EVALUATION OF MULTISPECTRAL VIDEO REMOTE SENSING FOR THE DETECTION OF HYDROCARBON SPILL THICKNESS

by

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Evaluation of Multispectral Video Remote Sensing for the Detection of Hydrocarbon Spill Thickness

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ABSTRACT

This study was designed to evaluate whether hydrocarbon spill thickness could be estimated by measuring light reflectance differences across the photographic spectrum (330 - 1100 nanometers). The theoretical aspects of hydrocarbon spill remote sensing were reviewed to arrive at an understanding of how hydrocarbons act on water and how the electromagnetic spectrum can be utilized for imaging oil spills. The literature dealing with operational and experimental oil spill remote sensing revealed that operational systems have been mainly complex and expensive, but not designed for determining spill thickness. Several experimental studies disagreed as to whether selected photographic spectrum bands could be effectively used for thickness discrimination.

Initial photographic experiments and the high level of radiometric resolution of video cameras strongly favored their potential use to test the possibility of detecting hydrocarbon spill thickness. Graphical and statistical analyses of controlled laboratory test data showed that video imagery collected with specific filters could provide comparative estimates of hydrocarbon thickness up to 1000 microns (1 mm). Oil thickness discrimination was better for translucent hydrocarbons such as 10W30 oil, diesel oil and gasoline than for crude or waste oils. The most effective filters were 88A, 550nm bandpass and a 301A/46 combination.

Analytical results of a field trial using a controlled spill in Burrard Inlet confirmed that it was possible to identify relative diesel oil spill thickness from reflectance measurements, although not with the same statistical significance as in the laboratory tests. The most effective

filters were 18A and 500nm bandpass under the specific environmental conditions encountered. Analyses of 35 mm color photographic imagery also acquired during the field trial confirmed the importance of the blue-green band in imaging spill thickness.

ACKNOWLEDGEMENTS

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Environment Canada was instrumental in making the project a success and was at all times very supportive of my efforts. The Environmental Emergencies Branch of that Department offered access to its records and oil spill literature. Keith Hebron carried out surface sampling during the field trial. Richard Strub provided lab assistance, Lee Harding and Roger McNeill made available their knowledge in computer systems and statistics, Hal Nelson and Duane Brothers expedited the Ocean Dumping Approval Process for the field trial and Merv Fingas generously donated funds from Environment Canada headquarters. Karl Kupka and John Millen permitted considerable flexibility in my work schedule at Environmental Protection to enable me to undertake the study.

Industry support included that of Andy Hofbauer of Shell Canada Limited who provided hydrocarbon samples, dock usage and 45 gallon drums. Blair Humphrey of Seakem Oceanography Limited loaned equipment for field trial surface sampling. Martyn Green and staff of Burrard Clean Limited were essential in my gaining permission for a marine diesel spill because of the responsibility they assumed for spill control and cleanup.

Lillian Pearson is appreciated for her drafting assistance, Vivian Wray for her prompt and accurate word processing, and Deb Sherwood, my wife, for her patience and understanding.

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CHAPTER 1. INTRODUCTION

Two hundred and eleven major hydrocarbon spills occurred in British Columbian marine waters between 1972 and 1984 (Canada, 1986a). These spills were widely distributed along the coast, but the major concentrations were in the industrialized southwest (Figure 1).

