, (2) determine retardant quantity needed for extinguishment relative to the application rate, (3) determine the effect of droplet size on extinguishment, and (4) determine the effect of combined viscosity and retardant salt content on extinguishment.

Knowledge to be Developed:

1). What is the relative effectiveness of water, thickened water, and long-term retardant in knocking down and holding a fire of specified intensities and fuel type?

2). What is the most effective manner to apply retardant (direct or indirect attack) and what is the optimum physical-chemical combination?

3). What droplet size or combination of retardant rheological properties provides the best extinguishing action as opposed to the most uniform and effective retarding action?

Knowing specific fire extinguishing capabilities and limitations of retardant applications under different fire/fuel conditions will help prevent misuse of retardants and consequently improve the efficiency of current chemical suppression activities. Both long-and short-term retardants have their particular uses for controlling wildfires. Quantification of application/use parameters outlined in this study will help to define the conditions when long-term and short-term retardants are most effective.

Studies:

Existing study 2107-02-08 with amendments as determined necessary.

Proposed Time Scale:

```
     Milestone          FY 1985   FY 1986   FY 1987   FY 1988   FY 1989
Experimental burns:
   Extinguishment (wet)------------------------------
   Retardant (dry) ----------------------------------
Processing Data:
   Analysis of results ----------------------------------------------
   Documentation                        ------------------------------
   Verification                                                -------
```

Cooperators:

Within RWU-4402, Blakely will conduct the study with technical support from G. Johnson in instrumentation and data analysis, and C. Johnson in chemical preparation and analysis. Temporary technician support will be used as needed.

Data gathered during the Operational Retardant Evaluation (ORE) being conducted by RWU-4402 in cooperation with Forest Service-- Aviation and Fire Management, California Department of Forestry, and Bureau of Land Management, will be used to provide field comparisons to information gathered in the laboratory and will be used for verification.

Facilities:

Combustion chamber, wind tunnel and air processing facilities, as well as the chemical laboratory and computer facilities for data processing and analysis.

Operational Retardant Effectiveness (ORE) Study (2107-02-ORE)

Need:

Although preliminary ORE results are beginning to provide some insights for improving fire retardant operations, many questions remain unanswered. The following are considered priority areas for seeking additional quantitative information:

1. Effectiveness of fire retardant chemicals: What is the relative effectiveness and most appropriate use of water, short-term retardant, long-term retardant, and other specialty chemicals when applied from fixed-wing aircraft, helicopters, or ground equipment in various fuel/fire situations?

    o How does chemical effectiveness relate to volume applied, type and concentration (salt content), and physical properties (viscosity, wetting ability, etc.)?

    o How does effectiveness change in different fuel/fire behavior situations?

    o What is the most effective method of application?

    o When can short-term retardants be used instead of long-term?

2. Aerial delivery systems: What are optimum delivery system characteristics for various chemicals over the range of fuel/fire behavior situations?

    o What are optimal performance and design criteria for all aircraft types (including helicopters)?

    o What combination of type, size, number, and deployment of aircraft is most cost-effective in various situations?

    o What is required to improve the flexibility of existing delivery systems to ensure performance at all desired coverage levels?

3. Operational guidelines and training aids: Answers to the preceding questions will be useful in developing:

    o Training aids to improve operational understanding of retardant use and application at all levels.

    o Simple guidelines to determine required coverage levels for different fuels/fire behavior and tactical options.

    o Guidelines for evaluating and selecting tactical options.

Summary:

During the 1983 and 1984 fire seasons, an operational effectiveness pilot study was completed. It accomplished limited verification of the study techniques and instrumentation, and also provided some early insights on best operational methods and requirements. Abnormally low fire occurrence for these years resulted in few opportunities to evaluate retardant effectiveness in moderate or high fire intensity situations. Several useful spinoffs were derived nonetheless, and have been summarized in Fire Management Notes (vol. 46, No. 2, 1985).

The 1985 fire season, in contrast, offered a wealth of opportunities for retardant evaluation. In all, 43 incidents were instrumented and measured between July 4 and October 16. Six of these were Forest Service fires in the Pacific Northwest Region, while the remaining 37 involved the Forest Service, California Department of Forestry (CDF), Bureau of Land Management (BLM), and Bureau of Indian Affairs (BIA) in California. On these fires, 268 retardant drops were recorded on video/FLIR; 41 drops were evaluated by the Ground Team; and 125 fuel/retardant samples were taken for laboratory analysis.

Findings of the study conducted to date have been:

o Effective retardant coverage/requirement can vary as much as 800 percent, depending on fire intensity, in the same NFDR/NFFL fuel model. The effective coverage level for California mixed chaparral of 6+ gpc encompasses fuels that may require as little as 1 gpc or as much as 10 gpc.

o Estimates for tank and gating system performance (best capability), using existing performance guide information for current airtankers, are adequate for present use. This offers partial validation of the airtanker performance guides.

o It is impossible to apply retardant using existing guidelines without major advances in drop sequencing systems. (A number of other operational insights from the study have been made and presented to Aviation and Fire Management.)

Objective:

A. To determine how much chemical or retardant (physical and chemical properties) is needed to do a given fire suppression job and relate the answer to fuel and fire behavior.

B. To develop guidelines for the effective application of aerial retardants.

C. To develop training materials to improve the management and effectiveness of aerial retardant application.

Knowledge to be Developed:

Quantitative relationships between fuel/fire situations and retardant effectiveness can be used to:

A. Optimize tank and gating system performance (prescribed flow rates, flexibility, and standardization).

B. Tailor retardant properties to needs (both chemical and physical properties).

C. Develop adequate guidelines for optimized selection, allocation, and real-time use (including limits of effectiveness).

Integrated information in these three areas can provide a quantitative basis for airtanker and retardant selection and use decisions.

Studies and Schedule:

The existing operational retardant evaluation study will be continued and will be updated as necessary to coincide with ORE operational and work plans as jointly prepared by participants. The nature of the study and support requires a work plan and schedule be prepared for each fire season and location for the study. The number of fuel types and fire situations that the study can be conducted in, is dependent on regional support. Thus the study will be conducted in yearly or seasonal increments.

Cooperators:

All personnel in RWU-4402 will be involved to some extent. Primary field evaluation teams will be composed of agency personnel from Forest Service, CDF, BLM, Research, and possibly interested cooperators from Canada. Research will provide program management, technical support, and maintenance for airtanker instrumentation and personnel for ground measurements and observations, chemical analysis support, and general data tabulation, analysis, and interpretation.

Facilities:

Retardant chemical analysis laboratory, fuels, laboratory, computer facilities to process data and aid analysis, video analysis equipment, and four technicians during the study.

Physical-Chemical Properties

There are many physical/chemical properties that affect the performance of forest fire retardants. Due to budgetary and time constraints, three parameters will be considered in this problem analysis as priority areas for research. They are retardant rheology, corrosivity and inhibition, and impacts to personnel and the environment. The latter is an area in which effort will primarily involve literature reviews and consultation between users and specialists in health and safety.

RETARDANT RHEOLOGICAL PROPERTIES

Research Summary

For many years researchers have long recognized that additives to alter the rheology of fire retardants, extinguishing agents, etc., have a significant effect on the local efficiency of fire suppression. Aidun and Grove (1961) found that viscous water produced much more rapid extinguishment than plain water, reduced the danger of reignition, reduced runoff, and minimized the overall water requirements. Trout (1970) and Livingston (1972), working with thickened water for indoor sprinkling systems, showed the distinct advantage of larger droplets in penetrating the heat column and reaching the base of the flame (direct attack as an extinguishing agent). Davis and others (1962, 1965) reported incorporation of viscosity increasing agents in aerial and ground retardant formulations to provide better adherence of the retardant to the fuels and to minimize runoff.

Additives were found to have important effects on the breakup characteristics and dispersion behavior of liquid retardant dropped from aircraft (Miller and Wilson 1957), Johansen and Shimmel 1963). Davis (1959), George and Blakely (1973), and George (1975) recognized several advantages of thickened retardant for aerial delivery: (1) greater shear resistance during breakup; (2) larger mean droplet sizes; and (3) less material lost to drift and evaporation.

George and Blakely further noted differences in the effect of various types of additives on aerial delivery characteristics and the resulting ground patterns. These differences were dependent on retardant rheological properties other than simply viscosity. These latter studies clearly indicated that the rheological properties of the retardant play a significant and in some cases dominant role in controlling the aerial dispersion of the retardant and consequently the concentration and physical properties of the retardant cloud as it interacts with the fuel complex.

Further progress in improved fire suppression capabilities required additional knowledge of fire retardant rheological properties and an understanding of how they affect the various processes involved in retardant applications. To gain this knowledge the USDA Forest Service added an investigation of retardant rheological properties to the retardant research program. Shock-Hydrodynamics was contracted to conduct a number of studies to establish the relationships between the rheological properties of a liquid fire retardant and its drop behavior, breakup and dispersion characteristics, wetting out properties, and interaction with elements of the fuel complex.

During this effort, Andersen and others (1974a, 1974b, 1976) developed analytical models to describe the aerodynamic breakup of aerially released retardant including effects of such variables as retardant rheological properties, drop velocity, and wind speed. A correlation of the rheological properties with the aerial delivered performance was made by Andersen and others (1976) as a result of full scale testing in which retardant rheological properties were controlled and release characteristics, distribution patterns, cloud droplet sizes, and impact velocities were measured. The study helped to validate the model and confirmed that the effective viscosity, combining the effects of fluid viscosity and the elasticity at a specified shear rate were the primary rheological properties of the solutions that determined the aerial delivery performance of the retardant.

