LASER IGNITION OF ARCTIC MARINE OIL SPILLS

M.B. Frish
M.A. DeFaccio
P.E. Nebolsine
G.A. Simons

Physical Sciences Inc.
Dascomb Research Park
PO Box 3100
Andover, Massachusetts 01810
USA

ABSTRACT

A technique for using lasers to remotely ignite oil spills has been developed and demonstrated. A continuous-wave CO_2 laser heats a localized area of the oil pool for several seconds, thereby raising the surface temperature above the fire point. A fire is then ignited by a focused high-power pulse from a second laser. Experiments have shown that the fire will self-sustain and spread when the absorbed laser energy is distributed, by convection in a thin surface layer, over a sufficiently large area. Cold, moderately weathered crude oils can potentially be set afire using an airborne version of this scheme.

INTRODUCTION

In the event of an Arctic oil spill, either from a shipwreck or maritime well blowout, it is envisioned that oil reaching the surface of an ice field melting during springtime will form tens of thousands of pools, each having typical dimensions of a few tens of meters.[1] The technique of choice for removing these pools before they transform into unremovable tar is to set each afire within a few days of its appearance. Due to the remote location of the potential accident, ignition of the oil must be accomplished from an airborne vehicle. Previous research[2] has led to the development of pyrotechnic ignition devices which may be dropped from helicopters onto the oil pools and are capable of starting fires which spread across the pool surfaces. Unfortunately, these devices have shelf lives of only about five years, and production of sufficient stock to cleanup one major spill requires a recurrent cost of several million dollars.

A novel dual-laser approach to starting pool fires has now been developed. The technique has been tested both in the laboratory and in outdoor conditions simulating an Arctic environment, and should be helicopter deployable using slightly modified commercial lasers. The technical advances that have led to this achievement were: (1) learning the requirements to start a small diffusion flame which is able to both sustain itself and spread over a large pool of cold oil, and (2) determining how to satisfy these requirements using lasers.

Environment Canada. Arctic and Marine Oilspill Program (AMOP) Technical Seminar, 8th. Proceedings. June 18-20, 1985, Edmonton, Alberta, Canada, Environment Canada, Ottawa, Ontario, 166-175 pp, 1985.

A schematic illustration of a one-dimensional diffusion flame is presented in Figure 1. At the surface of the cold liquid is a relatively hot layer from which fuel evaporates and mixes with the air above. Combustion occurs in a very narrow layer located a small distance above the surface of the fuel, and combustion products, such as hot soot and gases rise above this zone. As the fire burns, combustion energy is radiated and conducted through the air back to the oil pool, thus providing the power required to continue vaporization of new fuel and sustain the burning. If this power is insufficient to overcome the heat flux transported to the bulk liquid by conduction and convection, the surface cools to a temperature below that at which sufficient vapor is produced, i.e. below the flashpoint, and the fire extinguishes itself. Thus, the liquid will burn only after several criteria are satisfied: 1) The surface of the liquid must be hot enough to provide a vapor above the surface which, when mixed with ambient air, is combustible; 2) This vapor/air mixture must be raised briefly to a temperature sufficiently high to initiate combustion; and 3) The liquid fuel must establish temperature and flow fields which transport less power into the liquid's volume than a nascent flame is capable of supplying back to the liquid surface.

Cold, aged crude oils fail to satisfy any of these criteria. To generate a combustible vapor mixture, the surface of the liquid must be heated to its flashpoint temperature, typically[3] as high as 100°C. To ignite the vapor mixture, it must be exposed to a heat source of 700°C or more. The third criteria requires that the liquid absorb a certain amount of energy before the fire is ignited.

Laser beams, which act as remote infrared energy sources, may be used to satisfy each of these requirements. It is possible to select combinations of laser power, intensity (power/unit area), and irradiation time which enable ignition of sustained, spreading fires on the surfaces of cold, aged oil pools. The power and intensity delivered by the beam are controlled by the choice of lasers and the use of focusing or defocusing optical components.

