LASER IGNITION OF OIL SPILLS

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ABSTRACT: *A major oil spill in the Arctic, whether from a tanker or an oil rig, could result in large concentrations of oil among broken ice and/or thousands of oiled melt pools. The remoteness of the area and the inadequacy of other countermeasures make in-situ burning the only possible response. Helicopter-deployable igniters have been developed to ignite the oil, but studies have shown that use of these devices has severe logistical constraints. The use of a helicopter-borne laser system as an alternative to, or in conjunction with, the igniters has been pursued from conceptual development to completion of the engineering design phase.*

The concept was examined by theoretical analysis combined with laboratory studies. This work indicated that a dual-laser system would ignite both fresh and weathered crude oils at temperatures representative of an arctic spring or fall day.

A series of outdoor experiments was carried out in Kanata, Ontario, Canada, in March 1985. These experiments, under climatic conditions very similar to those in the Canadian Arctic in June, demonstrated that a two-laser system would ignite both fresh and weathered crudes.

An engineering feasibility and design study was undertaken. The study confirmed that a system having the required performance can be assembled from existing, proven hardware and operated effectively from a helicopter.

The development of the laser ignition of oil spills from concept through engineering design is described.

If oil is spilled in the Arctic when ice is present or forming, it very rapidly becomes encapsulated in the ice, where it remains until the onset of breakup. At that time the oil surfaces through a combination of ablation of the ice and upward migration of the oil via brine channels. The oil, which is relatively fresh, floats on the melt pools that cover the surface of the rotting ice and is concentrated by wind herding.[8]

A study done for Environment Canada[9] has shown that if 35,000 m^3 of oil is spilled over 24 hours as the result of a tanker accident, the area occupied by oiled melt pools could amount to 1,600 hectares.

During the period in which the oil is surfacing on the melt pools, the ice is on the verge of breakup. When combined with the remoteness of the area, this makes remedial action from the ice difficult, if not impossible. Environment Canada and the oil industry, therefore, developed helicopter-deployable igniters for the in-situ combustion of oil. Although these igniters are efficient and easily deployable, the numbers required and the logistics of deployment make their use in a large spill difficult at best. Based on the Balena and McKinley Bay experiments,[3,7] Ross has estimated that up to 30,000 igniters could be required in the event of a 35,000 m^3 spill over a 24-hour period—more than could be manufactured in Canada in a year. Far greater numbers would be required in the case of a well blowout.[9] This, combined with the cost of the igniters ($40 to $60 Canadian each, 1982), made the possibility of laser ignition from a helicopter an area worth pursuing.

Concept development

This phase and the subsequent laboratory experimental phase were conducted at the PSI facility in Andover, Massachusetts. The first stage of development involved studying the burning of crude oil under arctic conditions. Previously, Twardus and his co-worker Brzustowski had studied the unconfined burning of fresh and weathered oil,[2,10] and several others[1] had studied small open fires. However, not enough was known about how a small fire starts, and how small a fire may be and still sustain and grow. This was particularly true for the arctic oil spill scenario where the firepoint of cold, weathered oil may be as much as 100° C above ambient.

A liquid will burn only after several criteria are satisfied. First, the surface of the liquid must be hot enough to provide a vapor that is combustible when mixed with ambient air. Second, this vapor/air mixture must be raised briefly to a temperature sufficiently high to trigger combustion. Third, the liquid fuel must establish temperature and flow fields that transport less power into the liquid's volume than the nascent flame is capable of supplying to the liquid surface.

Cold, aged crude oils fail to satisfy any of the above criteria. To generate a combustible mixture, the surface of the liquid must be heated to its flash point, typically 100° C. To ignite the vapor/air mixture requires exposure to a heat source of 700° C or more. The third criteria requires depositing a large amount of heat into the liquid before igniting the fire. This energy must not be carried away by the essentially infinite sink of underlying cold oil, ice, and water.

After the initial theory of combustion for small fires had been learned, an experimental phase began. This was intended to provide empirical data where theory was lacking to determine the feasibility of remote heating and ignition.

Laboratory experimentation

The experimental phase began with a series of experiments designed to determine the laser parameters required to provide a pulse of intense heat, or spark, that would start a fire. A spark was provided by a burst of energy from a focused pulsed Lumonics model K-102 TEA CO_2 laser. Each pulse provided approximately 15 joules of radiation at 10.6 μm in approximately 2 μs, an average power per pulse of 7.5 megawatts, with a pulse repetition rate of approximately one pulse every two seconds.