Further research effort concerning the dynamic interaction of fire retardant droplets with the fuel and correlation with the rheological properties of the retardant was sponsored by the Forest Service conducted by Andersen and Wong (1978). These studies provided some quantitative basis and potential for developing a model to predict the wetting out characteristics of an actual fuel by a real retardant cloud/rain. These relationships illustrated that the interactions of the retardant, applied aerially or by ground equipment to the fuels, are very complex and include many variables. The retardant droplet size and velocity (influenced by rheological properties) coupled with fuel characteristics (including size and arrangement, and fuel surface physical/chemical characteristics) primarily determine the retention and distribution of the retardant in the fuel complex.

Although in recent studies various models have been developed and relationships defined that have helped to understand and interpret numerous related phenomenon, additional experiments and analyses are needed to broaden, verify, and integrate these models. The models thus far developed are based on defining a fuel complex in terms of individual layers or strata, whose pertinent properties can be grossly defined in terms of certain known parameters. Fluid loss factors (fluid lost experimentally due to splatter from fuel/retardant impacts) are needed to evaluate the developed equations as is further information to characterize the surface composition of the fuel. All models need to be verified or modified.

Several studies are needed to complete and test the wetting out model (Andersen and Wong 1978):

A. Characterization of the effect of fuel surface composition on the adhesion of a retardant on fuels with specified properties,

B. Determination of information regarding the fluid loss factor as applied to the wetting out model over a sufficiently large range of variables that control the wetting process,

C. Parametric correlation and analysis of computed data to obtain a simplified and generalized expression for the fluid loss factor that can be used with the basic stratum wetting equation for field type calculations.

These studies should be completed and all models verified and integrated.

References

Aidun, A. R.; Grove, C. S., Jr. Additives to improve the firefighting characteristics of water. Report Ch.E. 504-6112F. Syracuse, NY: Syracuse University Research Institute; 1961. 155 p.

Andersen, W. H.; Brown, R. E.; Louie, N. A. Investigation of rheological properties of aerial delivered fire retardant. Second quarterly report, Shock-Hydrodynamics, Contract 26-3198 to Intermountain Forest and Range Experiment Station; 1974a. 20 p.

Andersen, W. H.; Brown, R. E.; Louie, N. A.; Kato, N. G. Investigation of rheological properties of aerial delivered fire retardant. Third quarterly report, Shock-Hydrodynamics, Contract 26-3198 to Intermountain Forest and Range Experiment Station; 1974b. 50 p.

Andersen, W. H.; Brown, R. E.; Louie, N.A. [and others]. Correlation of rheological properties of liquid fire retardant with aerially delivered performance. Final report, Shock-Hydrodynamics, Contract 26-3198 to Intermountain Forest and Range Experiment Station; 1976. 95 p.

Andersen, W. H.; Wong, J. Y. Dynamic interaction of fire retardant droplets with fuel, and correlation with the rheological properties of the retardant. Final report, Shock-Hydrodynamics, Contract 839-2031-76 to Intermountain Forest and Range Experiment Station; 1978. 114 p.

Davis, J. B. Air drop tests. A report for the California air attack coordinating committee. Sacramento, CA: California Division of Forestry; 1959. 22 p.

Davis, J. B.; Dibble, D. L.; Phillips, C. B.; McBride, R. S. Viscous water and algin gel as fire control materials. Technical Paper 21. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1962. 25 p.

Davis, J. B.; Dibble, D. L.; Richards, S. S.; Steck, L. V. Gelgard--a new fire retardant for air and ground attack. Fire Technology August: 216-224; 1965.

George, C. W. Fire retardant ground distribution patterns from the CL-215 airtanker. Research Paper INT-165. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1975. 67 p.

George, C. W.; Blakely, A. D. An evaluation of the drop characteristics and ground distribution patterns of forest fire retardants. Research Paper INT-134. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1973. 60 p.

Johansen, R. W.; Shimmel, J. W. Increasing the viscosity of water and chemical fire retardants with clays and gums. Georgia Forest Research Paper 19:1-7. Macon, GA: Georgia Forest Research Council, State of Georgia; 1963. 7 p.

Livingston, W. L. The fireball method of fire protection evaluation. Factory Mutual Research Corporation, Norwood, MA; 1972. 55 p.

Miller, H. R.; Wilson, C. C. A chemical fire retardant--results of field trials using sodium calcium borate on forest fires in 1956. Technical Paper 15. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1957. 11 p.

Trout, E. W. J. The high challenge fireball: a trademark of the seventies. Technical Paper prepared for presentation at the 74th Annual Meeting of the National Fire Protection Association, Factory Mutual Research Corporation, Norwood, MA; 1970. 27 p.

Planned Research

The development of a procedure to characterize the rheological properties of fire retardant solutions should be given high priority. In addition to defining standard techniques for assessing retardant rheological properties, a method for handling the data and using existing liquid breakup models should be identified including adapting the models for interactive computer use.

The relative effectiveness of long-term retardants can be easily quantified in the laboratory combustion chamber. On the basis of these test results, decisions can be made about proper mix ratios for new or modified retardant formulations and whether the retardant's performance is within required limits. Comparison of results for various modifications allows the manufacturer to use the least expensive salt or mix ratio that is still effective.

With the increased cost of long-term retardants, there has been considerable interest in the use of short-term retardant. Because these products are essentially thickened water, effectiveness cannot be evaluated in the same manner as for long-term retardants and since there is no currently available measure of effectiveness, the use level is determined by cost rather than effectiveness. Most thickeners used in short-term retardants are synthetic polymers that impart elasticity but very little viscosity while the thickeners used in long-term products impart much more viscosity and less elasticity. The breakup and drop size models that have been developed for long-term retardants do not work under these conditions. New methods or test requirements need to be developed for the evaluation of short-term retardant effectiveness. A possible approach would be to use current techniques for measuring the rheological properties of long-term fire retardants and develop limits of useful concentration from correlations of the measured values of long and short-term retardants and actual drop data. This same technique could be used to study the effect of water hardness or other parameters on elasticity (viscosity is known to be affected) and determine the adjustment in use level necessary to maintain an effective elasticity. Results of such studies can provide information necessary to develop performance models suitable for polymers. This information is needed in application as well as in procurement requirements and cost analyses for short term retardants.

Completion of this study is also important as an input to the retardant effectiveness/fuel-fire situation studies (retardant effectiveness section of this problem analysis) because the retardant rheological properties and resulting cloud/dispersion characteristics are primary variables affecting the retardant retention and distribution in the fuel complex.

Determining Retardant Rheological Properties (2107-02-01)

Need:

For efficient use of fire retardants more information is needed about the effects of their rheological properties on the delivery, adhesion to fuels and subsequent fire suppression effectiveness.

Summary:

Millions of gallons of fire retardant are delivered to wildland fires each year, and many of those gallons are ineffective because of evaporation and dispersion losses, inaccurate placement, wind drift effects, or they are not in a form that effectively coats the critical fuels. Studies have shown that retardants should fall as large droplets to be most effective when delivered from high drop heights. In other cases, fuels are coated better with small droplets. With increased costs of long-term chemicals, many users have become interested in using simple short-term retardants (thickened water). The short-term retardants must be carefully applied and only in specific situations can perform as effectively as long-term retardants. Elasticity is a primary factor influencing drop characteristics and fuel coating. However, very little information is available that relates the level of elasticity to performance or identifies the factors that determine the level of elasticity in a particular retardant (i.e. compatibility with other chemicals, concentration, water quality).

Objective:

The overall objective is to determine rheological properties of short-term and long-term fire retardants that are most important for controlling (1) retardant breakup under high shear stress, (2) adhesion, and (3) flow characteristics that control retardant fuel coverage.

Specific Studies Will Include:

1. Determine the elasticity of currently used and potential long- and short-term retardants.

2. Determine the effect of concentration on elasticity.

3. Quantify the effect of water quality (hardness and other dissolved ions) on elasticity.

4. Using existing models, estimate the mean droplet sizes for formulations of quantified elastic properties.

Knowledge to be Developed:

Many different chemicals have been used to improve the delivery and adhesion to fuels of water and retardant chemicals. Each material has had some advantages, but eventually either too many faults were found or better materials were discovered. The number of thickeners available has increased and some of them are chemically quite novel and different from those used before. Specific questions that will be answered are:

1. What level of retardant elasticity is needed under varied conditions for optimum operational use?

2. What thickener concentration is necessary to give desired elasticity?

3. What adjustments to thickener concentration are necessary to obtain optimum elasticity from a specific water source?

Proposed Time Scale:

Milestone	FY 1985	FY 1986	FY 1987	FY 1988	FY 1989
Effect of Water Quality	----------	----------			
Site specific use levels	----------	----------	----------	----------	----------
Concentration of retardant vs elasticity	----------	----------	----------	----------	
Specification Requirements	----------			----------	----------
Verification		----------	----------	----------	----------

Cooperators:

These studies will be conducted in cooperation with Monsanto Co., Chemonics, California Department of Forestry, Sanitek, and other chemical contributors. The major work will be performed by Dr. Wayne Van Meter during seasonal breaks from his duties at the University of Montana.

Facilities:

Studies will be conducted in the Intermountain Fire Sciences Laboratory using RWU 4402 equipment or in some cases on loan from cooperators.

RETARDANT CAUSED CORROSION

Research Summary

Corrosion of ground and airtankers and mixing, storage, and transfer equipment when exposed to fire retardant was recognized as a problem early in the retardant program (USDA Forest Service 1955b). The first retardants, formulated without corrosion inhibitors, were tested for stress and fatigue corrosion with varied results from immediate failures to minor damage over a long period of exposure (up to 1 year) (USDA Forest Service 1964).