LASER IGNITION CONCEPT

The scientific literature contains descriptions of several previous efforts to use lasers for removing oil slicks from water or for igniting liquid fuels. In particular, Laisk[4] has used a 125 W continuous wave (CW) carbon dioxide laser, focused to intensities exceeding 40 W/cm^2, for evaporating thin layers of oil from seawater. Due to the thinness of the slick, thermal losses into the substrative water precluded burning of the oil, and raised the specific energy required to evaporate the oil to as high as 10 kJ/g, which may be compared to the heat of vaporization of 0.4 kJ/g. In a separate effort, by focusing a 240-350 W CW laser to an intensity exceeding 260 W/cm^2, Kashiwagi[5] and Kashiwagi and Kashiwagi[6] have ignited, in a fraction of a second, vapor plumes above liquid fuels such as n-decane and 1-decene. However, since the fuel temperature outside the laser heated domain was below the firepoint, these flame plumes extinguished themselves when the laser was shut off.

This thermal condition is similar to that which prevails in the Arctic oilspill scenario, where the firepoint of the cold, weathered oil may be as much as 100°C above ambient. However, by using two lasers in tandem, self-sustaining the spreading fires can be ignited on these cold oil pools.

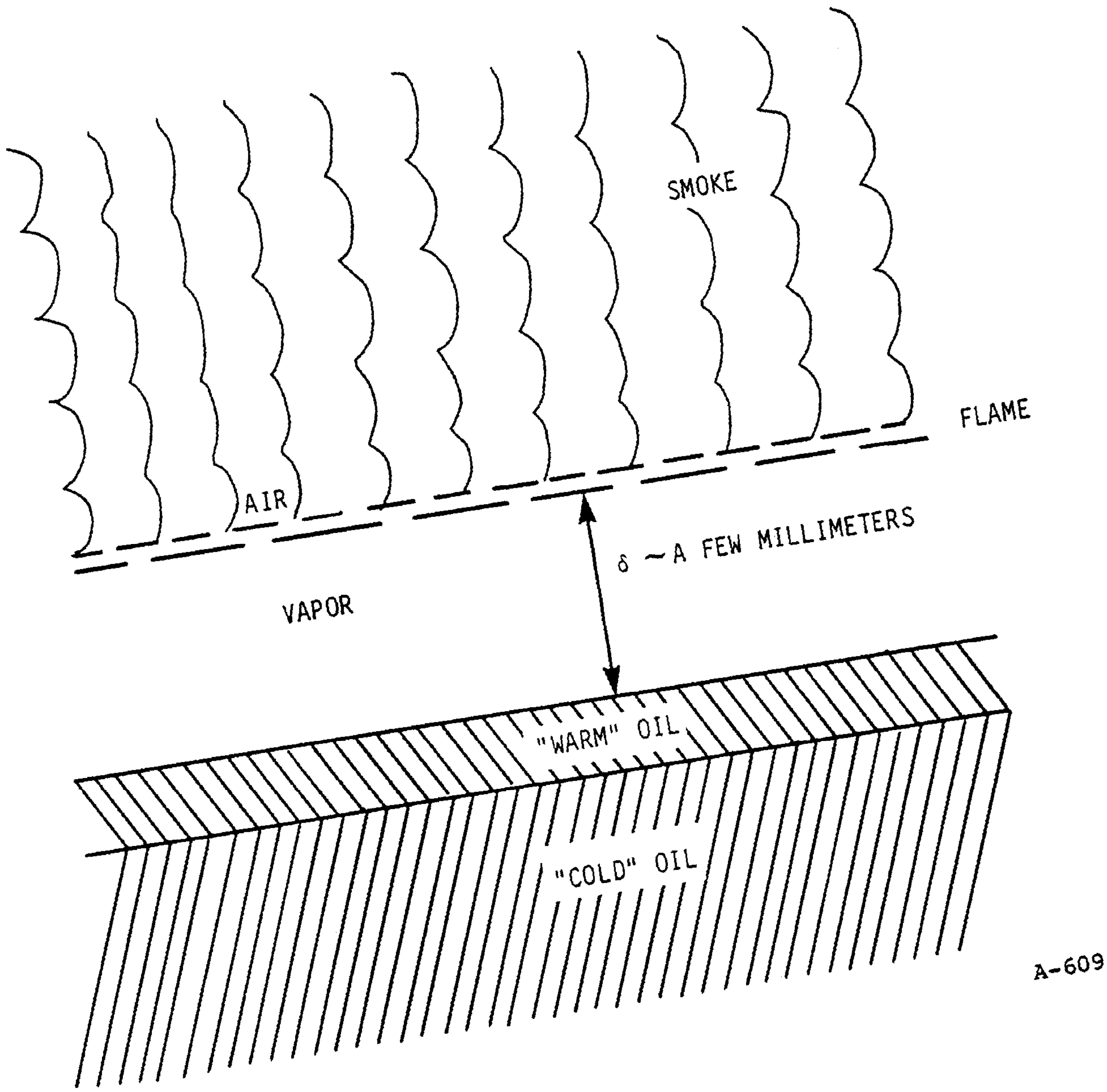


Figure 1. Schematic Illustration of a One-Dimensional Diffusion Flame

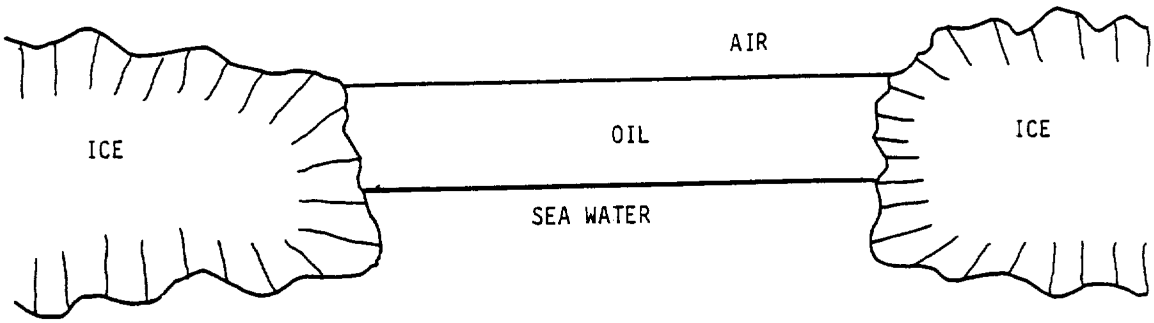