The experimental setup is illustrated in Figure 1. Two lasers were used, each focused by a single 760 mm focal-length concave mirror onto the surface of cold, weathered Alberta sweet mixed blend crude oil in a 10 cm diameter petri dish. The area irradiated by each laser, and thus the fluence, was altered by moving the focusing mirrors toward or away from the oil. The fluence of each laser was altered independently. After selecting the fluence and time interval between

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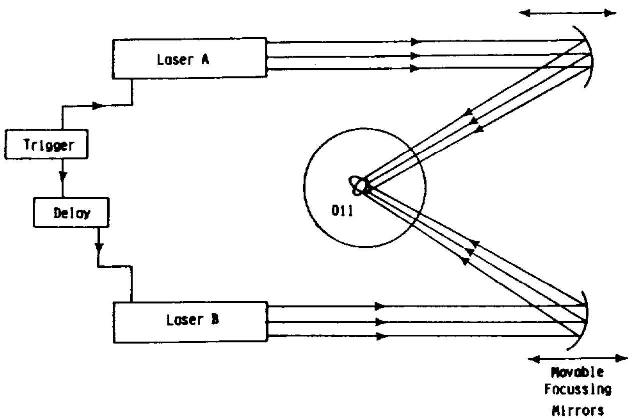

Figure 1. Setup for spark (laser fluence) experiments[4]

pulses, the lasers were fired sequentially, so that the first would generate a small amount of fuel vapor that the second would then ignite. No attempt was made to preheat the oil to ignite a sustained fire.

Ignition did not necessarily occur repeatably for each selection of laser parameters. Instead only a certain fraction of tests at each setting would provide ignition. By repeatedly firing the lasers in each configuration, the probability of ignition for each setting was determined.

The ignition probability of the fluence of laser B was determined for a variety of fluences of laser A. As the laser B fluence increased, so did the probability of ignition; however, there was a threshold of 3 J/cm^2 at which there was zero probability of ignition, and a value of 11 J/cm^2 laser intensity at which ignition always occurred. In addition, the vapor generated by the first laser pulse increased the absorption of the second laser pulse, thereby lowering the threshold for ignition.

In the next series of experiments, the pulsed laser fluence required for oil vaporization was determined by use of a ballistic pendulum.

Analysis of the data from this series of experiments showed a threshold value of 3 J/cm^2 below which no significant impulse was observed, the same threshold as that below which no ignition occurred using multiple laser pulses.

This series of experiments showed that it was possible to preheat efficiently with a pulsed laser. However, since no commercially available device has sufficient power to do so in the acceptable time of less than 30 seconds, it was decided that two independent lasers, one continuous wave (CW) and the other a pulsed model, were required.

Two series of experiments followed to determine the requirements for preheating cold oil. In the first series, small volumes of oil were irradiated with a CW CO_2 laser in a petri dish, over areas 2.5 or 4 cm in diameter. The thermal profile established within the oil was monitored as a function of time by the use of six thermocouples. To determine the thermal profile necessary for a flame to survive, a propane torch was swept across the oil surface every second during irradiation until a steadily burning fire was established.

The CW CO_2 laser used had a power of 1,000 watts, and the Alberta sweet mixed blend crude oil, aged up to 40 percent mass loss by evaporation at elevated temperatures, was contained in petri dishes 2.5, 5 or 10 cm in diameter and 1 cm deep.

The thermocouple data revealed that when the laser was turned on, the temperature of the irradiated surface increased rapidly compared with its surroundings. The temperature gradients induced gradients in the surface tension that caused a thin surface layer of oil to flow away from the hot spot. The outward flow was replenished continually by a cold, upward flow of oil from below the heated spot, thus preventing downward heat conduction. The warm surface flow had a velocity of about 2 cm/second, and its momentum continued for about one second after the laser was shut off.

The convective motions discovered in this series of experiments were unexpected. It had been postulated that heat conduction within the liquid and the mixing of fuel vapor above the liquid surface were the dominant mechanisms controlling fire ignitability. The presence of a radial flow away from the laser irradiated zone required that a fire of some minimum size be started to self sustain.

To test this theory, a 30 cm × 30 cm × 2.5 cm pan was filled with 32 percent weathered Norman Wells crude oil. Next, a portion of the oil was enclosed in an aluminum ring and ignited with a torch. Once the fire was well established, the ring was removed. It was discovered that if the ring diameter was less than 10 cm, the fire died out, while at much larger diameters, the fire spread rapidly. Near 10 cm the fire either would spread slowly or "creep" without much change in size toward the edge of the pan, from which it would slowly spread outward.