A field survey of airtankers after the 1964 fire season revealed varying amounts of corrosion damage and led to recommendations for housekeeping, repair, and tank fabrication designed to minimize further damage (Davis and Phillips 1965).

In the late 1960's corrosion tests using the Magna Corrater® were begun that introduced an electrochemical corrosion test into USDA Forest Service specifications for fire retardants (USDA Forest Service 1968, 1969, 1970). At that time 2024-T3 Al, a major alloy in airtanker construction, was the only alloy being tested. By the mid-1970's two more alloys (AISI C-1010 steel and naval brass) were added to the specifications (USDA Forest Service 1972, 1975) because concern over corrosion damage was widened to include ground tankers and mixing facilities; however, safety for airtankers was still a primary concern.

In 1973 the Forest Service awarded a contract to Ocean City Research Corporation (OCRC) for a comprehensive field survey to determine the extent and types of corrosion associated with fire retardants and the alloys most critical and commonly exposed that are susceptible to corrosion. Based on findings of the field survey, 10 alloys were selected for use in a laboratory research program involving a variety of fire retardants, uninhibited fertilizer solutions, and potential corrosion inhibitors (chosen after a literature search). Various alloy/retardant combinations were subjected to tests for uniform corrosion (weight loss and electrochemical), galvanic corrosion, corrosion fatigue, and stress corrosion cracking (Gehring 1974).

Results of the field survey and laboratory research indicated most retardants being used were significantly corrosive, created numerous maintenance problems, and if not inhibited, were often conducive to both stress corrosion and corrosion fatigue. (Inhibitors currently in use do not completely eliminate susceptibility to stress corrosion). Furthermore, the study demonstrated that Forest Service requirements were inadequate in terms of the test procedures used, exposure conditions, and the alloys selected. These findings led to an expanded laboratory corrosion research program aimed at better defining retardant corrosion characteristics, identifying improved inhibitor systems, and developing improved corrosion evaluation procedures that could be incorporated into Forest Service fire retardant specifications (Gehring 1978). It was recommended that corrosion testing procedures include partial and total immersion type uniform corrosion tests to simulate some of the severe corrosion seen at the liquid/vapor interface and in the vapor zone.

In 1977, a workshop was held at the Intermountain Fire Sciences Lab (Northern Forest Fire Laboratory), Missoula, MT, to discuss corrosion, user problems and concerns, and progress of ongoing research and development programs.[1] Several areas or questions requiring further study were identified by users, manufacturers, and Research and Development personnel in attendance:

1. Although many alloys are common to airtankers and ground equipment, more emphasis was needed on alloys used in ground tankers and mixing and storage facilities. Copper alloys were seen as a major problem because their use was widespread and corrosion resistance was known to vary widely with composition.

2. The effect of water quality on the corrosivity of the fire retardant was a concern in a number of situations. With water in short supply in many areas, consideration had been given to substitution of stream, recycled, or even sea water as well as other sources. Whether inhibitor systems designed for municipal and well water adequately protected against corrosion if such alternate water sources were used was a question.

3. It was concluded that further evaluation and verification were needed so that a more appropriate corrosion test could be included in Forest Service specifications. (This should include a partial immersion type exposure and a procedure to evaluate the effect of fire retardants on fatigue life of alloys, especially the aluminum, used in the aircraft structures, that is susceptible to this type of failure.) A new procedure, thought to be superior to previous test methods and more representative of field exposure and damage, for evaluating retardant corrosion was developed by the Intermountain Fire Sciences Laboratory (IFSL) RWU-4402 (2107) using in-house and contract (OCRC) data and proposed for inclusion in Forest Service specifications. However, this procedure, a weight loss technique using partial and total immersion conditions, several alloys and two different temperatures, should be verified. The corrosivity of currently used retardants under these conditions, should be determined and the results correlated with previous electrochemical and weight loss data and to damage occurring under field conditions.

The development of a test procedure to determine the fatigue susceptibility of structural aluminum alloys exposed to retardant corrosion involved more study than anticipated. Previous studies used a simple prenotched specimen with the notched area exposed to fire retardant. This technique was relatively fast and simple,

---

[1] Draft of proceedings on file at Intermountain Fire Sciences Laboratory dated May 3-5, 1977.

but it measured only the crack propagation phase, and totally eliminated the crack initiation phase. A preliminary investigation of crack initiation using an unnotched specimen suggests that an unnotched beam, combined with pre-exposure to retardant for 30 to 90 days, can be used for a screening test.

Further study should be made to develop and verify a test procedure that adequately characterizes the suscepitibility of structural alloys to fatigue and/or stress corrosion as a result of exposure to fire retardants.

4. A handbook or guide suitable for field use was recommended that contained the state-of-the art in fire retardant corrosion control. The handbook should include housekeeping and inspection procedures, use of protective coatings, material selection, and possibly inhibitor packages for various generic types of retardants.

In our attempt to answer some of these concerns identified in the Retardant Corrosion Workshop, contract and in-house research were initiated. An additional contract to Ocean City Research Corporation was let to address items 1 and 2 and to investigate development of a fatigue corrosion procedure.

A field survey of ground retardant application equipment was made.[2/] Many of the alloys found in airtankers and included in previous investigations were found in ground equipment. Copper alloys were the only alloys identified that were often not adequately represented. The corrosion resistance of these alloys was found to vary greatly with the copper content and it was recommended that ETP copper (.999 Cu, .001 O) be included in further investigations and evaluations. Inhibitor systems in retardants in use were adequate, independent of the water quality with the exception of salt water. Retardants mixed using salt water produced an increased corrosivity; therefore, that use was not recommended.

[2/] Gehring, G. Unpublished report on file at Intermountain Fire Sciences Laboratory, Missoula, MT; 1979.

References

Davis, J. B.; Phillips, C. B. Corrosion of airtankers by fire retardants. A report for California Air Attack Coordinating Committee, Sacramento, CA: California Division of Forestry; 1965. 38 p.

Gehring, G. A., Jr. An investigation of fire retardant-caused corrosion. Final report, Contract 26-3250, Ocean City Research Corporation, Ocean City, NJ. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1974. 121 p.

Gehring, G. A., Jr. Laboratory studies of fire retardant corrosion. Final report, Contract 26-3250, Ocean City Research Corporation, Ocean City, NJ. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1978. 54 p.

Gehring, G. A., Jr. An investigation of fire retardant-caused corrosion (extended study). Final report, Contract 40-0353-7-799, Ocean City Research Corporation, Ocean City, NJ. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980. 56 p.

U.S. Department of Agriculture, Forest Service, Operation Firestop. Progress Report No. 9, Aerial firefighting. I. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 1955b. 13 p.

U.S. Department of Agriculture, Forest Service. Corrosion test procedures. Progress Report Equipment Development and Testing 1117. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Equipment Development and Testing Center; 1964. 33 p.

U.S. Department of Agriculture, Forest Service. Corrosion testing. Project record Equipment Development and Testing 1117. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Equipment Development Center; 1968. 35 p.

U.S. Department of Agriculture, Forest Service. Fire retardant corrosion rate evaluations on brass and mild steel. Project record Equipment Development and Testing. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Equipment Development Center; 1969a. 21 p.

U.S. Department of Agriculture, Forest Service. Specification for retardant, forest fire, dry chemical for aircraft or ground application Interim Specification 5100-00301, Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office; 1969b. 15 p.

U.S. Department of Agriculture, Forest Service. Corrosion rate evaluations on brass, aluminum, steel, and zinc. Project record. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Equipment Development Center; 1970a. 11 p.

U.S. Department of Agriculture, Forest Service. Specification for retardant, forest fire, liquid chemical, unthickened for aircraft or ground application. Interim Specification 5100-00302. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office; 1970b. 19 p.

U.S. Department of Agriculture, Forest Service. Specification for retardant, forest fire, liquid chemical, unthickened for aircraft or ground application. Interim Specification 5100-00302a. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office; 1972. 19 p.

U.S. Department of Agriculture, Forest Service. Specification for retardant, forest fire, dry chemical, for aircraft or ground application. Interim Specification 5100-00301a. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office; 1975. 20 p.

CORROSION

Planned Research

As the cost of retardants has soared in recent years, the manufacturers have looked for lower cost raw materials in order to stay competitive and not be priced out of business. Because the retardant salt is by far the major component, the search for means of lowering the cost has centered here. The switch from diammonium phosphate to monoammonium phosphate and finally to ammonium sulfate or blends of sulfate and phosphate, while lowering costs, has increased the severity of retardant-caused corrosion by orders of magnitude especially at elevated temperatures that most accurately represent corrosion behavior in the field. Inhibitors that were effective for phosphates are often not effective for sulfates. In addition more stringent health and safety requirements have eliminated many possible inhibitors. Increased use of short-term retardants also has brought increased concern about the corrosivity of these products. Retardant manufacturers have initiated cooperative efforts with the Forest Service to conduct research and aid in the development of suitable inhibitors for improved fire retardant formulations. This cooperative research will reduce the corrosivity and damage caused by fire retardants and should provide the cost effective products while improving safety.

Several field surveys and research studies have been conducted in attempts to better define the problem of fire retardant caused corrosion. This information can be found in various sources. There is a definite need to consolidate this information in a state-of-knowledge paper, a single comprehensive bibliography, and to prepare user guidelines for minimizing the impact of retardant caused corrosion.

At a recent meeting of retardant users and manufacturers, the need for a field-oriented guide to corrosion control surfaced. With costs increasing for equipment replacement and available funds decreasing, the need for such a manual is more urgent than ever and its preparation and circulation should be identified as a priority effort.

