NBSIR 85-3266

A Preliminary Analysis of Oil-Slick Combustion

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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Abstract

This preliminary study of oil-slick combustion contains a literature review, a formulation of a physical model of oil-slick burning, and some suggested experiments. The theoretical model is divided into three stages: (1) an ignition and acceleratory-growth cycle, (2) a slowdown regime, in which finite slick thickness effects become important, and (3) an extinction cycle. The proposed experiments emphasize the use of the Fire Research Laboratory located on the NBS grounds.

Keywords: buoyant flow, burning rate, combustion efficiency, combustion theory, experiments, ignition, liquid spills, oils.

1. INTRODUCTION

This report presents results of three tasks in this preliminary study of oil-slick combustion. Section 2 contains a review of literature that is relevant, directly or indirectly, to the combustion of oil slicks. Section 3 contains the formulation of a physical model of oil-slick burning, and Section 4 contains a discussion of some (potential) supporting experiments. The research literature relating directly to the combustion of oil slicks is scant. However, the literature dealing with various specialized aspects of oil-slick combustion is extensive (e.g., studies of pool-fire radiation, buoyant plumes, etc.). Since most of these subproblems are fairly well understood the literature review conducted in Section 2 is not exhaustive, just sufficient to motivate the development of the physical model of Section 3. The mathematical model(s) to be solved during the course of this study will be derived from the physical model. The experiments discussed in Section 4 support the development of the physical model discussed in Section 3. Small to medium scale experiments are given special emphasis herein.

2. LITERATURE REVIEW

A review of the literature on oil-slick combustion shows that relatively little work has been done to advance the fundamental understanding of the ignition and spread of flames over oil slicks. However, a large body of literature exists for the numerous (component) subproblems of oil-slick combustion, such as oil-slick spreading over a calm sea, flame spreading over a thin layer of combustible liquid, the radiant characteristics of a buoyant plume over a burning liquid pool, etc. It is believed here that these various component models can be combined, in some way, to produce a rational means for understanding this complex problem.

Some examples of reports dealing directly with oil-slick combustion are those of Brzustowski and Twardus [1], Buist, Ross and Twardus [2], Ross, et al [3] and the DOE review [4]. The simple model of Brzustowski and Twardus [1] describes the one-dimensional quasi-steady burning of a combustible fuel layer over water. The water underneath the slick is assumed to be a constant-temperature heat sink that eventually extinguishes the fire. The effects of wind deflection of the flame are included in an ad-hoc manner. There are no comparisons between theory and experiment. The studies of the Energetex group (Buist, Ross and Twardus [2], Ross, et al [3]) are an attempt to describe oil slick combustion over the entire range of slick sizes. Their theoretical analyses borrow heavily from previous studies using the same methodology (see, e.g., Fay [5], in which the spreading of oil slicks is described through simple dimensional arguments). Such an approach is useful for preliminary order-of-magnitude estimates, but is unlikely to produce highly-accurate predictions of burn efficiencies and other physical quantities. Thus, the theoretical analyses of Ross, et al [3] lead only to parametric correlations, of the type found by using dimensional analysis. In addition to their modeling efforts, they have conducted small, medium and large-scale experiments. The data for their small and medium-scale tests appear to be much more reliable than their large-scale test data. The effects of wind-herding are discussed in connection with the large-scale tests.

The DOE review [4] is a very useful compilation of relevant work on oil-slick removal by combustion, and contains an extensive bibliography. Many chapters are devoted to practical engineering and economic discussions; one chapter discusses previous (up to 1979) modeling efforts and experiments, and some of the fundamental physical principles of oil-spill burning.

The research literature of combustion contains numerous studies of idealized problems, various aspects of which are relevant to the study of oil-slick burning. Research (up to the late 1970's) dealing with the structure of buoyancy-induced turbulent flow fields over large (greater than ~ 0.2 m diameter) pool fires has been reviewed by Hertzberg, et al [6]. More recent studies have been conducted by McCaffrey [7]. The applicability and usefulness of integral methods is discussed at length, and comparisons with experiment are favorable. Estimates of the horizontal inflow velocites are made, and compare reasonably well with previous experiments. Although pool-fire analyses apply only to stationary (non-growing) fires over infinitely-thick liquid fuels, it is expected that these calculations, suitably modified, will apply in the initial growth stages of the fire over the slick. Such modifications will have to be made during the course of this study.