These experiments demonstrated conclusively that radial convection was a sufficiently large heat-loss mechanism to quench very small fires. There was clearly a minimum area that had to be preheated if laser ignition was to be successful.

The second series of CW laser experiments was designed to determine the minimum laser power and beam diameter to preheat an essentially infinite oil pool to the point at which a self-sustaining and spreading fire could be established. The effects of oil age, initial temperature, water and ice presence, and wind also were studied.

In these experiments, the area irradiated by the CW laser could be made as large as possible, and fires could be ignited with a pulsed laser. Since the pulsed laser could only be fired once every two seconds, it was occasionally replaced by a small pilot flame that burned continuously over the center of the pan during heating, igniting the oil once the appropriate thermal profile was established.

The setup is shown in Figure 2. The oil used was 18 to 30 percent weathered Norman Wells crude. One hundred thirty-two experiments were completed using laser powers of 80 to 800 watts. The beam diameters ranged from 1.25 to 15 cm, and the intensity at the oil surface was between 2.75 and 80 W/cm^2.

The specific goal was to determine, as a function of laser power, spot size, and oil age, the preheating time required before a sustained fire could be ignited. Initially, an oil age, laser spot size, and power were selected. The oil was preheated while the pilot flame burned closely above the oil surface. The time to establish a sustained fire was set. Once the correct preheating time was known, ignition was done by the pulsed laser to demonstrate that, for all practical purposes, laser ignition was an identical process. Different laser powers and spot sizes then were used to determine the upper and lower limits on the parameters.

The results are shown in Figure 3. For a laser power of 500 watts, there was no major change in "time to sustain" for a beam diameter between 4 and 10 cm with 18 percent weathered oil, but average preheating time increased with oil age. Above 4 cm diameter, spot size was unimportant for preheating times of less than 30 seconds.

The phenomenon of the small fire "creeping" toward an edge or a corner of the pan and expanding from there was also seen, suggesting that fires should be ignited near an edge, corner, or other partially enclosed region of an oil pool.

The conclusions of the concept development phase of the project were:

- Both a CW and a pulsed laser are required for the remote ignition of cold crude oil.
- As powerful a laser as is available should be used to minimize the heating time required until a fire will self-sustain.
- The pulsed laser must be focused to provide a fluence of at least 11 J/cm^2 at the surface of the pool.

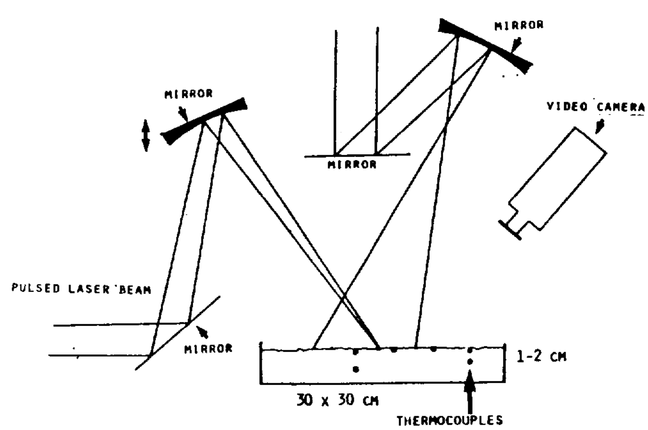

Figure 2. Setup for dual-laser experiments[4]