This new technique is summarized in Figure 2: A moderate power (<1000 W) continuous wave (CW) laser continuously irradiates or "preheats" a small portion of the oil surface thereby establishing the thermal and flow fields required for vapor production and flame survival (criteria 1 and 3), while a high power (7 MW) short-pulsed (2 μs) focused laser fires once per second until it ignites the vapor mixture (criterion 2). As soon as it is clear that the fire is self-sustaining, as indicated by the onset of spreading, the lasers are shut off. Carbon-dioxide (CO_2) lasers are used exclusively because of their advanced state of development, energy conversion efficiency, availability and cost. They radiate at a wavelength of 10.6 μm.

A pulsed laser is used as the ignitor because, when focused within the vapor above the oil, extremely high temperatures are generated. If absorption of the laser radiation by the vapor is strong, i.e., if the absorption depth in the vapor is short, then a laser pulse can deposit enough energy directly into the vapor to heat it to the ignition temperature. If absorption is weak, then the laser may be focused to sufficient intensity to generate an electrical breakdown of the air/fuel mixture. Ionized air is an excellent absorber of laser energy; a plasma having a temperature exceeding 20,000 K is rapidly created[7] and serves as the ignition spark. Our experiments used this latter mechanism to ignite oil pools having the necessary initial thermal profile.