Another fundamental problem that has received considerable attention is the spread of flames over thin layers of combustible liquids (in pans). The group headed by I. Glassman at Princeton University has produced a series of papers discussing the controlling mechanisms of spread, specifically, processes controlling the advancement of the flame over the unburnt fuel. Their work is summarized in the paper of Glassman and Dryer [8], where it is shown experimentally and theoretically that the physical mechanism governing flame advance is the gradient (in the direction of spread) of the surface tension. The flame spread rate is given (approximately) by $u \sim \sigma,_x h/\mu$, where $\sigma,_x$ is the streamwise gradient of the surface tension, h is the fuel layer depth and μ is the fuel viscosity. In addition, convincing arguments are made for the importance (in the flame-spreading process) of convective flows in both the gas <u>and</u> the liquid fuel. Since the experiments of the Princeton group were small-scale, the effects of radiation were not emphasized.

However, for flame spreading under any conditions other than small (or laboratory) scale, the influences of radiation will be important. The radiant preheating of the unburnt fuel ahead of the flame is expected to play a major role in determining the spread rate and hence the fuel consumption rate. The subject of radiation in fires has been reviewed by deRis [9]. The effects of radiation on pool fires has been discussed by Burgess and Hertzberg [10]; a simplified model of pool-fire radiation has been constructed by Orloff [11]. A very useful concept, that of a cylindrical flame, was used to model the effects of flame radiation on the surroundings (Dayan and Tien [12]). The effects of radiation will be included in the model of flame spread developed here.

3. THE PHYSICAL MODEL

The modeling efforts of this investigation are based on the physical assumption that an actual oil slick is a nonhomogeneous, variable-thickness layer, whose removal by combustion is most effectively performed by igniting its thicker areas. Such an assumption is consistent with the transient nature of oil spillage, with field observation, and with the detailed mathematical analyses of Cox, et al (see, e.g., Foda and Cox [13], DiPietro and Cox [14], DiPietro, Huh and Cox [15]), who show that even under highly idealized conditions oil slick spreading is accompanied by the growth of an exceedingly thin layer (monolayer) along the outer edge. Thus, an actual oil slick most likely resembles the physical configuration illustrated in Fig. 1, where regions of thick (say, of the order of 1 cm) oil splotches (less than ~ 10 meters in diameter) are surrounded by large regions of very thin monolayer. The combustion of such a slick obviously cannot be accomplished by generating a single large-scale fire over it (since the monolayer cannot support combustion) but must instead be removed by lighting smaller (local) fires in regions of the slick that are thick enough to burn. Thus, the theoretical and experimental emphasis of this investigation is on the small and medium-scale processes (small-scale means ~ 10^{-1} meter in diameter, medium-scale means ~ 1 meter in diameter; large-scale fires are assumed to be ~ 10 meters or more in diameter), since the large-scale processes are believed to be unimportant. This simplifies the problem considerably, since (as discussed in Section 2) large-scale experiments are costly and difficult to control, even under ideal conditions.

The theoretical model describing the aforementioned physical processes is anticipated to consist primarily of three distinct burning regimes. The first is an ignition and acceleratory spread (or initial growth) regime, in which the fire spreads radially from the ignition source until a medium scale (say ~ 1 m diameter) fire is established over the slick. The second regime exhibits a slowdown in the rate of fire growth, because of fuel depletion, heat losses, etc.; the first signs of flame quenching are evident in this burning stage. The third regime has quenching in the center (ring fire) and a decreasing mass burning rate.

Figure 2 illustrates the physical configuration for the ignition/acceleratory spread (initial growth) regime. The gas-phase flame is initially laminar, becoming increasingly turbulent as it grows. The mass efflux of combustible gases from the gasifying fuel continually increases; in this regime the slick thickness is effectively infinite (i.e., the oil slick appears to be an infinitely deep pool). After ignition, while the fire is still quite small, the initial radiant preheating of the unburnt liquid (ahead of the fire) is assumed negligible, so that initial spread is controlled by conduction processes near the flame foot. The combined effects of air entrainment, oil circulation and the oil surface tension gradient (Glassman and Dryer [11]) produce the observed spread rate. As the fire grows, radiant preheating becomes more important. The oil slick is now heated to a wider radius, and flame spreading is accelerated.