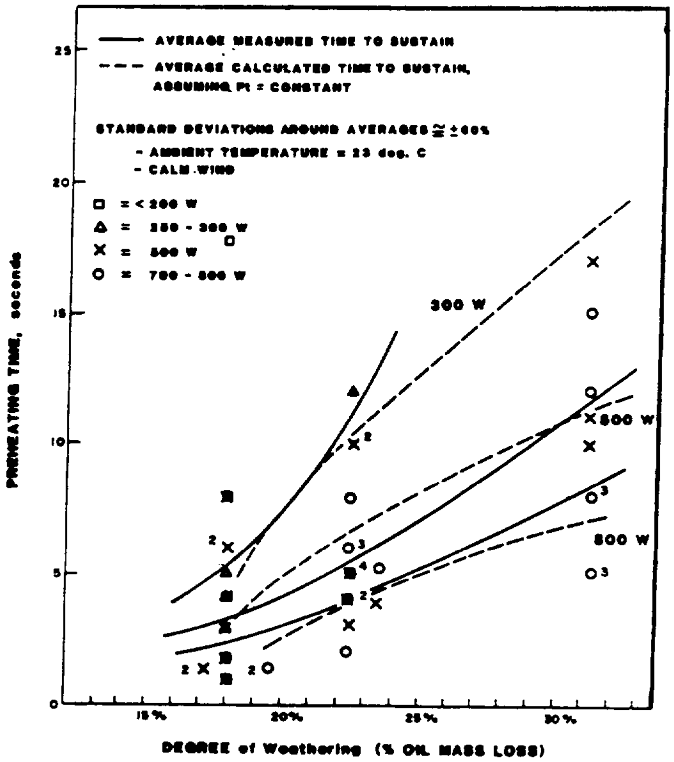

Figure 3. Results of Phase 1 Study (Norman Wells crude)[4]

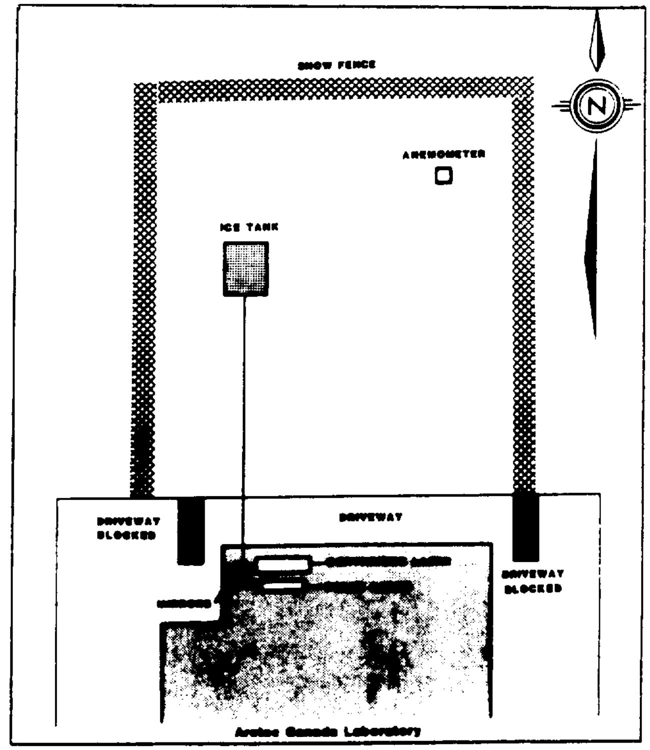

Figure 4. Test site layout[6]

Outdoor demonstration experiments

The objective of this phase of the experiment was to plan and conduct an outdoor demonstration of the laser ignition of crude oil under simulated conditions of melt pools and broken ice fields. The experiments were performed just outside Arctec Canada's facility in Kanata, Ontario, in March 1985. Climatic conditions closely resembled those of an arctic spring.

From the results of the laboratory phase of the study, it was realized that a CW laser having at least 500 watts of irradiated power was preferred. The only available laser that could satisfy this requirement was a Coherent 600 W CW CO_2 Everlase Model 525, which was borrowed from the National Research Council. The pulsed laser was a Lumonics Model K-103 TEA, 12 J. Fresh and weathered Alberta sweet mixed blend and Norman Wells crude oils were used. Attempts to use Tarsuit crude were abandoned when the two samples available were found to be badly contaminated with a gritty material and water.

The test site layout is shown in Figure 4. Both lasers were located in the laboratory building. A small hole was cut in the wall to project the beams through. Mirrors were used to deflect the laser beams onto the oil slick. All tests were performed in a reusable steel tank in a fixed location. This ensured that the laser travel distance was constant at 30 to 35 m for each test. Figure 5 is the detailed layout for the melt pool tests. An anemometer and recording thermometer were located about 21 m from the ice tank for all tests.

The melt pool ice samples were prepared by freezing fresh water in a 1.8 m by 1.5 m rectangular tank. A pit approximately one meter in diameter by 10 cm deep then was carved out of the center of the block. Fresh water was added to simulate a melt pool. Oil was added, to a depth of 5 mm, and left to come to a stable temperature.

For the broken-ice tests, a 0.85 by 0.15 m cut was made in the block. A recess was cut at one end to permit the laser beam to reach the water surface. Water was added to give a 0.2 meter ice freeboard, equivalent to a two-meter-thick ice flow. Five mm of oil was added and allowed to come to a stable temperature.

Since the intent was to provide results independent of weather, it was attempted to perform duplicate tests on different days under differing weather conditions. A summary of the test conditions and results is given in Table 1. All of the tests were conducted using the maximum available laser power; thus, the quantity of greatest interest is the time necessary to preheat and ignite a self-sustaining fire.