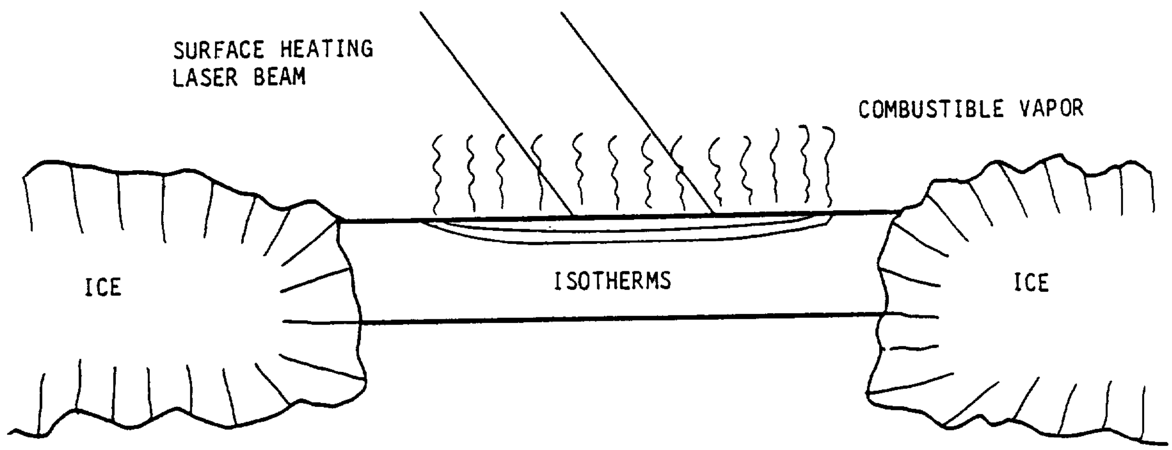
For the laser ignition technique to be practical, ignition and sustained combustion must be performed from airborne vehicles with only a few seconds of irradiation allowed for each oil pool. Due to the amount of energy required, it is impractical in this time period to preheat the entire volume of the liquid to its firepoint, defined as the temperature at which sustained burning is possible after uniform volumetric heating under laboratory conditions. It is necessary therefore to heat, prior to ignition, only a thin layer near the liquid surface having a thermal profile which is incapable of absorbing more power than the fire is able to supply, and having a surface temperature not less than the flashpoint. The power which this heated area can then absorb from a nascent flame depends on the amount of laser energy deposited, and the mechanisms by which heat is transported from the heated surface into the bulk of the oil.