Mechanism of Fire Retardant-Caused Corrosion (2107-02-04)

Need:

Knowledge of corrosive behavior inhibition systems that will enable us to find combinations of treatment that will control corrosion without exposing fire control personnel and the general public to toxic chemical inhibitors and at the same time hold costs to a minimum.

Summary:

Retardants are being formulated with salts that are lower cost than those previously used (especially diammonium phosphate). While this has lowered overall cost of retardant the severity of corrosion has increased significantly. Different inhibitors or different amounts of the currently used inhibitors may be needed. Conscientious housekeeping and maintenance by equipment operators and owners will definitely help minimize corrosion damage.

Objective:

Determine the severity of corrosive behavior of presently used retardant salts.

Quantify the effect of potential inhibitors on the corrosive behavior.

Study new methods (housekeeping, coatings) that will aid in controlling the problem.

Knowledge to be Developed:

1. What are the corrosion rates of commonly used alloys when exposed to currently used fire retardants when tested by 90-day weight loss tests?

2. How are these corrosion rates affected by changes in source of raw materials?

3. How are these corrosion rates affected by changes in inhibitor type or concentration?

4. How are these corrosion rates affected by changes in retardant mix ratio, especially as salt content approaches zero?

5. What effects do other preventive measures, such as housekeeping and coatings have on corrosion damage?

Studies and Schedule:

Existing study 2107-02-500 (with amendments 1 and 2) will be continued. Further amendments may be added as the study progresses.

Cooperators:

C. W. George, C. W. Johnson within RWU-4402. Other agency personnel as appropriate: P. Hill (San Dimas Equipment Development Center), G. Roby (Washington Office Avialton and Fire Management), D. Day (California Department of Forestry), other State agencies, Regional Aviation and Fire Management units, and Research and Development Managers of Retardant Manufacturers (Monsanto, Chemonics, Omega, Sanitek or other).

Facilities:

Retardant laboratories and computer facilities. Operational sites such as retardant mix bases and retardant airtanker operations may be involved to a limited degree.

RETARDANT IMPACTS TO PERSONNEL AND THE ENVIRONEMENT

Research Summary

The effect of fire retardants on the environment and on the health and safety of personnel concerned with their use has been a concern of fire control officials since the beginning of the retardant program. Sodium calcium borate was the first chemical retardant used operationally and only after several years use were its soil sterilizing effects recognized (Fahnestock 1958, Fenton 1959). Many other retardants were subsequently evaluated and used for short periods but gradually were replaced with diammonium phosphate (DAP) and ammonium sulfate (AS) based formulations. The latter were not considered a problem environmentally, since both compounds were commonly used as agricultural fertilizers and, in some cases, as a source of nitrogen and phosphorous in cattle rations with no adverse effect (Bell and others 1968).

Several incidents occurring during the operational use of DAP and AS fire retardants led to skepticism concerning the nontoxic effects of their use. They were accused of causing nitrate poisoning in livestock in an isolated case (Dodge 1970), and killing fish in a number of situations (George and others 1976). Although other similar instances of detrimental retardant impact have been documented, experience indicated the main effect of retardant on the environment came through its impact on water quality, and subsequently fish and other aquatic life.

The assessment of the effect of retardants through a literature review has not been totally feasible due to the complex nature of the problem and the possible antagonistic or synergistic effects of the multiple retardant ingredients; i.e., corrosion inhibitors, organic thickening agents and spoilage inhibitors, coloring agents, and other additives. The literature indicated a primary toxic ingredient to fish and other aquatic life was ammonia (NH_3), a component of presently used retardants.[3] Studies by Blahm and others (1972, 1974) supported these conclusions and directly correlated the toxicity with the concentration of free ammonia (NH_3) that was dependent on the NH_4^+ in the retardant and the pH of the solution and water. Van Meter and Hardy (1975) developed a method for estimating the time/distance for retardant impacting a stream to be diluted to a nontoxic level. Norris and others (1978) conducted a comprehensive study of the behavior and impact of chemical fire retardants in forest streams in which actual direct and indirect applications of retardant were made in selected streams in the western United States and the stream organisms and chemistry measured for over 1 year after application. Findings indicated that direct applications of chemical were the most likely to cause concern (fish kill) and that the actual impact depends on numerous factors from stream flow

---

[3] George, C. W. Literature review on the environmental impact of fire retardants. Unpublished report on file at the Intermountain Fire Sciences Laboratory, Missoula, MT; 1971.

characteristics to water temperature. Indirect application of retardant appears to be of much less concern due to the limited mobility of the retardant components and the dampening effect over time of the application.

A primary difficulty in assessing the value and effect of retardant use is the inability to determine the effect of nonuse or the "fire effect." Little data is available for a "trade-off" type analysis of the effects of fire and/or retardant use.

A draft Fire Retardant Environmental Assessment (EAR) has been prepared by Region 6 of the USDA Forest Service which has incorporated much of the current knowledge in fire retardant environmental effects.[4/] The assessment has utilized knowledge of the chemistry of the retardants and their components which are often complex in nature. Although a final EAR has not been completed, it is anticipated that the Region 6 EAR will serve as a format for other Regions to follow and will provide most if not all of the technical information for the assessment.

Over the last several years concern has shifted from environmental impacts of fire retardants to the health and safety of workers who will be exposed to the retardants. A second literature review was done and consultations held with experts from the Environmental Protection Agency (EPA) and National Institute for Occupational Safety and Health (NIOSH) with emphasis on possible hazards to people who might be exposed to fire retardant during handling and mixing operations or during retardant drops (Pickett 1979). In conjunction with and as a result of this review, tests were made during typical retardant mixing operations and also during a control burn of fuels to which retardant had been applied. Recommendations from this work included use of suitable protective gear for handling each of the retardants evaluated. In the early 1980's when a new Forest Service retardant specification 5100-00304 was written, potential toxicity test procedures and requirements were evaluated for inclusion. Although tentatively adopted, the use and assessment of the procedures for newly submitted retardant formulations is still in progress.

[4/] USDA Forest Service. Working draft, Fire retardant environmental assessment. Pacific Northwest Region (R-6), Portland, OR; 1979; 157 p.

References

Bell, T. Donald; Orme, L. G.; Baker, J. P. Ammonium polyphosphate as a source of nitrogen and phosphorus in cattle rations. Agriculture Experiment Station Bulletin. Moscow, ID: University of Idaho; 1968. 15 p.

Blahm, Theodore H. Effect of chemical fire retardants on the survival of juvenile salmonoids. Prescott, OR: National Marine Fishery Service Environmental Facility; 1972. 27 p.

Blahm, Theodore H.; Marshall; Snyder, G. R. Effect of chemical fire retardants on the survival of juvenile salmonoids. Prescott, OR: National Marine Fishery Service Environmental Facility; 1974. 44 p.

Dodge, Marvin. Nitrate poisoning, fire retardants, and fertilizers--any connection? Journal of Range Management 23(4):244-247. 1970.

Fahnestock, G. R. Borate firelines toxic to southern vegetation. Forest Notes 118. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station; 1958. 2 p.

Fenton, R. H. Toxic effects of a firefighting chemical. Journal of Forestry 59:209-210; 1959.

George, C. W.; Blakely, A. D.; Johnson, G. M. Forest fire retardant research. General Technical Report INT-31. OGden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1976. 22 p.

Norris, L. A.; Hawkes, C. L.; Webb, W. L.; Moore, D. G.; [and others]. A report of research on the behavior and impact of chemical fire retardants in forest streams. Corvallis, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1978. 152 p.

Pickett, Ted L. Fire retardant health and safety, project record. Equipment Development and Test Project 8118. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Equipment and Development Center; 1979. 20 p.

Van Meter, Wayne P.; Hardy, Charles E. Predicting effects on fish of fire retardants in streams. Research Paper INT-166. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1975. 16 p.

Planned Research Participation

The amount and quality of information concerning the effect of individual retardant components on water quality, flora and fauna, and on the health and safety aspects of humans is growing immensely. Effort in defining various retardant effects and relationships is expected in several areas by a number of researchers and scientists. Although additional effort is warranted and could be justified, the best potential input by the present retardant research team in this problem area is related to an understanding of basic retardant chemistry, interaction of retardant components, etc. Modifications are continually being made to improve the performance of retardants, reduce the cost, etc. These modifications require an assessment of the chemistry influencing health and safety and environmental impact aspects. While some studies or specific analytical analysis may be required, they will be minor in terms of effort. Retardant research being conducted by the team in other areas can provide knowledge, understanding, and a basis for assessing potential effects and making recommendations to other research and user personnel as to considerations for study and interpretations of effect. Thus effort in the area of environmental impact, health and safety, will be primarily of a consulting nature with inputs to applicable specifications and guidelines as appropriate. No specific formal studies in this area are presently planned.

Retardant Application/Delivery Systems

RESEARCH SUMMARY

Since Operation Firestop (USDA Forest Service 1955c) demonstrated the practicality of aerial delivered water and fire retardants, many different types of airtankers have been used. The variety of delivery systems produced radically different ground patterns which were for the most part undefined. In 1970 the Northern Forest Fire Laboratory began a series of air drop tests, at first to quantify the rheological characteristics of retardants relating to ground pattern distribution. As an outgrowth of these studies, the effects of different tank and gating systems were included in later studies (George and Blakely 1973, George 1975). The airtankers tested included many different types ranging from the single engine TBM to the MAFFS system in a C-130.