Figure 6 is a plot of "time to sustain" versus degree of oil weathering, from which the preheating energy may be determined, and related to such external factors as the temperature and the wind speed. The data show that the time required to ignite a sustaining fire in-

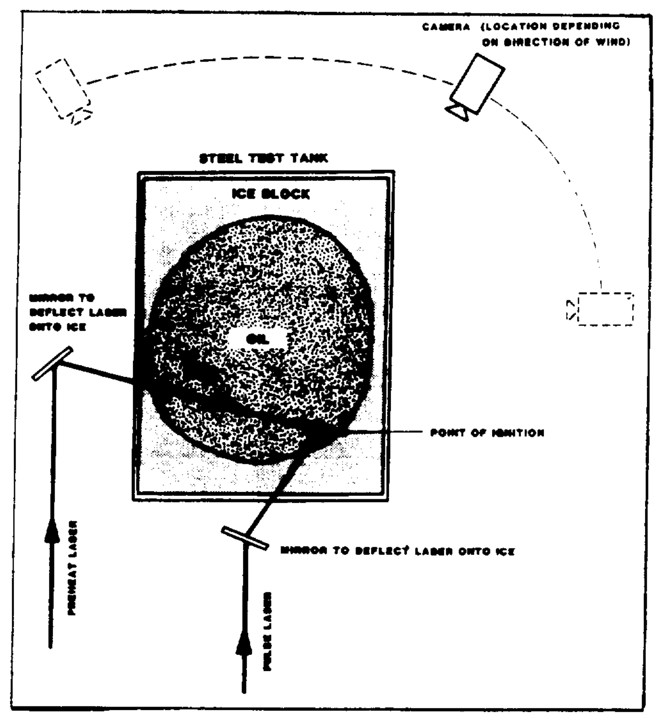

Figure 5. Melt pool test layout[6]

Table 1. Summary of test conditions and results

Serial no.	Test no.	Type[1]	Oil type[2]	Weathering (%)	Oil thickness (mm)	Air temp (°C)	Wind speed (km/h)	Oil temp (°C)	Surface area[4] (m^2)	Sustain time (s)	Spread rate (min/m^2)	Burnout rate (min/m^2)	Comments
1	1-1	P	A	15–20	10	+2.5	16.7	+5.3	1	12	1.33	6.0	Turbulent wind
2	1-2	P	N	35	—	+2.0	11.1	—	1	70	3.75	7.75	
3	2-1	P	T	Fresh	5	−13.0	28.6	−5.7	—	—	—	—	
4	3-1	P	A	15–20	5	−11.5	12.5	+0.2	0.33	13	2.02	13.6	
5	3-2	P	A	Fresh	5	−10.0	12.5	−0.1	0.7	30	0.5	4.3	Strong wind, turbulent
6	3-3	P	N	Fresh	5	−7.5	11.8	+1.5	0.85	4	1.8	4.2	Turbulent wind
7	3-4	C	A	Fresh	5	−6.0	11.1	+0.0	0.1	3	6.7	43	Turbulent wind
8	3-5	C	N	Fresh	5	−7.0	12.5	−2.3	0.16	3	3.2	25	
9	3-6	C	N	32	5	−7.0	12.5	−1.6	0.2	42	10	32	
10	4-1	P	N	32	5	−2.5	16.7	+2.2	0.7	60	1.9	6.8	Strong wind
11	4-2	P	N	15	5	+0.5	15.3	+5.7	0.5	50	3	12.0	Strong wind
12	4-3	P	N	20	5	+2.0	14.3	+3.0	0.75	24	4.4	9	Strong wind
13	4-4	C	A	Fresh	5	+3.5	15.4	+1.5	0.1	2	2.2	57	
14	4-5	C	N	15	5	+3.5	14.3	+6.0	0.17	68	5.9	35	Windy
15	4-6	C	N	Fresh	5	+3.0	11.0	+2.2	0.11	4	2.4	50	
16	4-7	C	A	15–20	5	+3.0	12.0	—	0.18	10	6.5	29	
17	4-8	P	T	Fresh	—	+3.0	12.5	—	—	—	—	—	
18	5-1	P	N	15	—	−1.5	11.1	+1.6	1	3	1.8	4.5	
19	6-1	P	A	[3]	5	−7.0	16.7	−1.2	—	—	—	—	

1. P = melt pool on ice, C = broken ice channel
2. A = Alberta sweet, N = Norman Wells, T = Tarsuit
3. Mixture of 20% weathered (to 15% loss) and 80% fresh
4. Estimated

creases with the age of the oil, but is essentially independent of oil type and configuration of the pool. Superimposing the laboratory data on the field data demonstrates that the time to sustain was always longer in the outdoor tests.