PREHEATING: MECHANISMS AND EXPERIMENTS

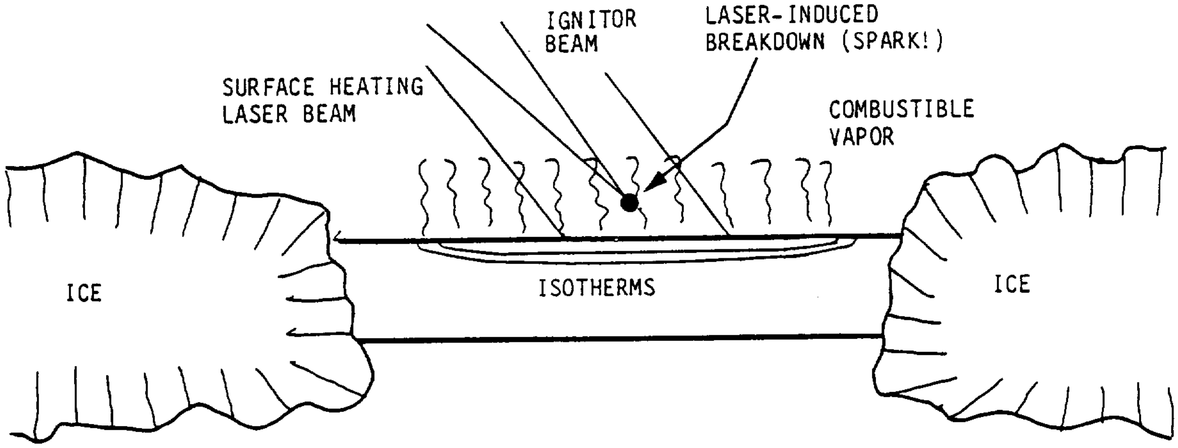
Two mechanisms, convection and conduction, play a role in redistributing the absorbed preheater laser energy, and in removing energy from a nascent fire. The comparative role played by each depends on how the fire is confined; complete confinement emphasizes conduction, while zero confinement emphasizes surface convection. Experiments[8] have shown that if the fire is ignited away from the walls or edges of the oil pool, then the most important energy sink is a radial surface flow which carries hot oil outward from the laser irradiated zone. The presence of this surface flow requires that a fire be started with a diameter exceeding a minimum value, determined by the flow velocity and the rate of heat transfer from the fire to the liquid. Since the depth of the heated layer has been found to be nearly constant over the area which it covers, there is a minimum amount of energy which must be supplied by preheating:



(a) A pool of cold (and therefore, unignitable) oil rests on an ice sheet



(b) A CW laser heats a surface layer of the oil pool, thus providing a combustible vapor mixture above the surface, and a thermal profile capable of sustaining combustion once ignited.



(c) A high intensity laser pulse ignites the vapor, creating a sustained, spreading flame.

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Figure 2. Laser Ignition of Oil Spills Concept and Sequence

$$E > \pi\rho C_p r^2 \ell \Delta T, \quad (1)$$

where ρ is the liquid density, C_p its specific heat, and ΔT the difference between the heated oil's surface temperature and its bulk temperature. The radius of the preheated area, r, and the depth of the surface layer, ℓ, are controlled by the radial flow velocity, u_r, the heat transfer rate from the flame to the fuel, q_f, and by ΔT:

$$r > (2\alpha u_r)(\rho C_p \Delta T/q_f)^2, \quad (2)$$

$$\ell = (\alpha r/2u_r)^{1/2}, \quad (3)$$

where α is the thermal diffusivity of the fuel. Recognition of these constraints, and using them to estimate the minimum laser requirements for ignition, has led to the success of the laser ignition scheme.

Three series of experiments determined empirically the energy requirements for preheating of cold oil, and demonstrated the feasibility of the technique. In the first series, small volumes of oil contained in petri dishes were irradiated with a CW CO_2 laser over areas of less than 4 cm in diameter. The thermal profile established within the oil by absorption of this laser flux was monitored as a function of time with six strategically located thermocouples. To determine the thermal profile required for a flame to survive, repeated efforts were made to ignite the oil by propelling a pulse of flame from a propane torch across the oil surface after each second of irradiation, until a steadily burning fire was established. These experiments revealed the importance of the surface flow, and indicated that irradiation of larger areas with a lower laser intensity was a more desirable preheating approach. Thus, in the second series, relatively large volumes of weathered Norman Wells crude oil, contained in square pans 30 cm per side and 1-2 cm deep, were irradiated with laser powers ranging from 80 to 800 W and beam diameters between 3 and 15 cm. Thermocouples again monitored the thermal profile, but this time a pulsed laser was used as the ignition source. Definitive values of the laser parameters required for ignition were determined, setting the stage for the third test series, the outdoor demonstration tests. In that phase of the program,[9] ignition experiments were performed in large, outdoor oil pools, infested with, surrounded by, or supported by ice and water. The pools were located 30-50 meters from the lasers (which were housed indoors), although laser focusing and beam steering optical components were positioned within two meters of the pools. The 600 W preheating laser beam filled a region approximately 10 cm in diameter at the oil surface, and the nominal 15 Joule/pulse ignition laser was focused to about 1 cm^2. Ambient air and oil temperatures, as well as wind and sky conditions, were similar to those that would be encountered in a late Arctic spring.