Such growth is expected to continue until the fuel supply in the vigorously-gasifying region (in the center of the fire) begins to dwindle, see Fig. 3. Thus, the second burning stage (in which the fire plume is assumed to be fully turbulent) contains the influences of finite slick thickness. Combustion is assumed to proceed until the slick vanishes. This assumption is necessary for two reasons; (1) the oil is assumed homogeneous, so that volatile burn-off is not the combustion-limiting factor and (2) experimental studies have shown (e.g., Hall [16]) that the water beneath the slick does _not_ behave as a pure heat sink, since the heat flux from the burning slick establishes a nearly continuous temperature gradient at the slick-water interface. Thus, the effects of thermal quenching are not considered in this study. The decline in the rate of increase of the volatile mass flux from the burning surface is accompanied by a decline in the rate of increase of the radiant preheating of the unburnt fuel (there is a _delay_ between these two processes, since the fuel leaving the surface at time t is combusted at a later time, $t + \Delta t$). The fire extinguishes first in the middle, forming a ring fire (see Fig. 4).

In this final stage the radiant flux and the volatile mass flux both decrease. The rate at which the mass burning rate decreases depends upon how quickly the quenching diameter approaches the flame-foot diameter (see Fig. 4). The diameter at which extinction occurs allows the calculation of the total oil-slick volume that can be combusted (under ideal conditions) by _one_ igniter.

The combustion regimes discussed here can be represented diagramatically, as shown in Fig. 5. In Fig. 5, t (time) is the process variable. Ignition occurs at $t=0$, and at t_1, the first loop is entered. This loop represents the initial growth regime, in which slick thickness effects are negligible, and the mass efflux, radiant heating and the spread rate all increase. At t_2 thickness effects become important, and the process leaves the first cycle, enters the second (the slowed-growth regime) and then (at t_3) the final quenching cycle. Quenching occurs at t_4, when insufficient heat is available for vaporization of the unburnt fuel.

4. SUGGESTED EXPERIMENTS

All supporting experiments can be performed at the research facility located in Building 205 on the NBS grounds. The size of the experimental facility is suitable for conducting small and medium-scale tests. Preliminary testing will emphasize the fundamental understanding of slick spreading and burning, to facilitate the associated modeling effort.

The combustible liquid will be poured over a layer of water contained in a transparent tank (roughly 2 m x 2 m in area), so that visual recording of subsequent events can be made. Particle tracking of the water motion is performed by seeding the water with visible particulates; of special interest should be the view from directly below the slick. The depth of the tank should be no more than approximately 20 to 30 cm, for reasons of safety, because temperature gradients become vanishingly small with increasing depth, and because the fluid-dynamical effects of circulation (if any) are expected to be confined to the near-surface region.

Initial experiments will be conducted with fuels whose behavior is well understood (such as heptane, for example); such fuels can be modified to simulate oil burning by adding suitable quantities of thickening agents. Effects such as air entrainment into the fire and flame-induced motion of the oil and water can easily be assessed through visualization techniques; quantitative measurements will be more difficult to make. The fire growth rate and spread rate are readily evaluated, while measurements of the radiant heat flux to the surface would be more complex; such measurements may require the positioning of numerous heat flux gauges in various locations around the fire. Experimental burn efficiencies are evaluated by dividing the weight of the residue by the weight of the original (unburned) fuel.

5. ACKNOWLEDGMENTS

The author wishes to thank Mr. Ed Tennyson and Mr. John Gregory of the Minerals Management Service, DOI, for their interest in and support of this study. Discussions of this problem with J. Quintiere (NBS) and T. Terai (Kyoto University) have proved very useful.