During the course of contracts let to Honeywell, Inc. (Swanson and Helvig 1974 and Swanson and others 1975, 1977) to study aerial retardant dispensing, an empirical retardant dispersion model (PATSIM) was developed based on a theoretical model by McPherson (1968) using analytical models of fluid breakup and ground distribution patterns from previous drop tests. Correlation of retardant flow rates with ground distribution patterns showed that it was possible to predict the patterns from the flow rates.

In recent years the cost of fire retardant delivered to the fire has increased dramatically to the point where a single drop from a DC-6 or DC-7 aircraft can cost $2,000 for retardant alone, not including the aircraft costs. Another cost increasing factor in aerial firefighting has been the elimination of the small single engine airtankers such as the AF and TBM while increasing the use of large airtankers such as the C-119, DC-6, and DC-7. Although the use of increasing amounts of retardants in larger airtankers has increased fire suppression capability, it has opened the door to gigantic waste due to misuse or inefficient use of this capability (George 1978). Knowledge of performance and capability of the diverse airtankers used would provide a useful tool for systematic planning of the aerial delivery of fire retardants.

It was recognized that PATSIM could be used to predict the capabilities of an airtanker from data obtained during ground testing (static tests). Honeywell, under contract to the Forest Service (Swanson and others 1975), used PATSIM as a basis for developing a method and format for predicting and presenting an airtanker's performance in the form of User Guidelines.

The controlling input to PATSIM was flow rate and it was thought that the flow rate could be predicted from tank geometry and door opening rate. It was also found that retardant rheological characteristics (water or gum-thickened) had more effect on ground pattern responses than PATSIM accounted for. After the production of User Guidelines for current airtankers had begun, their allowable operational volumes were decreased for aircraft performance and safety considerations. In addition, it was recognized that in many instances, due to the temperatures and altitudes where airtankers were operated significant load size reductions were necessary to perform safely (depending also on runway lengths). To address these problems (prediction of flow from geometry, rheology, volume) an additional contract was let to Honeywell (Swanson and others 1977). Refinements were made to PATSIM to include the effects of rheology for two types of retardant, and a somewhat successful attempt to predict flow rate from tank geometry was incorporated in the model. A separate rule determining the performance for an airtanker that had been downloaded was developed such that it could be applied to any other downloaded airtanker (Luedecke and Swanson 1979).

To date most of the older airtankers in the fleet have been static tested and airtanker guides for them have been developed. Managers have been using these guides as a factor in selecting airtankers that perform best under a given management area's specific fuel/fire requirements. This use of airtanker guides has caused airtanker operators to develop new tanks and modify existing tanks in order to meet different management criteria. These new and modified tanks need to be tested to provide managers with current information.

An experimental tank and gating system (ETAGS) (Swanson and others 1978) was designed and constructed to study the variables affecting ground distribution patterns. One output from this program was the compilation of information into a Tank Design Guide for Fire Retardant Aircraft (Swanson and Luedecke 1978). During the ETAGS test, flow rate information was collected and used as input to PATSIM. When the ground pattern response predicted by PATSIM was compared to the actual ground patterns, it was found that the exit geometry had a large effect on ground pattern response. They found that adjustments of constants within the model did not provide the dynamic range necessary to accommodate the range of length to width ratios observed. An attempt was made to review the basic equation as a differential of length with respect to time, but this treatment did not preserve the model and further efforts to include exit geometry were abandoned.

In 1982 RWU-4402 (previously RWU-2107) cooperated with Australian forest research on project Aquarius, a program to determine the practicability of using large airtankers on wildfires in Australia. Our Unit's part included both drop and static testing a Conair DC-6 and producing a detailed guideline for its use. It was found that PATSIM did not properly predict the ground pattern due to the exit geometry of this particular tank. Modifications to PATSIM were made that corrected the prediction errors and also gave insights for modifications to PATSIM that would allow PATSIM to properly predict ground response patterns for a wide range of exit geometries.

Due to the increasing use of helicopters for aerial retardant delivery, drop pattern and flow rate tests were conducted on several helitanker systems (Bussey and Harrington 1973).[1/] Preliminary analysis of this data indicated that helitanker systems, due to their differences in drop speed and relatively low flow rates, yield different responses to external variables and produce ground pattern distributions different from fixed-wing aircraft. As a result PATSIM in its present form is unable to predict ground pattern response with sufficient accuracy for the production of helitanker performance guides.

Parameters including drop heights, drop configuration and tank release sequence, delay time, acceleration, indicated airspeed, minimum height above fuel, and various use characteristics, were recorded using an S2F airtanker on actual fire missions. Results confirmed the validity of aircraft evaluation procedures and instrumentation. Drop heights measured during actual operations support guidelines and general assumptions from previous studies for S2F aircraft (C. George 1982). Since the S2F test, instrumentation has been installed in C-119 and DC-4 airtankers.

References

Bussey, A. H.; Harrington, J. J. Helicopter modular airborne firefighting system test device (H-MAFFS). Final technical report, FMC Corporation, contract 26-3197 to Intermountain Forest and Range Experiment Station; 1973. 47 p.

George, C. W. Fire retardant ground distribution patterns from the CL-215 airtanker. Research Paper INT-165. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1975. 67 p.

George, C. W. Current trends in the aerial application of fire retardants. Canadian Aeronautics and Space Journal 24(3); 1978. 9 p.

George, C. W.; Blakely, A. D. An evaluation of the drop characteristics and ground distribution patterns of forest fire retardants. Research Paper INT-134. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1973. 60 p.

George, C. W. Measurements of airtanker drop conditions during firefighting operations. Research Paper INT-299. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. 10 p.

Luedecke, A. D.; Swanson, D. H. Procedures to adjust airtanker performance guides for downloaded operations. Honeywell, Inc., Contract 786-2031-76 to Intermountain Forest and Range Experiment Station, Ogden, UT; 1979.

MacPherson, J. I. An improved theoretical model for the ground distribution of water released from a fire-bomber. National Resource Council Canadian Aeronautics, Report LF-498; 1968. 46 p.

Swanson, D. H.; Helvig, T. N. Extended high altitude drop mechanization study: final report Honeywell Contract 26-2888 to Intermountain Forest and Range Experiment Station; 1974. 151 p.

Swanson, D. H.; Luedecke, A. D. Tank design guide for fire retardant aircraft. Honeywell Contract 26-3245 to Intermountain Forest and Range Experiment Station; 1978. 41 p.

Swanson, D. H.; Luedecke, A. D.; Helvig, T. N. Experimental tank and gating system (ETAGS). Final report, Honeywell Contract 26-3245 to Intermountain Forest and Range Experiment Station. 1978. 284 p.

Swanson, D. H.; Luedecke, A. D.; Helvig, T. N.; Parduhn, F. J. Development of user guidelines for selected retardant aircraft. Final Report. Honeywell Contract 26-3332 to Intermountain Forest and Range Experiment Station; 1975. 154 p.

Swanson, D. H.; Luedecke, A. D.; Helvig, T. N.; Parduhn, F. Supplement to: development of user guidelines for selected retardant aircraft. Final report. Honeywell Contract 26-3332 to Intermountain Forest and Range Experiment Station; 1977. 88 p.

U.S. Department of Agriculture, Forest Service, Operation Firestop. Progress Report No. 9, aerial firefighting. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1955. 13 p.

PLANNED RESEARCH

Data from the ETAGS and Tank and Gating Studies will be used to form a base for the refinement of PATSIM to include tank length-to-width rations. The flow data and tank exit geometry and the resultant ground pattern response predicted by the refined PATSIM will be compared with actual drop patterns to verify the predictive capabilities of the model.

Quantization of design criteria for the optimal performance of delivery systems over a wide range of coverage levels will be examined using the refined PATSIM. Possible optimal tank designs will include variable flow and variable exit geometry arrangements requiring the refinements to PATSIM.

Due to the increased use of helicopters for aerial retardant and water delivery drop pattern and static tests have been conducted for several fixed tank and slung bucket systems. (Data on file at IFSL.)

Initial analysis of this data indicates that a ground pattern response model can be produced using the drop pattern data as a base. A small amount of static testing of fixed tank systems will be required in order to quantify flow rates from a few of these systems. Ground patterns from this model will be compared with known drop pattern responses and verified or refined.

Once both the fixed wing and helicopter models are verified they will be used to complete user guides for existing delivery systems as well as establishing delivery system design criteria.

Fixed Wing Delivery System Modeling and Performance (2107-02-05,07)

Need:

Fire management organizations (USDA-FS, BLM, NPS) have begun to consider differences in ground patterns (performance) in relation to their fuel-fire needs when selecting airtankers for given areas. This performance information has come from published airtanker performance guides. In order to become more competitive in selection processes and awards, airtanker operators are attempting to modify airtankers to improve performance. This is being accomplished primarily by utilizing some release systems with length-to-width ratios and subsequent flow rate. These length-to-width ratios are outside the PATSIM ability to predict accurate ground patterns. Application of flow rate--door area design criteria that optimize delivery system performance will result in more efficient design of delivery systems that would be more applicable to diverse fuel/fire situations.

Summary:

A module of a proposed tank system for KC-97 airtankers was constructed and static tests were conducted using various options for flow rate control. PATSIM was used to estimate the ground pattern response of the various options and recommendations were made for tank design parameters including flow rate control and tank sequencing. In cooperation with the Australian Government (CSIRO) a Conair DC-6 with a large length-to-width ratio was drop and static tested to determine ground pattern response. It was found that PATSIM could be modified to correctly predict ground pattern response. During the ETAGS Study over 200 drops were made over a test grid, in an effort to quantify the effect of several variables on ground distribution patterns. The variables included door speed, door open area, exit geometry, fill level, venting, and several drop heights and speeds. On board instrumentation recorded the door open speed, internal tank pressure, and flow history. This large data base can be used to modify PATSIM for almost any new or old tank and gate system configuration.