RESULTS

Analysis of the laboratory data shows that, as expected, the total energy supplied by the preheating laser is the essential parameter which controls flame sustenance. At an ambient temperature of 23°C, and with no wind, Norman Wells crude oil, weathered to 10% mass loss, requires an average of 1400 J of preheated energy, while 23% and 32% weathered oil require 3300 J and 5700 J respectively. In Figure 3 the preheating time required before a nascent flame will sustain itself has been plotted as a function of oil mass loss, using laser power as a parameter. Curves like these can be used by a systems engineer to select the optimum laser for oil spill cleanup, or conversely to determine the optimum time to irradiate a pool of known oil type with a fixed power laser.

Figure 4 compares the preheating times projected from the laboratory data with those that were experienced during the outdoor tests. It was learned from these latter experiments that cold air delays the ignition, apparently because more energy is required to preheat the oil, as predicted by Eqs. 1-3. Wind further delays ignition, primarily by cooling the surface of the preheated oil and effectively decreasing the power absorbed from the CW laser.[9]

It has also been found that ignition of a properly preheated oil pool by a single firing of the pulsed laser requires that laser to be focused to provide a fluence exceeding 10 J/cm^2 on the surface of the pool. Lower fluences provide a decreased probability of ignition on each pulse; fluences below 7 J/cm^2 are insufficient to ignite at all. The laser used in this program supplied 15 J/pulse, therefore focusing the beam to a spot size of roughly 1 cm in diameter was adequate to assure ignition. Although this was possible using relatively short focal length, inexpensive mirrors, designing an optical system for helicopter deployment will require a modest additional effort.

CONCLUSION

The feasibility of using lasers to remotely ignite pools of fresh or moderately weathered oils has been demonstrated. Current commercial laser technology dictates that two lasers be used for this procedure: 1) a continuous wave carbon-dioxide laser to preheat the oil surface thereby establishing a thermal field capable of sustaining a fire, and 2) a focused pulsed carbon dioxide laser to provide the spark which ignites the fire. This ignitor should be able to provide at least 10 J/cm^2 per pulse to the oil surface. Lasers capable of providing this fluence, after some modification of their standard optical configurations for aerial application, are presently available.

The energy which must be supplied by the preheating laser is typically several kilojoules and is independent (within limits) of the laser spot size or intensity, but increases with the degree of oil weathering. It also depends on the ambient air temperature and wind velocity. To minimize the heating time required until a fire will self-sustain, it is desirable to use a laser providing as much power as is possible. Presently available lasers suitable for helicopter mounting supply up to 800 W, though an increase to about 1500 W is anticipated during the next few years. The average time required to preheat Norman Wells crude oil of known weathering with these