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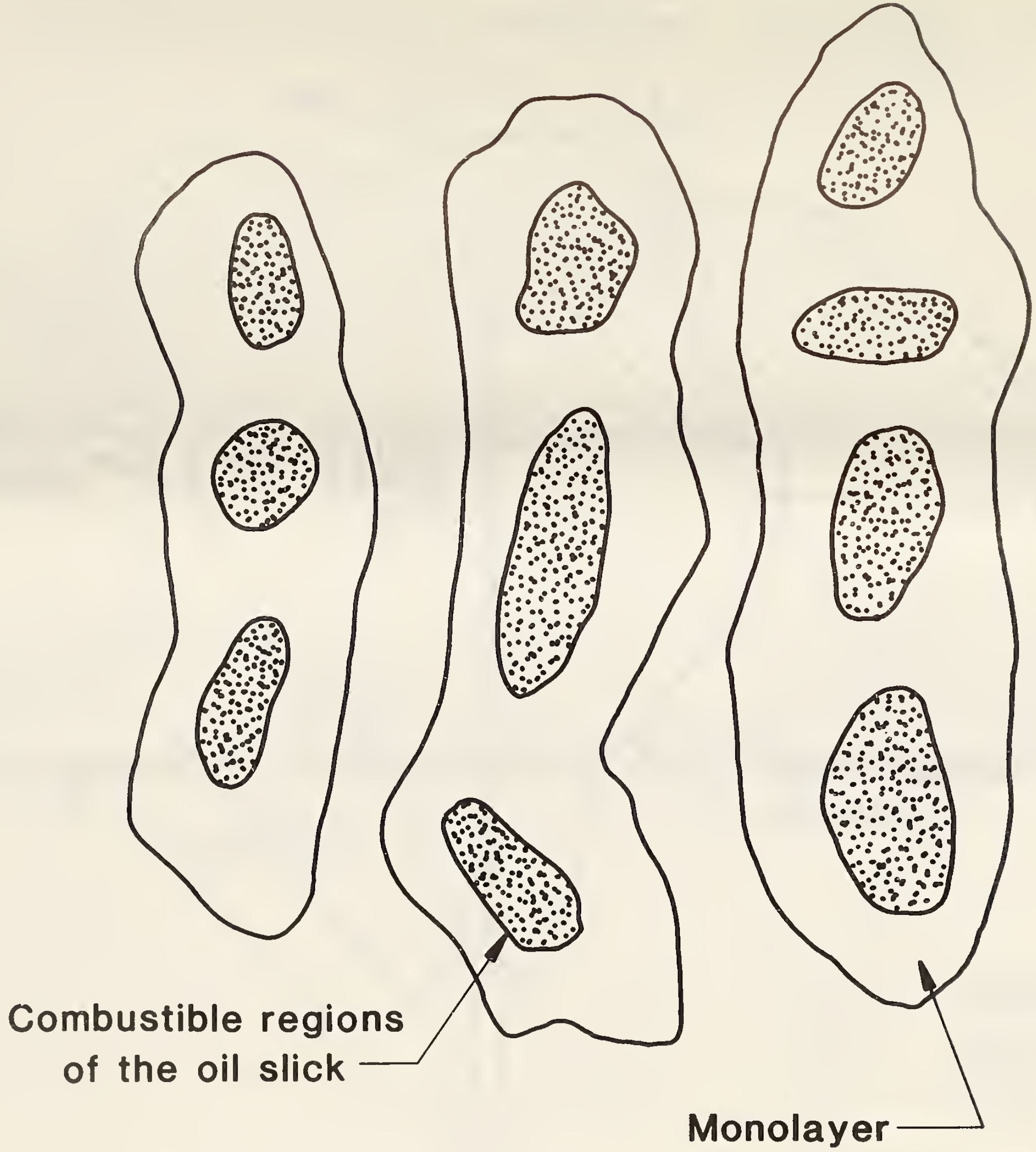