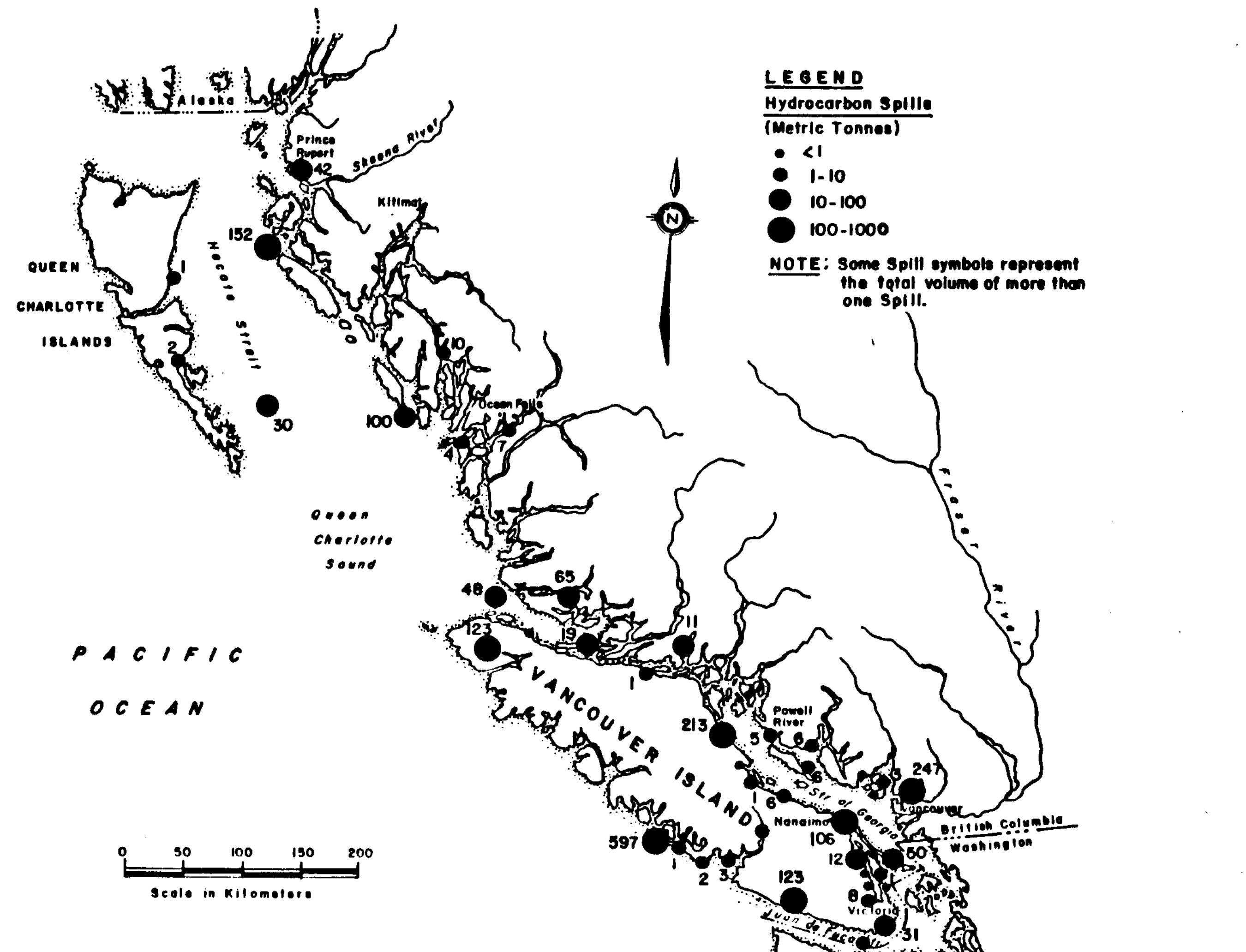
Environmental and economic losses from such spills can be significant. In a January 1986 spill, an estimated 350 waterfowl were seriously oiled in Sooke Bay from what appeared to be clandestine bilge pumping (Canada, 1986b). A 1973 spill off West Vancouver from a ship collision resulted in cleanup costs of over $600,000 (Canada, 1983b: 34).

Early detection and knowledge of the distribution and thickness of such spills can assist in reducing their environmental and economic costs by effectively guiding cleanup efforts to areas of maximum hydrocarbon concentration. A number of remote sensing systems varying considerably in complexity, accuracy and cost have been developed for spill delineation, but none have been able to depict the thickness of such relatively thin spills.

1.1 Study Objective

The objective of this study was to evaluate whether hydrocarbon spill thickness could be estimated by measuring light reflectance differences using multispectral video remote sensing. Video was chosen because it has potential for real-time, analog to digital image analysis using microcomputers. Video cameras also have a high level of radiometric

FIGURE I. MAJOR MARINE HYDROCARBON SPILLS IN BRITISH COLUMBIA, 1972 - 1984



Adapted from: Canada, 1986a: 12

resolution and therefore can be expected to perform better than film. In addition, they are much lower in cost than other systems such as multispectral scanners.

Logistically, video systems have the advantage of compactness and low weight for installation in light aircraft. Use of a four-camera array made a multispectral approach possible by permitting simultaneous imaging of up to four bands within the photographic spectrum (300-1100 nanometers). Subsequent analyses determined the more effective filters for estimating spill thickness. The system selected for the study was intended to be experimental only; a fully operational video system would require additional evaluation under a broader range of field conditions.

CHAPTER 2. THEORETICAL ASPECTS OF HYDROCARBON SPILL REMOTE SENSING

2.1 The Behaviour of Hydrocarbons on Water

Hydrocarbons associated with marine spills include napthas, gasolines, kerosenes, diesel fuels, bunkers and crude oils. Their appearance on water depends on quantities present, spill duration, weathering and viscosity. As shown in Table 1 and originally described by Hornstein (1973), hydrocarbon spills can be characteristically silvery, iridescent, dark brown to black, or a lighter brown representing a thickness range of 0.0001 to 1 mm. However, appearance also can vary depending on hydrocarbon type and environmental conditions; a more reliable sensor than the human eye is therefore required.

There are several major weathering processes which determine the fate of hydrocarbons, or oil colloquially, on marine waters (Figure 2). These include physical processes such as evaporation, chemical influences as would occur through the use of dispersants and biological processes like biodegradation. Evaporation usually is the dominant factor in the decomposition of hydrocarbons.