Objectives:

Develop accurate airtanker ground pattern predictions based on static test flow rates and exit geometry that can be applied to the production of user guidelines and optimal design criteria.

Studies:

Preceding studies: Experimental Tank and Gating System Study No. 2107-75-510, Application of Existing Delivery System Design Criteria and Performance Evaluation Methods in Tanking the KC-97 Study No. 2107-02-07, Static Tests for Predicting Airtanker Retardant Drop Patterns Study No. 2107-02-05, and Development of User Guidelines for Airtanker Mission Planning Study No. 2108-02-05 form a base for the next studies that will apply exit geometry and flow control options to the model.

Proposed Time Scale:

Milestone	FY 1985	FY 1986	FY 1987	FY 1988	FY 1989
Modify PATSIM	----	----	-----	------	------
User Guides	--------	--------	--------	--------	--------
Design criteria			----	--------	--------

Cooperators:

RWU-4402 personnel for required coverage levels (ORE data) with NFS and airtanker operators.

Facilities:

IFSL computer, Tektronix graphic computer system, Data General network, temporary mathematician/statistician.

Helicopter Delivery System Modeling and Performance

Need:

Advances in the capability and availability of helicopters for delivery of water and fire retardant chemicals for fire suppression has resulted in interest in a ground response prediction model, similar to PATSIM, for helicopters. Such a model would enable the production of user guides for helicopters as well as design criteria for future helicopter delivery systems.

Summary:

Several helicopter delivery systems, both fixed tank and slung bucket types, have been static and drop tested. Initial examination of this data has identified the parameters controlling the ground distribution pattern (drop speed, drop height, and flow history). Initial examination using the fixed-wing simulation (PATSIM) has indicated that PATSIM is not capable of predicting helicopter drop patterns.

Objectives:

1) Develop ground distribution pattern predictions for helicopter delivery systems (both bucket and fixed tank) as a function of flow rate, drop height and drop speed, and (2) develop criteria for different types of helicopters within their usable flight envelopes.

Studies:

Existing study 2107-02-2 will be continued with amendments as necessary.

Time Scale:

Milestone	FY 1985	FY 1986	FY 1987	FY 1988	FY 1989
Determination of Parameter relationships	--------	--------	--------		
Assembly of model	--------	--------	--------	----	
Model verification		----	--------	--------	
Guidelines			----	--------	--------
Design criteria				--	--------

Cooperators:

WU-4402 personnel; National Forest System and helicopter operators

Facilities:

IFSL computing facilities and existing in-house constructed static testing equipment.

PROBLEM 2 - RESEARCH APPLICATION AND TECHNOLOGY TRANSFER

Problem 2 of RWU-4402 is the application of suppression knowledge gained in Problem 1 and from the completion of carryover mechanical suppression studies from the work unit description for the previous 5-year period. In general, the application and technology transfer efforts of Problem 2 will be focused toward the following efforts:

- o Develop real-time and planning guidelines for individual suppression activities related to primary fuel/fire variables.
- o Integrate production rate knowledge into real-time and planning guidelines for fire suppression strategies and tactics.
- o Develop design criteria for chemical formulations, and aerial and ground delivery systems for primary strategies and tactics.

Application of Chemical Suppression Research

RETARDANT EFFECTIVENESS/USE

Currently available aids or guidelines to determine the amount of retardant necessary in specific fire situations, although linked to fuel models, do not adequately consider the fire behavior/fuel situation. Guidelines will be developed for specific fuels that adjust the coverage level requirements as a function of field measurable fire behavior (probably flame length). This may require a further breakdown or classification of fuels beyond those used in behavior or the NFDRS models (for example a system for typing Southern California fuels may be used in place of the "California mixed Chaparral" description). Existing retardant coverage guidelines assume retardant to be applied in a "fully dry" or moist condition, representative of use in direct attack situations where no benefit of retardant moisture is obtained. This is not the case as most retardant is applied "close in" to the fire where moisture is a significant contributor to retardant effectiveness. Operational effectiveness data coupled with data from the laboratory retardant extinguishing capabilities study will be used to better define actual retardant needs in various situations and tactical applications. Methods developed in these studies will be utilized to assist Aviation and Fire Management and other fire management agencies to operationally evaluate suppression effectiveness of specific operations, new fire retardant formulations, delivery systems, etc. The retardant effectiveness information will also be utilized as a basis for developing guidelines and training materials for effective use of aerial retardants.

APPLICATION/DELIVERY:

Fixed-wing Delivery System Applications

Previous research performed by the retardant research team led to development of a computer pattern simulation model (PATSIM) which predicts airtanker drop pattern distributions from a detailed description of the various retardant release characteristics including flow rate from the tanks. Static test data collection and analysis procedures were developed in detail such that the expected performance of any airtanker can be determined, performance guidelines prepared, design changes evaluated, or its performance directly compared to the delivery system.

Airtanker Performance Guides were developed for major types of airtanker delivery systems. The detailed airtanker performance guide data was synthesized to form pocket-sized retardant coverage computer slide charts that can be conveniently used for planning or in the confines of an operational aircraft. The slide charts and guides contain the best state-of-the-art estimates on recommended retardant requirements for major fuel and fire behavior models. Guides and slide charts have now been developed for most of the airtanker delivery systems available to fire management agencies. As new delivery systems are developed or improvements made to existing systems it will be necessary to evaluate their performance and develop similar guides and coverage computers. It would also be timely to develop a data system (perhaps using the Data General) so that fire managers would have this data at their finger tips by simply defining a particular delivery system or airtanker.

Various operational parameters have been measured on actual retardant dropping missions using several types of instrumented airtankers. The variables included drop height, drop configuration and tank release sequence, delay time, indicated airspeed, minimum height above fuel, and various use characteristics. The interpretation of real-time operational data was investigated and the importance of various factors determined. Results of the pilot study have confirmed the validity of aircraft evaluation procedures and instrumentation. Drop heights will continue to be measured during actual operations to support guidelines and associated retardant research studies where these factors are important inputs, i.e., the ORE Study.

Information from the performance guides, evaluation of operational effectiveness (ORE Study) drop conditions study, and tank geometry study (ETAGS) should provide insight into optimum aerial delivery system design/performance criteria and provide a basis for a tank design guide, as well as retardant formulation/use guidelines. The end goal of the application/delivery research is to describe systems tailored to the retardant formulation and retardant coverage requirement and provide use guidelines for application.

Helicopter Delivery System Applications

A study of helicopter delivery system performance was undertaken to determine the applicability of fixed-wing delivery system performance physical models and general understanding of mechanism of helicopter retardant delivery. A combination of slower operational drop speeds, smaller volumes, and lower flow rates made existing models inapplicable for helicopter delivery systems. A number of helicopter delivery systems (buckets and fixed tanks) were selected for static and drop testing to provide a range of release/performance characteristics that will provide a basis for development of an empirical helicopter performance model. Data collected during the study is adequate for future analysis, performance model development, and identification of helicopter delivery system criteria and requirements.
Retardant Formulation Chemistry

RETARDANT FORMULATION CHEMISTRY

Effectiveness:

Specific levels of retardant salts must be maintained in the mixed products for fire retardants to be effective. In addition, the retardant must be appropriately applied (location and coverage level) for the salts to be effective to do their job. Field studies should provide realistic information on how much, when, and/or if retardant should be applied. Programs must be developed to assure that this information is available to fire control personnel responsible for retardant application. Laboratory analysis can ensure the proper proportions of chemicals are used but these procedures are seldom suitable for on-site/field screening. Tests have been developed to partially fulfill that need, but additional tests of some parameters are still needed. Reference handbooks and consultation in cooperation with agency field personnel are needed to ensure understanding and implementation of a systematic field test program to promote effective retardant use in the field, and efficient use of tight budgets.

Rheology:

The ability to place retardant where it is needed on the fuel complex and keep it there long enough to be effective is directly related to the elasticity of the retardant. The type and quantity of elastomer used and the concentration in the retardant (use level) at the time of application will help determine how effective the fire retardant will be. Results of basic studies allow specific comparison of different types of elastomer to determine the concentration needed to do the same job. Because elasticity and viscosity are particularly susceptible to affects of other chemicals the study will address specific problems (product degradation) that may occur when products are contaminated or combined as may happen in a field environment. To assure that products continue to perform as designed, test procedures suitable for field use as well as in the laboratory are required. As these procedures are developed and verified and laboratory performance criteria necessary for suitable field behavior will be provided to Forest Service and other agency personnel for inclusion in specifications and contracts.

Corrosion:

Corrosion damage caused by fire retardants can be minimized by the selection of suitable combinations of inhibitors and construction materials. Laboratory studies of numerous alloy and inhibitor combinations in varying concentrations, have led to one or more potential inhibitors for each of the different retardant salts. Provided that there is no adverse behavior (or affects on other properties) when fully formulated retardant is produced, a retardant can be designed and produced (by prescription) for special use areas or applications. This information, plus that accumulated during field inspections can provide other opportunities to control corrosion through proper housekeeping and maintenance practices. All of these findings as well as the test procedures developed for the basic laboratory studies can be provided to the field through personal consultation, incorporation into the existing system of specifications (test procedures and requirements), contract requirements, and manuals and handbooks developed specifcally for that purpose.

Health, Safety, and the Environment:

Effort in the area of toxicity and environmental impact will be minimal and on an as needed basis in consultation with Aviation and Fire Management, other agencies, and retardant manufacturers as new formulations are developed and/or different chemicals incorporated into existing products.