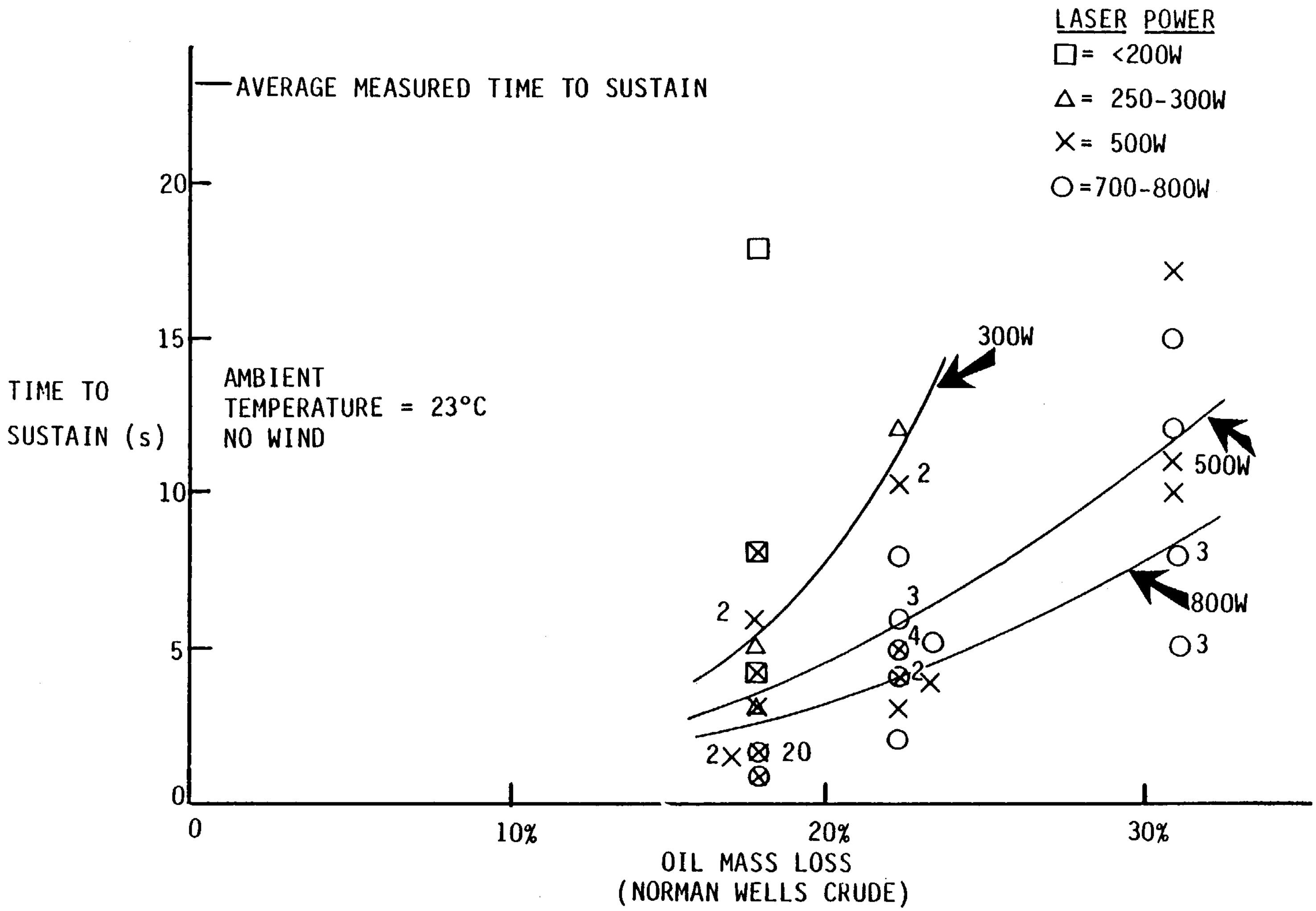

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Figure 3. Preheating times, under laboratory conditions of 23°C air temperature and no wind, required for igniting sustained fires on oils of various degrees of weathering. Numerals next to data symbols indicate number of runs with the plotted parameters.