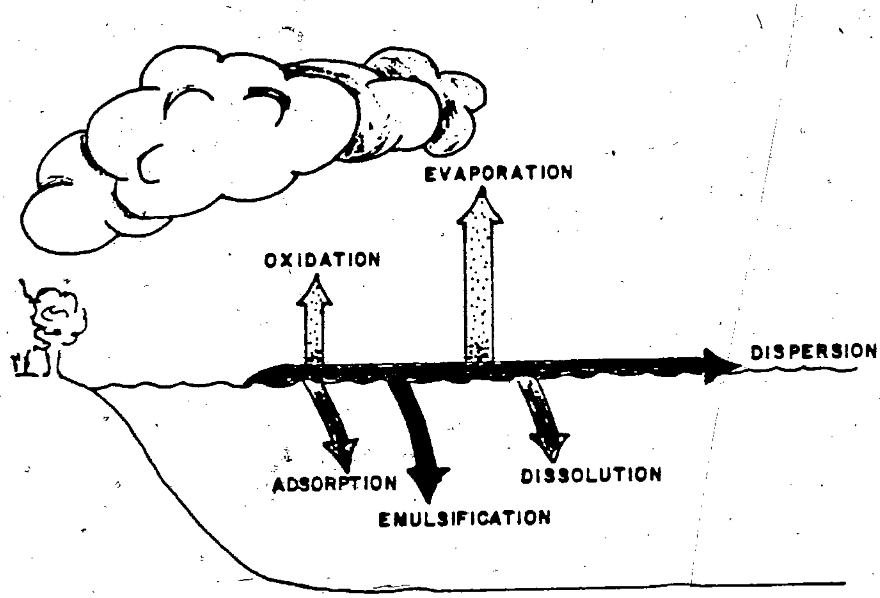
Environmental conditions and weathering can result in a variety of physical configurations of oil spills on water (Table 2). Smooth slicks are the common conception of spills. However, in many cases, spills can appear in streamers or windrows, isolated pancakes or consolidated tarballs. Hollinger (1974) has shown that thick regions of slicks contain more than 90 percent of the oil in less than ten percent of the slick area. This emphasizes the advantages for spill cleanup if relative thicknesses can be remotely detected.

TABLE 1. A GUIDE TO THE RELATION BETWEEN THE APPEARANCE, THICKNESS AND VOLUME OF FLOATING OIL

OIL CONDITION	APPEARANCE	APPROXIMATE THICKNESS (mm)	APPROXIMATE VOLUME (m^3/km^2)
Light sheen	Silvery	0.0001	0.1
Heavy sheen	Iridescent	0.0003	0.3
Unemulsified oil	Black/dark brown	0.1	100.0
Emulsified oil	Brown/orange	1 or more	1000.0

Adapted from: Canada, 1984a: 11

FIGURE 2. GROSS WEATHERING PROCESSES AS THEY AFFECT OIL ON THE SEA SURFACE



ADSORPTION: PROCESS OF OIL ADHERING TO THE SURFACE OF SOME SUBSTANCE- GENERALLY LEADS TO SINKING.

BIODEGRADATION: CHANGES IN THE CHEMICAL AND PHYSICAL PROPERTIES OF AN OIL THROUGH BIOLOGICAL ACTIVITY.

CHEMICAL DISPERSION: REDUCTION OF OIL/WATER INTERFACIAL TENSION BY THE ADDITION OF SURFACTENTS TO OIL WHICH AID ITS DISPERSION.

DISSOLUTION: A PROCESS WHICH ACCOUNTS FOR THE SOLUBLE HYDROCARBONS IN OIL DISSOLVING IN THE WATER.

EMULSIFICATION: A MIXTURE OF OIL AND WATER WHICH IS CAUSED BY SOME STIRRING ACTION (SUCH AS WAVES), EMULSIONS ARE EITHER WATER IN OIL OR OIL IN WATER, DEPENDING ON THE RELATIVE PERCENTAGES OF EACH SUBSTANCE.

EVAPORATION: CONVERSION OF A LIQUID TO A VAPOR, THE RATE OF EVAPORATION DEPENDS ON THE VOLATILITY, TEMPERATURE, WIND AND SURFACE AREA OF THE SLICK. EVAPORATION WILL USUALLY ACCOUNT FOR A LARGE PORTION OF LOST OIL.

OXIDATION: THE COMBINATION OF HYDROCARBONS WITH OXYGEN. SUNLIGHT WILL AID OXIDATION. THIS IS CALLED PHOTO-OXIDATION, PRODUCING OTHER COMPOUNDS WHICH MAY DISSOLVE IN WATER OR DISPERSE QUICKER. THIS IS A SLOW PROCESS AND LIMITED TO THE SURFACE OF A SLICK.

SOURCE: Pavia, Robert, and D.L. Payton, 1983: 346

TABLE 2. DESCRIPTIVE TERMINOLOGY FOR OIL SIGHTINGS

MOUSSE: A WATER-IN-OIL EMULSION FORMED WHEN WATER IS MIXED WITH OIL BY SOME AGITATION PROCESS SUCH AS WAVE ACTION. THIS FORM OF OIL IS MORE READILY FORMED BY HEAVIER OILS THAN LIGHTER OILS. IF A MOUSSE IS FORMED IT CAN RANGE IN COLOR FROM LIGHT BROWN TO RUST AND DARK BROWN. THE COLOR IS DEPENDENT ON THE TYPE OF OIL, AMOUNT OF WEATHERING IT HAS UNDERGONE AND THE PRESENCE OF SURFACE ACTIVE AGENTS.