Application of Mechanical Suppression Research

MECHANICAL SUPPRESSION PERFORMANCE/USE GUIDELINES

Need

The successful implementation of suppression alternatives (a specific mix or structure of control forces and activities) that minimize the sum of suppression costs plus resource damage is dependent on knowledge of the effectiveness of each suppression activity and strategy in quantitative terms relative to situation variables. The lack of fire suppression effectiveness information is a major barrier in the analysis of suppression alternatives and identification of the mix of suppression forces and strategies to most efficiently meet stated resource management objectives.

Suppression capabilities relative to production need to be expressed in terms that go beyond simply the time required to build a fireline between two points or a given distance. Decisionmakers need more detailed information and precise tools. Suppression capabilities need to be expressed in terms that lend themselves to more sophisticated analysis and application. Recent developments in fire models, fire danger ratings, and economic evaluation procedures all require improved suppression capability information linked to site, behavior, and other situation parameters.

Summary:

Limited studies aimed at quantifying the fire suppression capability of specific suppression activities have been undertaken. Production rates for modern bulldozers (manufactured since 1975) have been revised utilizing production indexes manufacturers have devised to indicate comparative capabilities of various models. Construction rates with new equipment have improved significantly, often by as much as 20 percent. Limited field opportunities would allow verification of the new production data. Interest in fireline explosives lead to limited testing with water-gel and fireline cord in an effort to define the quality of constructed fireline and provide a basis by which handline explosive line could be compared. It appears that fireline constructed with explosives may be less harmful on the site than other conventional methods (handline, plows, dozers, etc.). Studies of handline built by various crews with different makeup, abilities, training, size, etc., indicate that production rates may have significantly changed from those used in the past (for which current production rate data is based). Modifications or adjustments for today's suppression organization is necessary.

<u>Objective</u>:

Bulldozer production model, field verification (contract effort by Clint Phillips) in cooperation with Forest Service R-5, and California Department of Forestry. (2107-01-10)

Linear fireline explosives (cooperative effort with RWU-4402, University of Montana, and Montana State Division of Forestry) determine production rates and assess environmental consequences; also development of a handbook for certified fireline blasters and crew and/or trainees. (2107-01-06)

APPENDIX I - RELATIONSHIP OF STUDY AREAS IDENTIFIED IN PROBLEM ANALYSIS TO GENERAL "CHEMICAL SUPPRESSION ACTIVITIES" IDENTIFIED IN RWUD

Problem 1 (RWUD)	Problem 1 (Problem Analysis)
Chemical Suppression Activities	Study Areas and Studies from Problem Analysis[1]
1. Determine fire retardant requirements as a function of fuel, fire, retardant chemical, and application variables (including limits of effectiveness in various tactical situations). 15-17	A. Retardant Effectiveness 1. Retardant extinguishing capabilities, p. 13-14 2. Operational/retardant effectiveness study, p. 15-17 B. Physical-Chemical Properties 1. Retardant rheological properties p. 24-25
2. Define the characteristics of more cost-effective fire control chemicals, including long and short term retardants, and foams in terms of chemical and physical properties (combustion, effectiveness, rheological properties, corrosivity, environmental impact, health and safety).	A. Retardant Effectiveness 1. Retardant extinguishing capabilities p. 13-14 2. Operational/retardant effectiveness study p. 15-17 B. Physical-Chemical Properties 1. Retardant rheological properties p. 24-25 2. Mechanisms of retardant caused-corrosion p. 32-33 3. Retardant impacts to personnel and the environment p. 34-35
3. Correlate known parameters influencing the performance of fixed and rotor wing application systems and delivery system design to improve performance flexibility, standardization, effectivensss, and safety.	A. Application/Delivery Systems 1. Fixed-wing delivery system modeling and performance p. 44-45 2. Helicopter delivery system modeling and performance p. 46
4. Conduct fundamental studies to determine primary variables influencing the distribution of aerial and ground delivery retardant within representative three-dimensional fuel arrays.	A. Physical-Chemical Properties 1. Retardant rheological properties p. 24-25

Problem 2 (RWUD)	Problem 2 (Problem Analysis)
Transfer of Results	Study areas and studies from Problem Analysis[1]
1. Develop real-time and planning production/effective-ness guidelines for individual suppression activities related to primary, fuel, fire, variables.	A. Application of Chemical Suppression Research 1. Retardant effectiveness/use p.47 2. Application/delivery p. 48-50 B. Application of Mechanical Suppression Research 1. Mechanical Suppression Performance/Use Guidelines (continuing studies in mission problem from RWUD) p. 51-52
2. Synthesize and integrate production rate knowledge into real-time and planning guidelines for fire suppression strategies and tactics.	A. Application of Chemical Suppression Research 1. Retardant effectiveness/use p. 47 2. Application/delivery p. 48-50
3. Describe design/performance relationships useful in tailoring chemical formulations, and aerial and ground delivery systems for primary strategies and tactics.	A. Application of Chemical Suppression Research 1. Retardant formulation chemistry p. 49-50

---

[1] Strong interactions exist within and between study areas (from Problem Analysis) and, as a result, studies may provide a primary input to several "generally defined" activity/investigative areas as defined in the RWUD. Page numbers provided on listed studies refer to pages in the Problem Analysis.

APPENDIX II - SUMMARY OF STUDIES (RWUD 4402)

Study Plan	Title	Short Objective	Initiated	Completion
2107-02-08-Blakely	Extinguishing abilities of fire retardants	Quantify retardant requirements for extinguishing flaming and glowing combustion.	10/82	10/88
2107-02-ORE George & Blakely	Operational retardant effectiveness evaluation	1) Determine actual operational retardant requirements for different fuel/fire behavior situations. 2) Verify existing performance models. 3) Evaluate usefullness of guidelines.	7/83 (amended 84, 85, 86	10/90
2103-20 Susott & George	Thermal behavior of fire retardant treated forest fuels	Investigate the reactions of retardant treated fuel.	7/81	8/87
2107-02-01 Van Meter & George	Retardant rheological properties	Determine if elasticity can be used as a measure of short-term fire retardant drop performance.	7/80 (last amend 1985)	10/87
2107-02-04 George & Johnson C.	Investigation of fire retardant caused corrosion	Determine adequacy/reproducibility of proposed uniform/intergranular corrosion test methods, define corrosion limits, and fire retardant corrosiveness related to mechanisms.	10/82 (amended)	1/88
2107-02-05 George, Johnson, G.	Performance of fixed-wing delivery systems/development of guidelines	Quantify airtanker performance 1) Develop appropriate pattern simulation models. 2) Use models to develop guidelines. 3) Identify tank & design criteria.	10/80	10/88
2107-02-07 George, Johnson C.	Application of existing delivery design criteria	Verify performance of PATSIM model/design criteria.	10/82 Inactive	10/87
2107-02-02 George & Johnson C.	Performance of helicopter delivery systems	1) Provide performance data for development of a pattern simulation model. 2) Use H-PATSIM to provide guidelines. 3) Develop helicopter tank design criteria.	2/81 (Rel. inactive)	10/90
<u>Problem 2 - Research, Application, and Technology Transfer</u>				
2107-02-ORE	Operational Retardant Effectiveness	(See above) Involve research, application, and technology transfer as a primary aspect; however, the application is not broken out as a separate study of Problem 2.	(See above)	
2107-02-04	Retardant-caused corrosion			
2107-02-05	Airtanker perforamnce guidelines			
2107-02-07	Delivery system design criteria			
2107-02-02	Helicopter performance guidelines/design criteria			
<u>Mechanical Suppression Research</u>				
2107-01-09 Noste & Barney	Revegetation flowing blasting line	Define impacts of fireline explosives and compare with conventional handline.	10/83	10/87
2107-01-10	Mechanical suppression performance (Dozer production rates)	Field verification of dozer production rates extrapolated from other than fire related data.	10/83	10/87
2107-01-06 UM, State of Montana Coop	Linear explosive fireline production rates	1) Determine production rates and assess environmental consequences 2) Develop blaster's handbook	10/82	10/86

APPENDIX III - MECHANICAL SUPPRESSION RESEARCH - PROBLEM STATEMENT

Introduction

In 1979 a major revision in the work unit description for the Fire Technology Project, INT-2107, resulted in the delineation of suppression capabilities as one of the major problems assigned for investigation. The 1985 planning process acknowledged the continuing need but limited resources have caused a change in emphasis.

The 1979 comprehensive review of user concerns and anticipated problems related to range and wildland fires identified the specified subject areas as being of immediate and long range concern at that time. Input into the research planning process came from a wide array of potential users of research, cooperators, and others interested in public land management. These sources identified the need for continuing research in suppression effectiveness. Immediate and future applications of results from such research would aid in several applications including: land-use planning and activity level planning to formulated support resource management objectives; planning and execution of prescribed fires to achieve specific resource management objectives; predicting potential fire behavior and effects as part of the basis for planning of activities in fire prevention, detection, and suppression; and evaluation of potential fire behavior and effects and anticipated suppression effectiveness in escaped fire situations to support the selection of suppression strategies.

Review in 1985 indicated that the 1979 analysis and concepts were still basically valid for the next 5-year planning period.