Figure 1. The probably distribution of oil in a typical arrangement of slicks

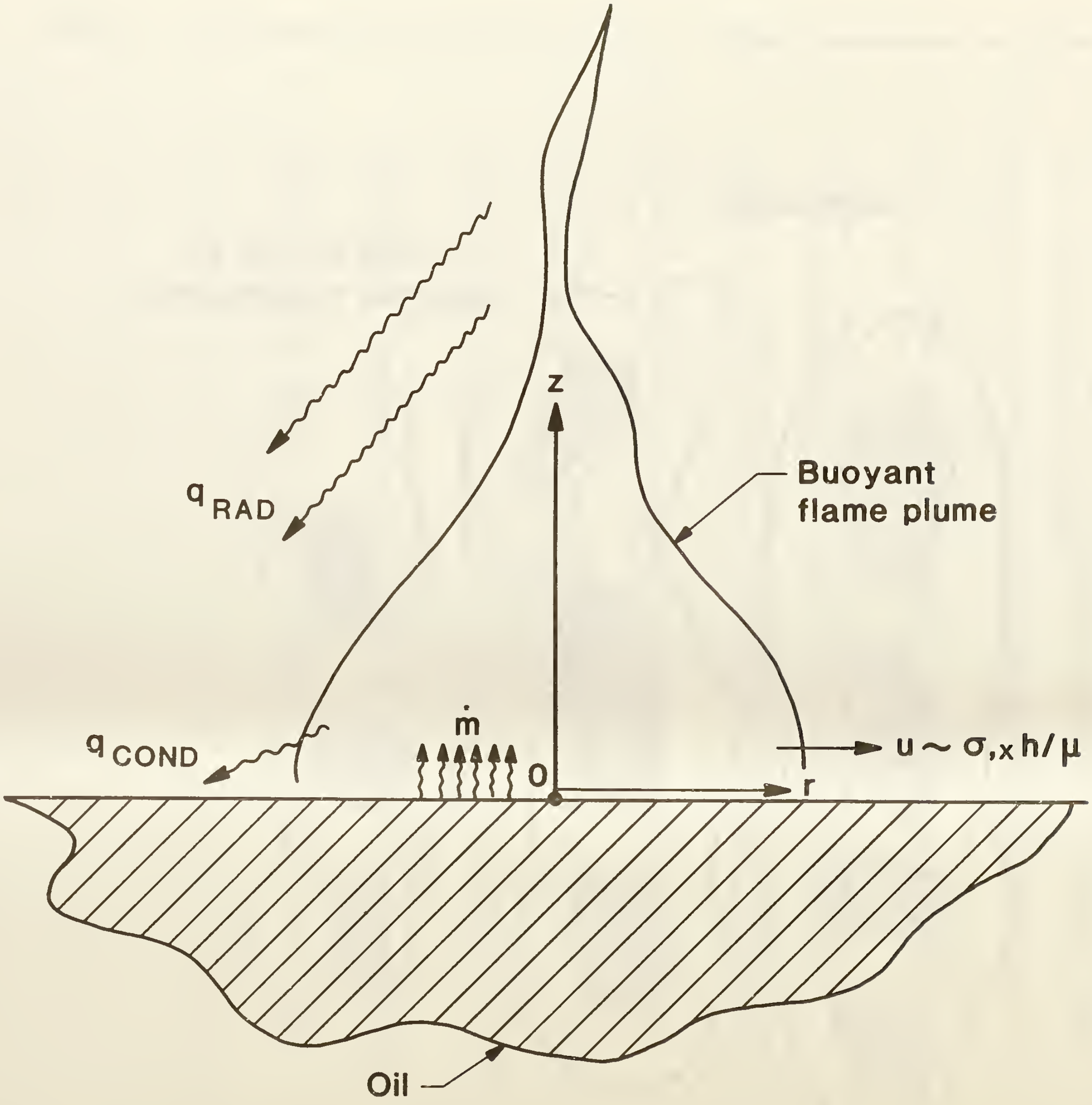

Figure 2. The initial (acceleratory) burning regime. The oil thermal thickness is effectively infinite