PANCAKES: ARE GENERALLY SEEN AS ISOLATED PATCHES OF WEATHERED OIL. THEY ARE ROUGHLY ROUND OR OBLIQUE, GIVING RISE TO THEIR NAME, AND CAN RANGE IN SIZE FROM ABOUT 6 CM TO A FEW KILOMETERS IN RADIUS.

SHEEN: THE NAME ASCRIBED TO OIL THAT IS DETECTIBLE BY A DAMPENED OR "SLICK" SEA SURFACE. SHEEN CAN RANGE FROM BEING VISIBLE ONLY BY THE SLICK IT FORMS TO HAVING A RAINBOW OR GRAY COLOR ASSOCIATED WITH IT.

SLICK: A SMOOTH SEA SURFACE AREA RESULTING FROM SUPPRESSION OF SMALL CAPILLARY WAVES BY OIL.

STREAMERS: LINES OF OIL, OF ANY FORM, ALIGNED IN SMALL WINDROWS.

TARBALLS: A FORMATION OF "GLOBULES OF OIL" OCCURRING WHEN WEATHERED OIL UNDERGOES A SERIES OF PHYSICAL PROCESSES THAT BREAK UP LARGER PATCHES OF OIL INTO COMPACT SEMI-SOLID OR SOLID MASSES RANGING FROM 5 MM TO 15 MM IN DIAMETER.

WINDROWS: PARALLEL BANDS OF FLOATING MATERIAL ON THE WATER SURFACE (OIL, SARGASSUM, ETC.) WITH THE LONG AXIS ALIGNED WITH THE WIND DIRECTION.

WIND SLICKS: PATCHES OF CALM SEA SURFACE CAUSED BY LOCALIZED AREAS OF WIND SHEAR WHERE WIND CONDITIONS CHANGE SO RAPIDLY THAT CAPILLARY WAVES DO NOT HAVE TIME TO DEVELOP. WIND SLICKS DO NOT CONCENTRATE MATERIAL ON THE WATER SURFACE AS DO WINDROWS. WIND SLICKS MAY BE CONFUSED WITH AN OIL SLICK.

Source: Pavia, Robert, and D.L. Payton, 1983: 347

Research undertaken by Ahmadjian et al. (1976) indicated that, although weathering affects the physical and chemical properties of spilled oil, it does not usually obviate the potential for remote detection. Far more critical to remote sensing are such factors as cloud cover and sea state which can entirely eliminate the use of some sensors such as satellite platforms. In development of the method for this study, these and other factors were taken into consideration and are explained accordingly.

2.2 Portions of the Electromagnetic Spectrum Used in Oil Spill Remote Sensing

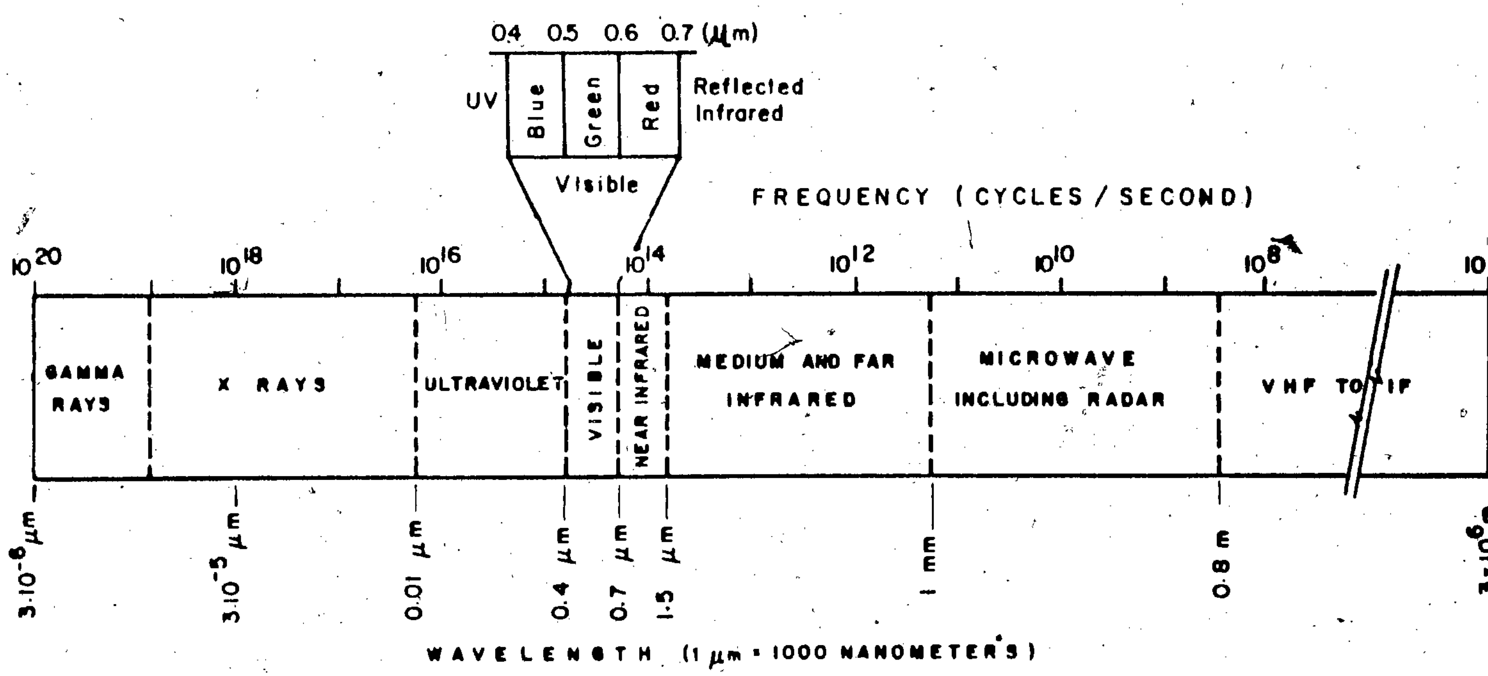
The electromagnetic spectrum is a continuum of energy travelling at the speed of light (3 X 10^8 sec m x sec $^{-1}$) and is described in terms of wavelength or frequency. Figure 3 illustrates the spectrum and provides descriptive terms for certain bands within it. Based on Canada (1984b), Canada (1983a), Axelsson and Ohlsson (1973), Catoe (1973) and Estes et al. (1972), a brief summary of the bands used in the remote sensing of oil spills follows.