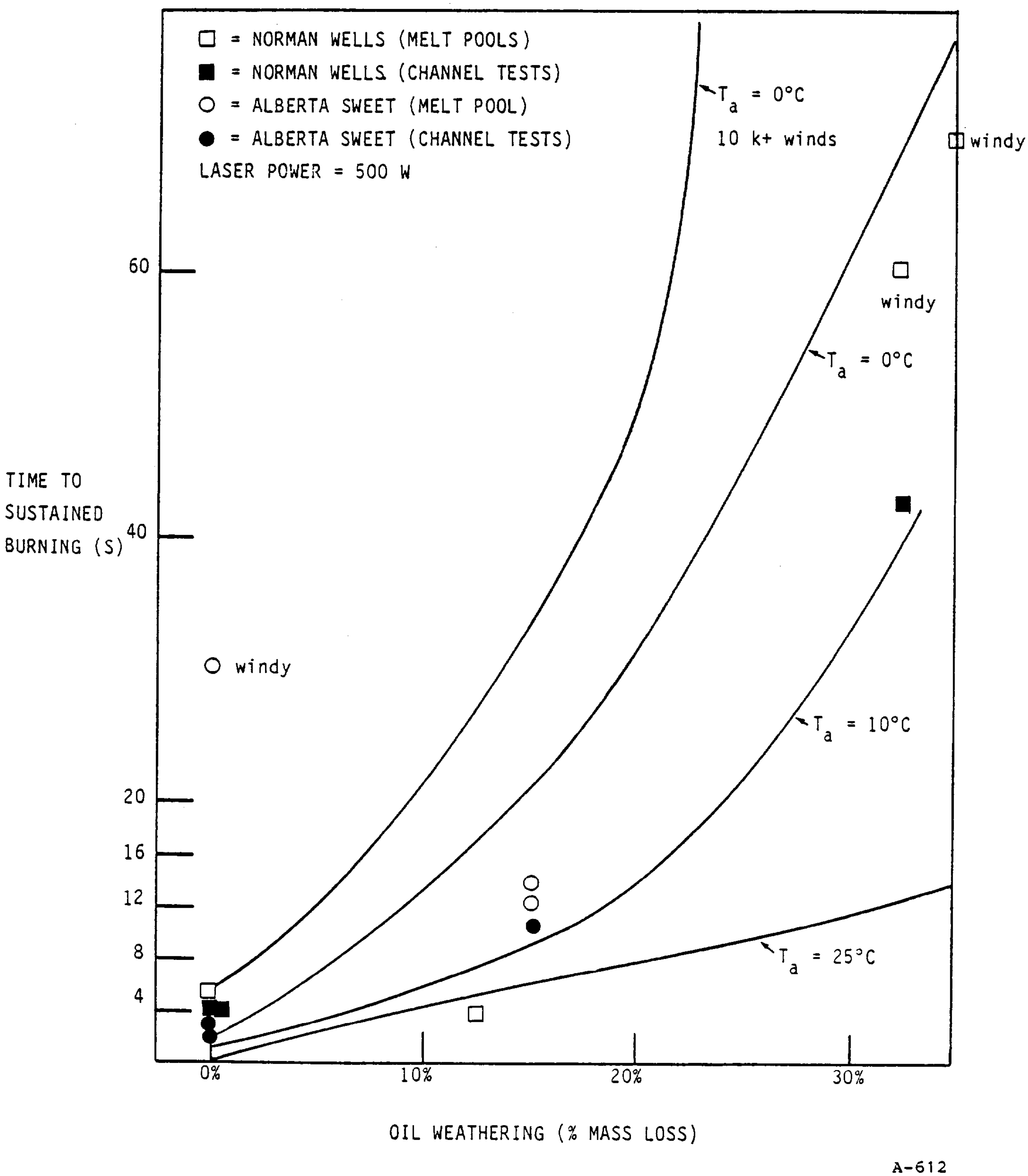

Figure 4. Preheating times measured during outdoor tests. Typical ambient air temperatures were 0°C. Points at which wind exceed 20 km/hr are indicated. Solid lines are theoretical projections based on data of Figure 3.

lasers may be estimated from the data presented in Figures 3 and 4. In the most difficult ignition scenario envisioned, with a temperature of -10°C and a 30 km/hr wind, about 30 seconds of preheating with 800 W will be required to ignite each oil pool. However, it would be useful to confirm this conclusion by obtaining additional data on preheating energy requirements under controlled, simulated outdoor conditions with various ambient temperatures, wind velocities, oil types, and degrees of oil weathering.

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