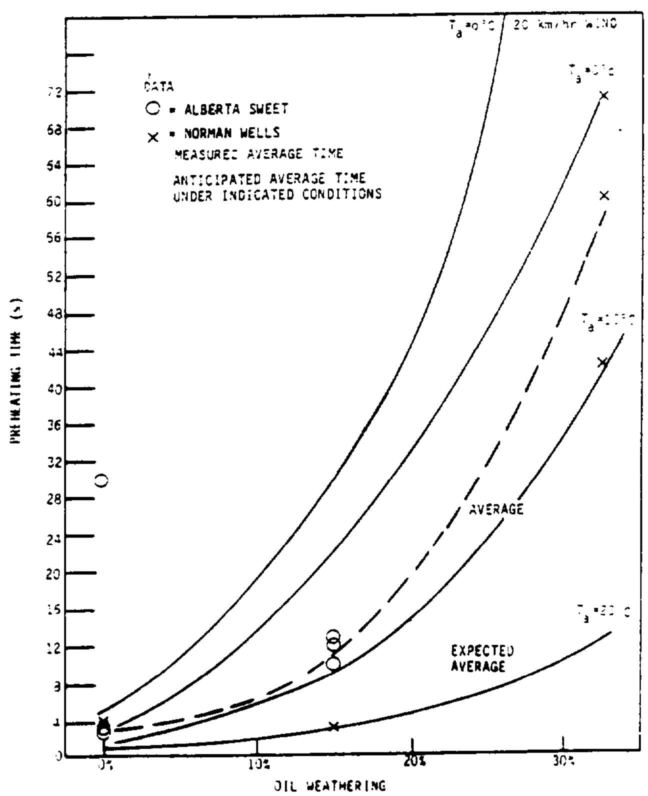

Figure 6. Anticipated and measured preheating times vs oil weathering[6]

Based on the outdoor tests, it was concluded:

- Preheating time requirements increase with the degree of weathering, as expected. The laser system was shown to ignite relatively fresh oil (less than 10 percent mass loss) in less than 15 seconds. Moderately weathered oils (10 to 20 percent mass loss) under moderate winds (approximately 20 km/hr) and temperatures warmer than −10°C were ignited in less than 30 seconds. Oils with greater mass loss took longer to ignite.
- Lower air temperature and blowing wind delay the ignition of oil with lasers. Theoretical analysis confirmed the variation trend.
- The size and shape of the oiled pools did not appear to influence the ignition process.
- The presence of ice in melt pools had no apparent effect on the ignition or flame spreading.
- Oil confined by broken ice could be ignited in the same manner as in melt pools. The ignition time is comparable to that of melt pools. However, the flame spreading, and burnout rate appear to be greatly reduced due to channel effects related to the close proximity of the walls.
- The results achieved suggested that the required laser intensities could be achieved with lasers in a helicopter hovering at an altitude of 50 to 100 meters.

Engineering design

It was decided, based on the results in the outdoor experiment phase of the project, to proceed with the engineering design of a helicopter borne laser-ignition of oil spills system (LIOS). The plan was to build and test a prototype system from a U.S. Coast Guard S-61R helicopter at the U.S. Environmental Protection Agency's Oil and Hazardous Materials Simulated Environment Test Tank (OHMSETT) facility in Leonardo, New Jersey, and, subsequently, in the Canadian Arctic. It was specified that the system must:

- Include a pulsed laser that is focused to provide sufficient fluence to ignite fires remotely on preheated spots in oil pools
- Include a CW CO_2 laser producing up to 1,000 W of power that is optically configured to irradiate an oil pool with the required preheating intensity
- Incorporate a means of aligning and holding the laser beams on target despite helicopter movements and vibrations

- Provide sufficient power and cooling capability to operate all of the components
- Be installable in a Sikorsky S61 or comparable helicopter without affecting airworthiness or safety
- Be operable by an aircraft maintenance technician

Where possible components were to be off-the-shelf items. The system was designed to meet all of these criteria. System operation is illustrated in Figure 7.