2.2.1 Ultraviolet.

The ultraviolet (UV) spectrum ranges from 0.1 to 0.4 micrometers (μm) or 100 to 400 nanometers (nm). The portion of the UV band generally used for remote sensing purposes is between 0.3 and 0.4 μm; absorption by the atmosphere is very strong below 0.29 μm.

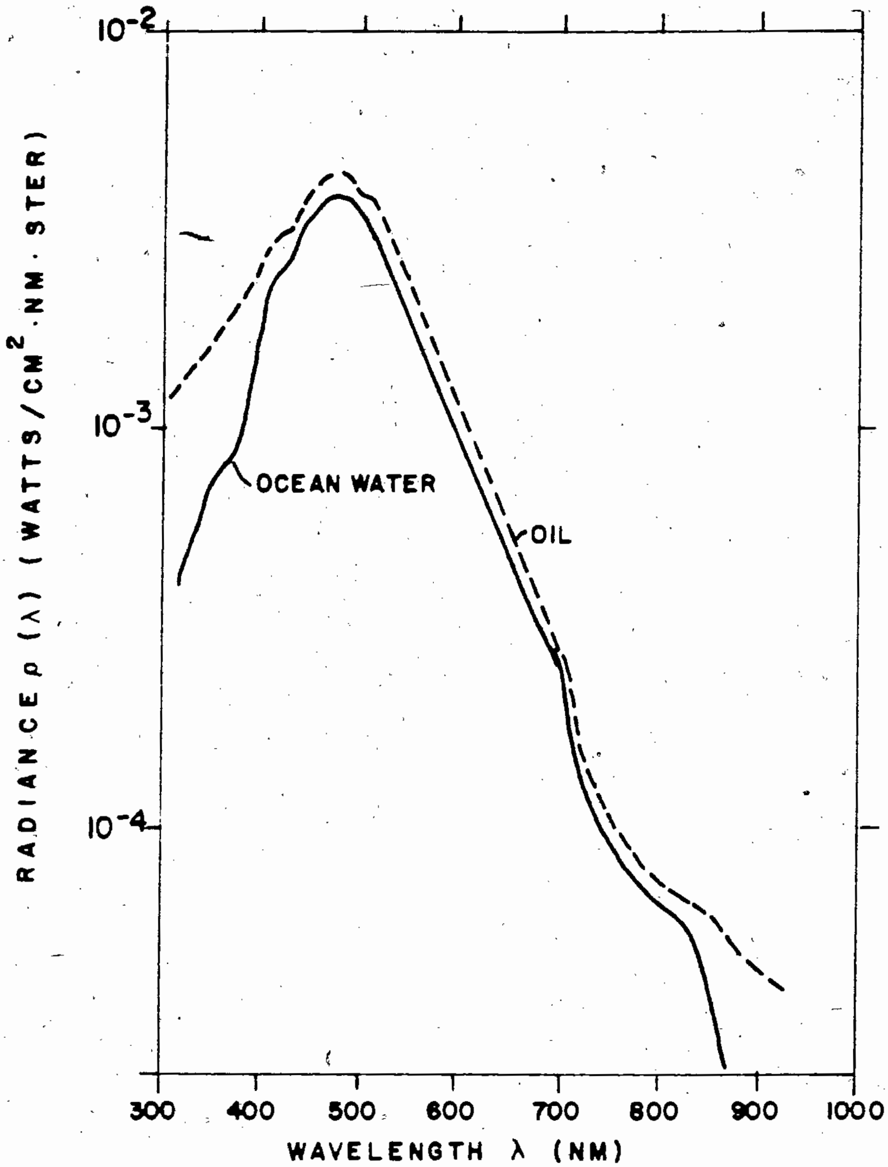
There are two mechanisms for detecting oil slicks in the UV: the reflectance differential between oil and water, and fluorescence. As illustrated in Figure 4, oil has a higher reflectance than sea water in the