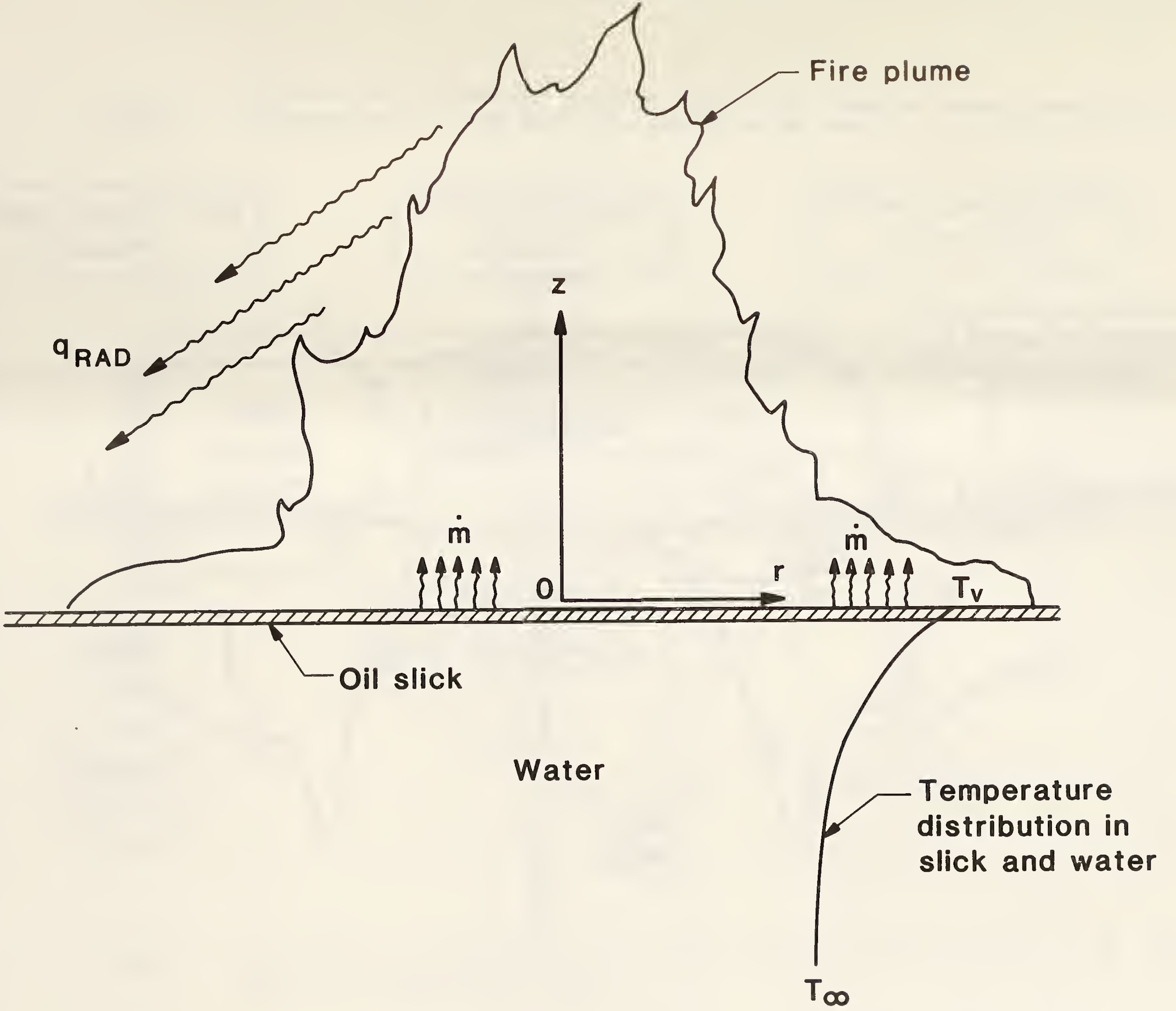

Figure 3. The transition regime between acceleratory growth and final slowdown. Thickness effects are important in this stage