In the target-acquisition phase, the operator would locate the position on the oil pool at which the lasers were to be aimed and point the laser. Since there probably would be little image contrast in the infrared before laser heating, a video camera would be used for this task. This camera was to be placed near an infrared scanner, with a dichroic beam splitter directing visible wavelengths to the camera and allowing the infrared to pass through to the scanner. The camera could be connected to the video tracker, thus allowing tracking cross-hairs to be superimposed on the visible image of the scene. Using the joystick controls, the operator could position the targeting mirror so that a selected point on the oil pool was centered within the field of view. The optical system would be adjusted to focus the lasers, which would be turned on. An infrared image of the laser-illuminated spot, which would appear within a second, would be used for tracking purposes.

At this point, the operator would continue to hold the lasers on target with the joystick or switch in the video tracker for automatic tracking. Motion of the helicopter would result in a displacement of the optical field of view, and hence a displacement of the infrared image of the heated spot. Since the heated spot requires a finite amount of time to cool, it would provide a thermal signature of long-enough duration to allow repositioning of the targeting mirror to keep the hot spot at the center of the scene. This adjustment procedure would continue until ignition of the oil was confirmed by the operator.

The LIOS system was to be operated only while the helicopter was hovering to facilitate the task of keeping the laser beams on target. Using a radar altimeter for feedback, an experienced pilot is expected to be able to maintain a large helicopter at a desired altitude within ±1 foot for up to a minute under normal flying conditions. The helicopter motion has a low frequency, typically less than 1 Hz, and could easily be compensated by the pointing system.

The system design was broken down into components: optics; pulsed laser and focusing; CW laser and alignment; power and cooling; targeting; target acquisition and tracking; vibration isolation; and helicopter installation.

An optical layout was designed that incorporates, in one integral platform, the two lasers and optical trains for focusing, range finding, and beam alignment. All of the components are mounted on two vertically stacked tables with mirrors placed to direct beams. The entire structure is isolated from high-frequency helicopter vibrations by the use of damped springs.

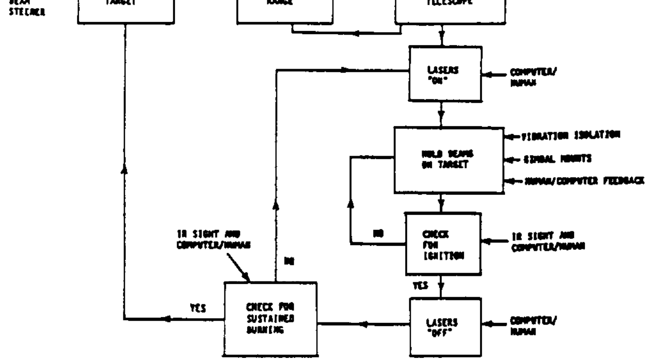

Figure 7. Schematic of laser-ignition of oil spills system operation[4]

The pulsed laser chosen was the Lumonics Model K1OZ TEA. It was selected on the basis of weight, size, beam quality, energy per pulse, repetition rate, structural integrity, power requirements, efficiency, and cost. When operated in the unstable resonator configuration, it provides 8 J per pulse with a nominal beam divergence of 0.8 mrad. Focusing was designed so either a passive infrared or active radar range-finder system could be used. The former was preferred because of simplicity and cost, but the accuracy was not known. For the latter, a Canadian-built Optec Model 60 laser range finder was specified.

On the basis of its size, weight, ruggedness, cooling and power requirements, gas consumption, ease of operation, and cost, the 1,000 watt Laser Corp. of America Falcon 800 was selected as the CW laser. Its beam emerges from the head with a diameter of 32 mm and has a far field divergence of 1.5 mrad full angle.

The CW and pulsed lasers are aligned colinearly without substantial power losses by using a "hole" in the pulsed beam formed by a hole in a reflector. Both laser beams can thus be directed at the oil pool by the same mirror.

The Falcon 800 laser consumes 21 kW of electricity to supply 1 kW of laser power; cooling water is used to reject the 20 kW of waste heat. A helicopter can have no external supply of water, so the system must be air cooled. A commercially manufactured heat exchanger was found to be the best solution. Three Lytron Inc. Model 632 1G3 heat exchangers were found to be adequate for use in arctic conditions.

The main power requirements for the LIOS system are those of the CW laser (21 kW). All other components require a total of less than 4 kW, which can be easily satisfied from existing aircraft power supplies. Installation of a Turbomach Auxiliary Power Unit (APU), coupled to a Bendix AC generator, can easily supply all of the power requirements of the CW laser.