FIGURE 3. THE ELECTROMAGNETIC SPECTRUM



ADAPTED FROM: Estes, John E., *et al.*, 1972 : 72

FIGURE 4. SPECTRAL RADIANCE FROM A THIN LAYER OF CRUDE OIL AND MODERATELY CLEAR COASTAL WATER OF INFINITE DEPTH WITH 43° SOLAR ALTITUDE



SOURCE: United States, 1971d: 701

near ultraviolet. Sensors which selectively focus on this part of the electromagnetic spectrum therefore are theoretically capable of superior oil spill detection. The second phenomenon, fluorescence, occurs when a portion of the ultraviolet absorbed by oil is re-emitted at a longer wavelength from 0.4 to 0.7 μm, providing a relatively weak signal for oil spill detection purposes.

2.2.2 Visible. The visible portion of the spectrum between 0.4 and 0.7 μm is the region sensitive to the human eye. The mechanism for oil detection in this band is the reflectance differential between oil and water. The differential is weakest between 0.45 and 0.5 μm; wavelengths below and above usually provide improved oil/water contrast.

2.2.3 Near Infrared. The near infrared region (IR) from 0.7 to 1.1 μm is not detectible by the human eye. Its primary usefulness for remote detection is also the result of the reflectance differential between water and oil as illustrated in Figure 4. In fact, in this region the radiance from an oil slick can be between 20 and 100 percent greater than from the surrounding water (Catoe, 1973: 269).

2.2.4 Thermal Infrared. The shortwave infrared between 1.2 and 3.0 μm has little utility in the remote sensing of oil spills on water. Beyond 3.0 μm, emitted (thermal) infrared becomes a primary source of detectible energy. In the thermal infrared, remote sensing is usually confined to spectral regions called atmospheric windows where the atmosphere is sufficiently transparent to allow radiation to travel over paths of significant length with little absorption. The main windows are from 3.1 to 4.1 μm and 8.0 to 14.0 μm. The oil spill detection mechanism in the thermal infrared is that of the thermal emission differential between water and oil which is greatest in the 8.0 to 14.0 μm region (Catoe and McLean, 1979: 4).

2.2.5 Microwave. The microwave portion of the electromagnetic spectrum ranges from 1 mm to 1 meter in wavelength. A principal mechanism for oil spill detection in the passive microwave region (0.1 cm to 30 cm) is the emissive differential between oil and water; the emissive signature of petroleum products is significantly higher than that of a calm sea (Canada, 1984b: 2.19). Sea surface damping (wave structure modification) also plays a role in the microwave region by reducing sea surface roughness and emissivity (Catoe and McLean, 1979: 8).

The active portion (1.5 cm to 70 cm) of the microwave spectrum is known as the radar region. In this band, the damping effect of oil on water can result in what is known as a backscatter cross-section differential. That is, oil's damping effect on surface waters reduces the amount of energy being backscattered compared to surrounding wave-tossed areas. According to to Catoe (1973: 270), a decrease of up to three orders of magnitude in return signals have been observed for natural oil slicks.

2.2.6 Summary. Table 3 summarizes the detection mechanisms appropriate to the electromagnetic bands discussed above. Table 3 also identifies weather constraints, false alarms and the potential for day and

TABLE 3. SUMMARY AND EVALUATION OF FACTORS RELATED TO OIL SPILL DETECTION

	SPECTRUM	DETECTION MECHANISM	WEATHER CONSTRAINTS	FALSE ALARMS	DAY OPS	NIGHT OPS
Photographic	Near UV	Reflectance Differential	Haze, Fog and Clouds	Fish-Oil Slicks Suspended Solids Wind Slicks	Yes	No
		Fluorescence			Yes	Yes, If active
	Visible	Reflectance Differential	Clouds and Fog	Fish-Oil Slicks Suspended Solids Shallow Water	Yes	No
	Near IR	Reflectance Differential	Clouds and Heavy Fog	Fish-Oil Slicks Suspended Solids Upwellings	Yes	No
		Thermal Emission Differential				Yes
	Thermal	Thermal Emission Differential	Heavy Clouds and Rain	Fish-Oil Slicks Suspended Solids Upwellings	Yes	Yes
Microwave	Passive Techniques	Emissive Differential Wave Structure Modification	Heavy Rain	Suspended Solids Calm Seas	Yes	Yes
	Active Techniques	Wave Structure Modification Backscatter Cross-Section Differential	Heavy Rain	Suspended Solids Calm Seas	Yes	Yes

Adapted from: Catoe, Clarence S., and James T. McLean, 1979: 20

night operations for each band. Weather constraints include haze, fog, clouds, hail and rain. False alarms which can complicate interpretation of sensor data include fish oil slicks, suspended solids, wind slicks, shallow water, upwellings and calm seas (United States, 1974). Remote sensing in all of the electromagnetic spectrum (between ultraviolet and microwave) is available under daylight conditions. However, passive remote sensing using the photographic portion of the spectrum (0.3 - 1.1 μm) is not possible during hours of darkness.