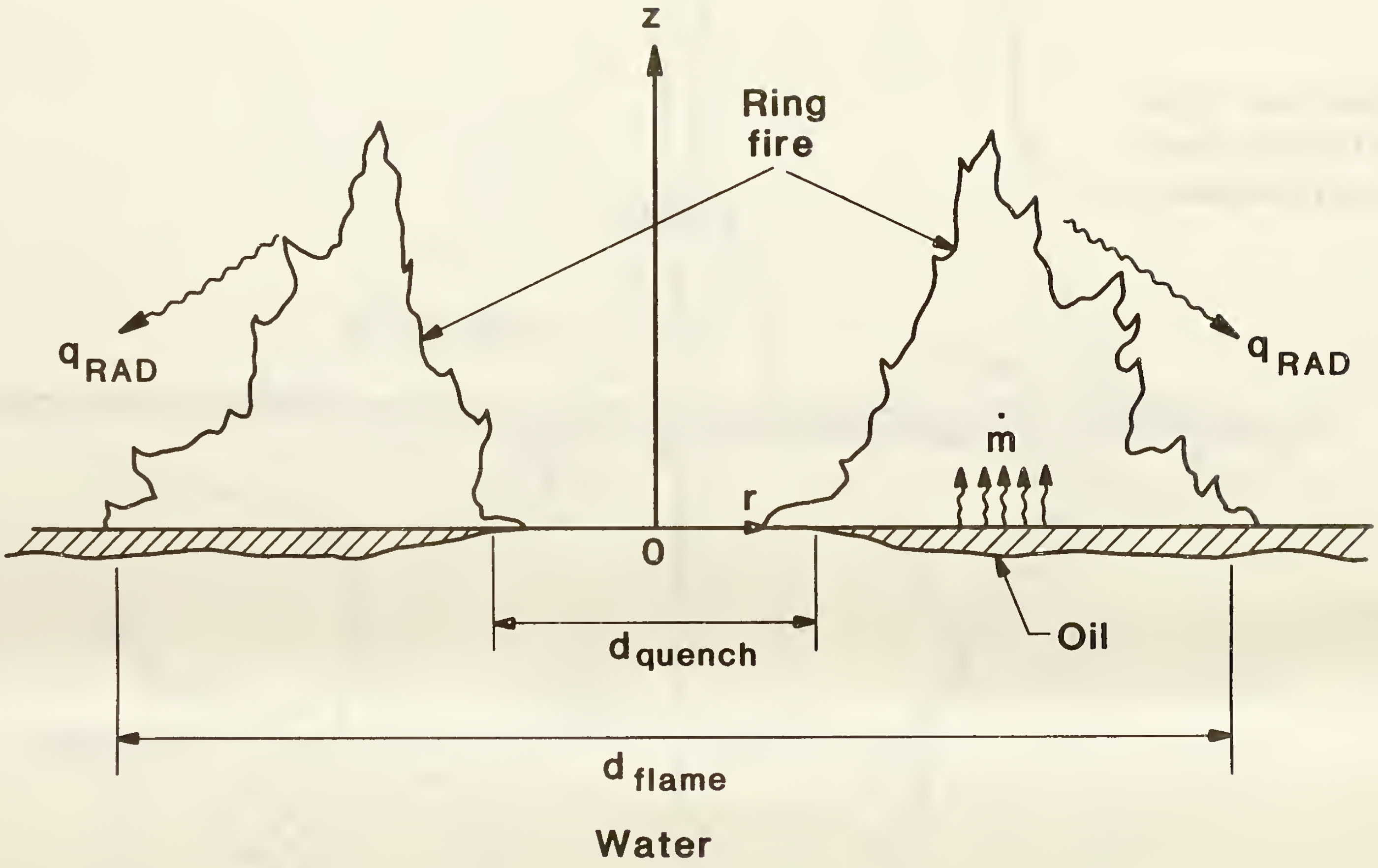

Figure 4. The formation of a ring fire. Extinction occurs when the radiation and gas-phase heat release can no longer sustain the required volatile mass efflux