To avoid major helicopter modifications, the power system was designed with its own fuel supply so that it was independent of the aircraft fuel supply and main power bus. The fuel tank and fire-extinguishing system are off-the-shelf items available from several suppliers but the APU housing, ventilaton system and refueling system will have to be custom designed.

A targeting system is required to prevent the laser beams from drifting off the oil pool. A survey of infrared targeting systems revealed that an imaging tracker is the best choice for LIOS. Such a system consists of an infrared sensor and signal-processing electronics. A good candidate for the former is the Inframetics Model 525, a scanning infrared radiometer that provides a TV-compatible video output. The video signal is processed by a DBA Systems Model 606 video tracker to keep the beams on target.

The helicopter's internal vibration could degrade the performance of the LIOS system. Using the Sikorsky S61 as an example, the five blades and a rotor speed of just over 3 Hertz result in a blade passage frequency of about 15 Hz. An isolation system that will attenuate at least 90 percent of the vibration at 15 Hz and above is thus needed. Several companies have the capability to custom design such a system.

It was, as previously stated, the intention to test the LIOS system at OHMSETT using a USCG S-61R helicopter. The prototype system was, therefore, designed to fit into that model.

As can be seen in Figure 8, the cabin of the S-61R is more than large enough for the LIOS installation. One of the major safety requirements is that access to available exits be preserved. With the 18-inch-wide aisle between the laser installation and the cabin wall, this requirement is satisfied. The cabin floor is rated at 200 lb/ft^2, more than adequate for LIOS since the total system weight is just over 2,200 lbs.

Postscript

As previously stated, it had been the intention to build and test a prototype system following the engineering design phase. The prototype was designed, and estimated to cost $750,000 Canadian for components, integration, and labor. Unfortunately, completion of the engineering design phase coincided with a severe decline in petroleum prices and, thus, exploration. As a result, industry funding was lost and the project was terminated.

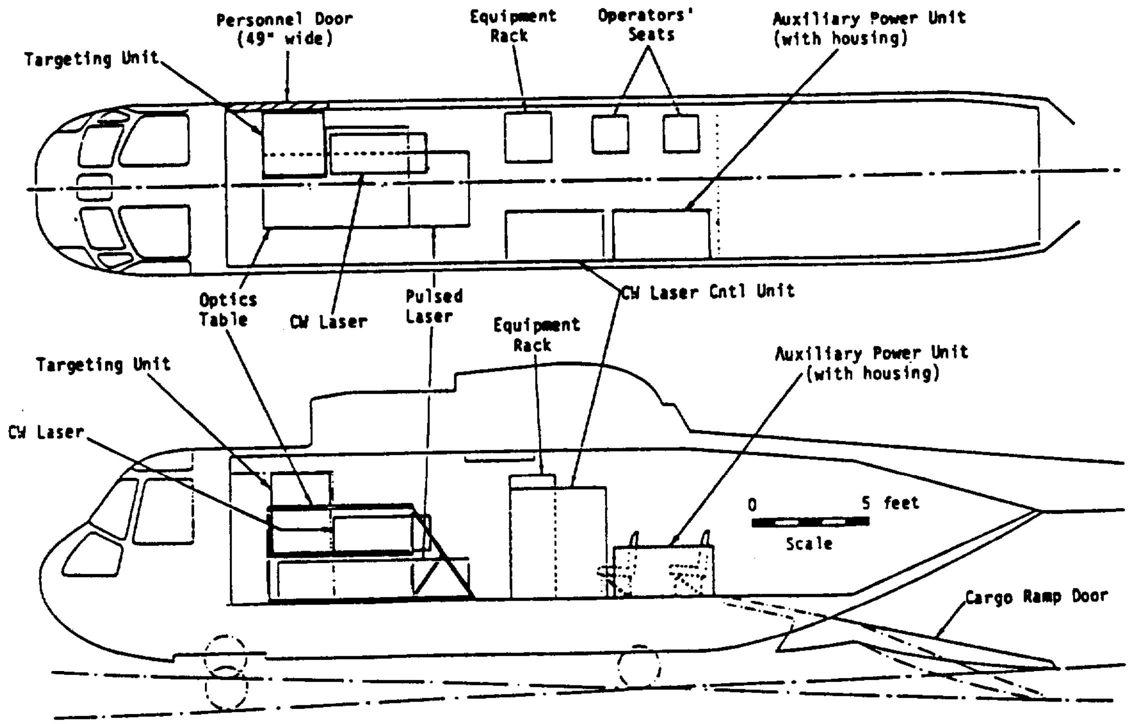

Figure 8. Installation of the LIOS system in the S-61R helicopter[4]

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