CHAPTER 3. OIL SPILL REMOTE SENSING

Much of the oil spill remote sensing undertaken to date has been in relation to large spills from tankers or offshore oil rigs. The oils involved have been primarily heavy crudes. Little remote sensing effort has been put into the more chronic problem of small harbour slicks of lighter hydrocarbons such as diesel or gasoline. This chapter examines the record of oil spill remote sensing by reviewing operational systems and summarizing the record of experimental studies.

3.1 Operational Systems

Considerable variation exists amongst countries in terms of their use of remote sensing for the detection of oil spills. There is no consistency in either system types or costs. The sections which follow describe systems used on spills in Canada, Europe and the United States.

3.1.1 Remote Sensing of Oil Spills in Canada. According to an extensive literature search, primarily through the Canada Centre for Remote Sensing (CCRS), there is little documented use of remote sensing of actual spills in Canada. Thomson and McColl (Canada, 1972) described a remote sensing survey on the 4 February 1970 of a Chedabucto Bay bunker C oil spill. That survey was undertaken to assist in delineating the distribution of oil and to evaluate the usefulness of an 8 - 14 μm infrared line scanner (Appendix 1) and several 35 and 75 mm photographic cameras. Flights were scheduled under day and night conditions. The authors determined that both sensor types were capable of monitoring slick area. The thermal scanner could only be used under limited conditions when there was a significant temperature difference between oil and water. The photographic imagery was limited to daylight fair weather observation. Photography was the authors' preference for simple surveillance, particularly with certain film/filter combinations such as Kodak Plus-X with a Wratten 39 (ultraviolet and blue) filter.

The only other major Canadian spill of opportunity noted in the literature was from the Kurdistan oil tanker. O'Neil et al. (Canada, 1980) used a relatively extensive sensor package to search for and map bunker C oil which had been spilled from the Kurdistan on 16 March 1979. Included in their choice of sensors was a multispectral scanner with infrared and visible channels, a low light level television (LLLTV) camera (Appendix 1), large format photographic reconnaisance cameras and a specialized "multi-detector electro-optical imaging scanner". Between 17 March and 2 April, a total of nine sorties were flown with oil being observed and mapped on six of these. Each of the sensors proved to be capable of oil detection under specific conditions, but the authors did not provide a comparative evaluation. Their only reference to spill thickness was that thin slicks showed bright against the dark water with UV and color photography.

Although CCRS, a few other government agencies and several private remote sensing firms have been involved in the development and evaluation of oil spill detection systems in Canada (Table 4), there is a lack of other published information on actual applications of these systems to real oil spills. While it is known that visual observations from aircraft are often accompanied by the use of 35 mm cameras with either or both skylight and polarizing filters (Canada, 1986c), it appears that more sophisticated

TABLE 4. CANADIAN AIRBORNE REMOTE SENSING CAPABILITY FOR OIL SPILLS

AGENCY OR COMPANY	AIRCRAFT	SENSORS
Canada Centre for Remote Sensing (Federal Department of Energy, Mines and Resources)	Convair 580 Falcon DC3 (2)	- LLLTV - Dual channel line scanner - Multispectral line scanner - Four channel research SAR - Laser fluorosensor - AGTV and cameras - MEIS (experimental)
Ontario Centre for Remote Sensing (Provincial Ministry of Natural Resources)	Navaho Chieftan	- Daedalus IR line scanner - 2 Vintens (70mm) and (9" x 9") - 4 Hasselblad (70mm) - Aerial video
Atmospheric Environment Service (Ice Branch) Federal Department of Environment	Electra (2)	- APS 94D Radar - Bendix thermal mapper - 70mm camera
Department of National Defense	Aurora CF104	- Reconofax X IIIA line scanners - Other classified military equipment
Atlantic Canada Airborne Sensing (Crown Corporation)	PA23 Piper Aztec	- LLLTV - B&W daytime TV (& color) - FLIR - Cameras
MARS Aerial Remote Sensing Limited	Grumman GI	- Motorola APS 94 D - SLAR - Aerial cameras - IR line scanner
Intera Technologies Limited	Cessna 411 Cessna 310 Piper Navaho	- Daedalus IR line scanner (single and dual) - Aerial cameras - LLLTV - SAR - SLAR

TABLE 4. CANADIAN AIRBORNE REMOTE SENSING CAPABILITY FOR OIL SPILLS - Cont'd

AGENCY OR COMPANY	AIRCRAFT	SENSORS
Aerial Mapping & Photography Limited	Beechcraft Super King Air B-200	- Zeiss RMK A 15/23 aerial camera - Radar altimeter (FP-RI) - LLLTV - TV (B&W) - B&W support photo lab
Les Releves Geophysiques Inc.	Flying by Aerophoto Inc.	- Bendix thermal mapper - 70mm camera
Norcor Engineering and Research Limited	Britten-Norman Islander	- Bendix RDR ground search radar - RCA 1040 ISIT TV system - 70mm camera