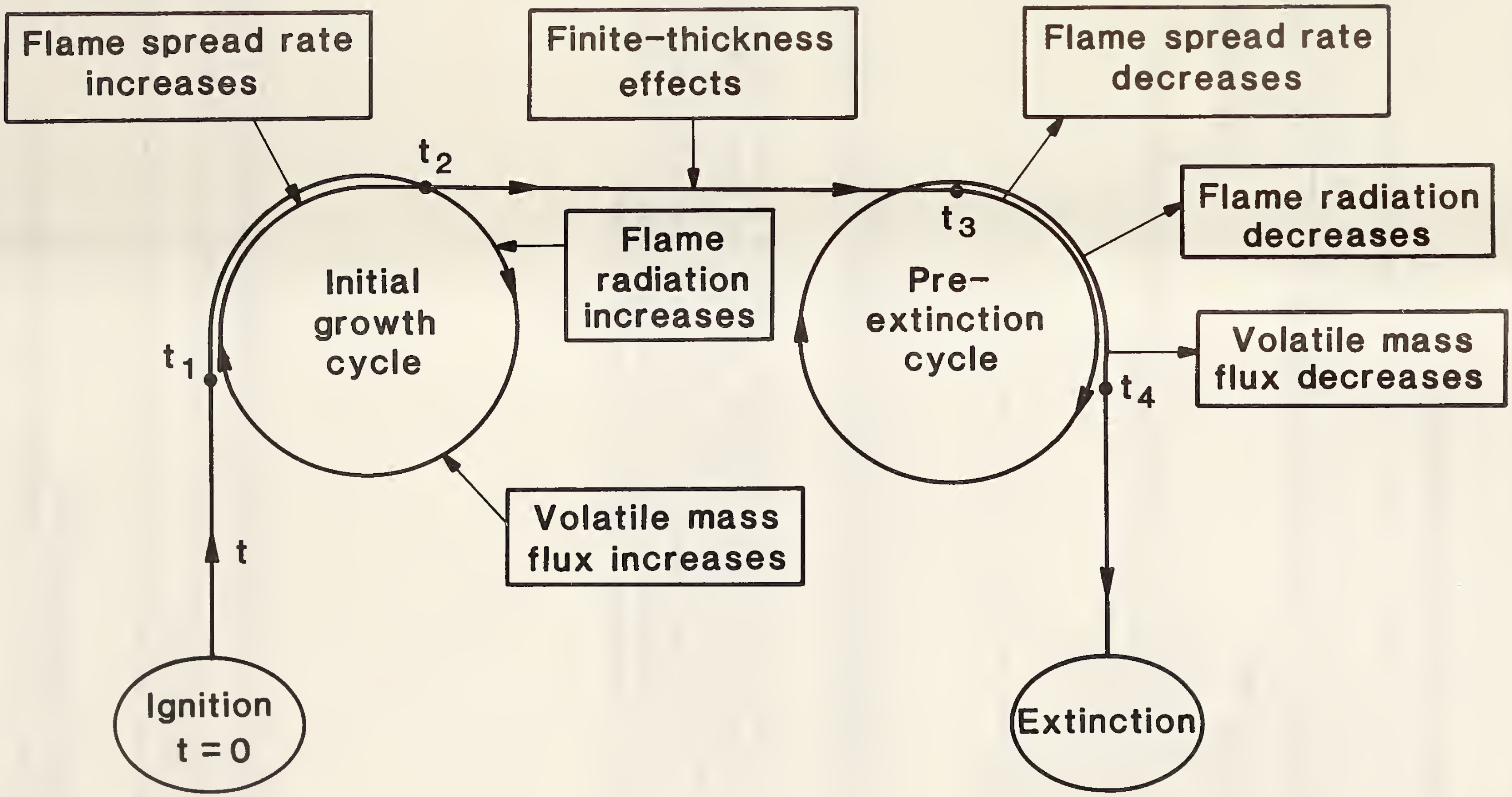

Figure 5. A qualitative illustration of the burning process described by Figs. 2-4. The time (t) is the process variable

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR-85/3266	2. Performing Organ. Report No.	3. Publication Date November 1985

4. TITLE AND SUBTITLE

A Preliminary Analysis of Oil-Slick Combustion

5. AUTHOR(S)

Indrek S. Wichman

6. PERFORMING ORGANIZATION (*If joint or other than NBS, see instructions*) **NATIONAL BUREAU OF STANDARDS** **DEPARTMENT OF COMMERCE** Gaithersburg, MD 20899	7. Contract/Grant No. 8. Type of Report & Period Covered Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (*Street, City, State, ZIP*)

U.S. Department of the Interior
Minerals Management Service
647 National Center
Reston, VA 22091

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here*)

This preliminary study of oil-slick combustion contains a literature review, a formulation of a physical model of oil-slick burning, and some suggested experiments. The theoretical model is divided into three stages; (1) an ignition and acceleratory-growth stage, (2) a slowdown regime, in which finite slick thickness effects become important, and (3) an extinction cycle. The proposed experiments emphasize the use of the Fire Research Laboratory, located on the NBS grounds.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

Buoyant Flow; Burning Rate; Combustion Efficiency; Combustion Theory; Experiments; Ignition; Liquid Spills; Oils

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