Problem:

Continuing increase in fire suppression costs, reduced budget allocations, and a greater awareness of the role fire plays in many forest and grassland ecosystems resulted in the reassessment of fire management policies and objectives. As demonstrated by implementation of the Forest Service Revised Fire Policy, the revised policy requires more intense fire management planning, assessment of fire effects in relation to land management objectives, and real-time analysis of the effects, controllability, and risks involved in allowing escaped fires to burn. Where fire meets management objectives and is allowed to burn under prescription, it is imperative that the limits for potential control be known. Lack of fire control effectiveness information is a major barrier to fire economics, fire planning, and decisionmaking research (for example, the USDA Forest Service fire plan evaluation program FOCUS relies on an input table of constant values for control line production rates). Therefore, a part of the 1979-1984 fire control technology research program was designed to answer the question "How can fire control planning and force structure evaluation be facilitated through knowledge of the productivity of fire suppression alternatives?" This question is still valid for the 1985-1990 planning period. However reduced budgets and the abolishment of existing fireline production work will make answering this question impossible. Nevertheless it is appropriate to provide a general problem statement which will allow and guide future research in this area when funding permits. No uniformly-applicable process for evaluating the effectiveness of fire suppression options is still presently available. Without such an analytical system, fire managers and fire management planners are forced to use arbitrary measures of effectiveness that often do not relate to various suppression actions. Thus, the success or failure of the "force structure" may be expressed in terms of number of fires, acreage burned, rate of change in the fire size or other similar measurable units. Such expressions do not allow quantitative comparisons to be made between specific suppression methods, techniques, or alternatives. Quantitative information is really basic to any allocation of resources and evaluation of their use (Noste and Davis 1975).

A process for evaluating fire suppression activities still needs to be developed. Its usefulness depends in part on understanding relationships between suppression capabilities and fire characteristics. Unfortunately, data needed to establish such relationships is incomplete or of questionable validity. Because productivity is often expressed in units-of-measurement not comparable between techniques a common denomination is also desirable. Continued effort in fire suppression is needed to support other systems and processes being developed.

In 1980 the components and linkages of a fire management decision system were detailed in a paper by Egging, Barney, and Thompson. In this discussion, the three basic ingredients of management and control were outlined. These components of a fire management system are prevention, suppression, and fire use. Review of this document, which was the cornerstone of today's planning and operational direction, would give the reader a solid perspective as to the system components (figure 1). A model of a fire suppression further details the basic activities. The paper developed by Barney in 1983 is a thorough discussion and breakdown of the suppression system itself. Although the paper was geared toward fireline production, it is generally applicable to the broader area of suppression efforts. Research efforts during the past research planning period (1979-1984) were barely able to scratch the surface of the mechanical side of suppression research.

Mechanical research efforts need to be centered around the general process elements which are (see figure 2, Barney 1983).

1. Management objectives
2. Suppression resource options
3. Theoretical production rate
4. Production rate modifier
5. Tactical application
6. Adjusted production rates
7. Production rate application
8. Cost, effects, probability of success

These eight areas all require additonal research efforts and management interface to meet the overall suppression requirements. Contrary to popular thinking fire use in any form or wildfire suppression still require more sophisticated information to meet today's and tomorrow's management objectives. Much of our suppression input has not kept pace with today's tools, options, and needs. All the computer models in the world will not contain or suppress a fire. All the BEHAVE information is purely academic and theoretical until some form of implementation occurs (see figure 1).

Figure 2 shows a detailed outline of the components of the suppression system. The interrelationships and their relative position and importance become more visible in this figure. This figure is in actuality a problem analysis. The boxes need to be filled with appropriate data and the linkages established and clearly defined.

Literature Review:

Interest in how fast firelines can be built has been apparent since the advent of formalized fire control organizaitons. The 1930's seemed to be the most productive period for developing production rate information on a systematic basis. In 1936 Hornby enumerated the most inportant factors affecting the construction of held fireline per man hour as follows:

1. Fuel resistance to control
2. Method of attack
3. Kind of tools, equipment, and food provided
4. Efficiency of directing officers
5. Training and experience of firefighters
6. Physical and mental ability of firefighters
7. Size of crew
8. Size of fire
9. Aggressiveness and heat of fire
10. Prevailing atmospheric temperature
11. Fatigue
12. Darkness

These items are still important considerations today. Studies of Abell (1937), Buck (1938), and Hanson (1941) all contributed to the development of early production data. Agencies, such as the Californis Division of Forestry, continued to improve information as management needs changed. More recently, Storey (1969) summarized existing productivity and line building data. He concluded that although the quantity of handcrew data might be adquate, its quality was suspect. This same observation was made for bulldozer productivity data. His remarks concluded by stating the following:

> "Solutions of force required to suppress a fire obtained from dispatching and probability guides in the fireline notebooks are only as good as the data on fire spread and force productivity on which they are based. As we have seen, force productivity data are limited in quality and coverage. Estimates of length of fireline requiring treatment are of limited accuracy due to a general lack of good data on fire behavior. Models of fire spread and control will require much better data on fire spread and force productivity than currently exist. Fire behavior studies are currently underway

> that should provide better data in the near future. It is recommended that they be continued and, if possible, accelerated.
>
> In order for mathematical models of fire behavior and control to be applicable nationwide, systems for rating fuels and weather from a fire effect standpoint must be applicable nationwide. Good progress is being made on a national fire danger rating system. A study to develop a national system for rating fuel for rate of spread and resistance to control is underway but not as far along. Such a system is urgently needed."

Work in the general area of fireline production rates has continued in a sporadic nature. Two reports developed during the 1970's are examples of the more recent efforts (Barney and Noste 1973) and Murphy and Quintilio 1978). It appears that all these diverse production data need further summarization and evaluation in a manner similar to that conducted by Storey in the late 1960's.

Research work during the most recent period developed a fireline production model (Barney 1983) which provided details and linkages of the suppression process. Work on more "exotic" construction methods such as line construction using linear explosives has led to better understanding of the method (Barney 1984). Revised bulldozer production rates (Phillips and Barney 1984) have also been used extensively.

RESEARCH NEEDED

Based on the literature reivewed, the problem discussion, more recent work, and background materials that formulated the revised Research Work Unit description, the need for research in the general area of suppression capabilities is seeminly unlimited. Research efforts still need to provide and develop additional basic background information. Included here would be the development of relationships between an array of fireline construction methods and physical measures such as flame length slope, soil type, etc. There is also a continuing need to assess and adapt existing procedures, information, and systems where possible. A parallel need is to develop new procedures, systems, philosophies, and approaches for fire suppression to meet economic and management demands. Finally, the technology transfer or implementation and utilization of information requires continued effort and evaluation.

What are the capabilities of various types and sizes of both crews and mechanical equipment for producing held fireline under various environmental conditions? How many firefighters or how much equipment do we need to supress fires? How wide should the fireline be? What are the fireline requirements in terms of fuel/fire potential type units? What units are best to combine construction methods, sich as dozers and engines, to arrive at a composite production rate? These kinds of questions are still an absolute necessity in determining the basic manpower and equipment requirements for accomplishing a given suppression job. Information of this type would also assist in obtaining the most out of each dollar spent on control efforts. Related cost information regarding fireline production is also a must. Data such as these can then link with various economic evaluation programs or simulation programs like FEES or BEHAVE.

PROPOSED RESEARCH PROGRAM

Studies cannot be developed around the ability of the present project research staff even with the aid of cooperators to meet the information demands. Initial studies can eventually be of a service nature used both to obtain data and more clearly identify those areas where more intensive work is required. Increased personnel or total project redirection will be needed to undertake work in this general subject area.

Study efforts should be both field and office oriented. Fieldwork should be generally geared to time studies both of a formal and opportunistic nature. Office efforts can center around assembly and evaluation of existing data as well as gleaning data from other sources such as daily fire records. The studies can also be aimed at two broad use areas, operational planning and simulation. Each of these applications has different information and resolution requirements.

It is envisioned that study results when implemented will lead to improvements in fire suppression hardware, application use guidelines, revised fireline construction tables for an array of personnel configurations and equipment. Additional spinoffs might include recommendations for improved strategies and tactics, combinations of suppression activities and related outputs.

The extent and duration of the efforts expended on this part of the problem will be based on available financial and personnel resources. In addition, continued contact with the field and related research projects can provide a basis to maintain proper priorities and appropriate level of effort within overall budget, manpower, and time limits.

References

Abell, C. A. Preliminary report: rate of spread and resistance to control data FDR Region 7 fuel types and their application to determine strength and speed of attack needed. Appalachian Forest Experiment Station, Asheville, NC; 1937. 38 p.

Banrey, Richard J. Characteristics of fireline blasted with linear explosives: initial test results. Research Note INT-345. Ogden, UT: U.S. Department of Aglriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 8 p.

Barney, Richard J. Fireline production: a conceptual model. Research Paper INT-310. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 7 p.

Barney, R. J.; Noste, N. V. Interior Alaska manpower and equipment fireline output standards. On file at Pacific Northwest Forest and Range Experiment Station, Portland, OR; Office report; 1973. 23 p.

Buck, C. C. Resistance to line construction. San Francisco, CA: U.S. Department of Agriculture, Forest Service, Region 5; 1938. 33 p.

Hanson, E. A. Man-hours of work required to construct varying lengths of line under different resistance-to-control classes. Fire Control Notes 3(2):84-89; 1941.

Murphy, P. J.; Quintilio, D. Handcrew fireline construction: a method of estimating production rates. Edmonton, Canada. Northern Forest Fire Research Centre, Information report No. 12-X-197, 27 p.

Noste, Nonan V.; Davis, James B. A critical look at fire damage appraisal. Journal of Forestry 73(11); 1975. 5 p.

Phillips, Clinton B.; Barney, Richard J. Updating bulldozer fireline production rates. General Technical Report INT-166. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 21 p.

Storey, T. G.Productivity and rates of substitution of line building forces in fire suppression--a summary of existing data. Progress Report. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1969. 32 p.