Adapted from: Canada, 1984b: 3-104 and 3-106 and Canada, 1983a: 248

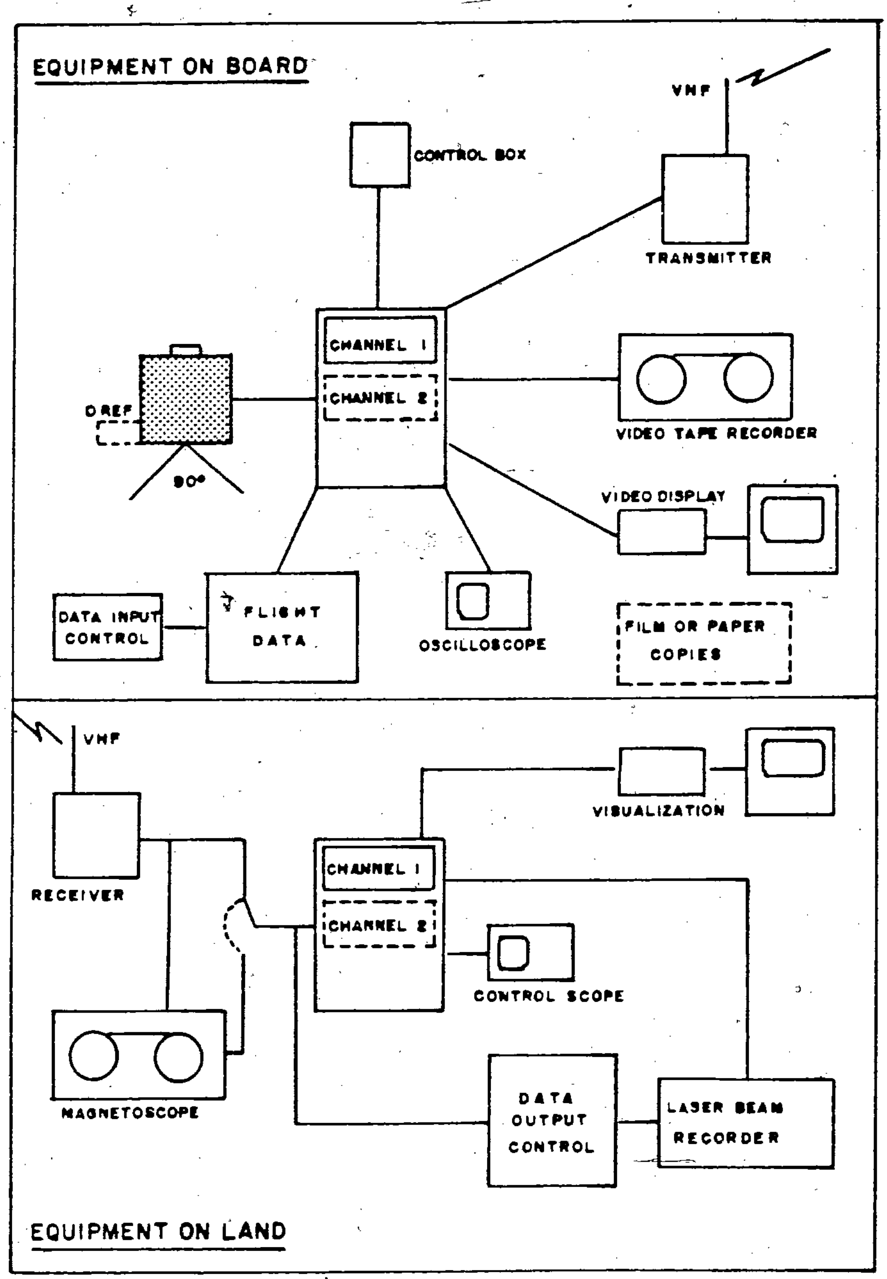
systems are infrequently utilized probably as a result of their greater complexity, lack of availability or greater cost.

3.1.2. Operational Systems in Other Countries. Massin (1981) described an airborne remote sensing system developed by France for detecting, identifying, classifying, mapping and tracking oil spills. The French sensor package included an infrared line scanner, a navigation system, a videotape recorder to combine the scanner and navigation data, a video display, a radio transmitter and various photographic cameras which could all be carried in a twin-engine aircraft. The ground receptor system was composed of a radio receiver, a system to separate scanner and flight data, a video display unit, a videotape recorder and a laser beam recorder for hard copy. Figure 5 provides a schematic of this "Supercyclope" system.

According to Massin, the system was operationally limited with respect to weather conditions and lack of consistency in the infrared band because of thermal variability caused by cold water rising in the wake of vessels or interference from clouds. Expansion of the system to overcome these limitations included a proposal for the use of a multispectral line scanner and a side-looking airborne radar. Massin also suggested that comparison of infrared and visible imagery could provide some information about average spill thickness, but did not detail how this could be achieved.

Backlund and Holmstrom (1983) described a Swedish package comprising an integrated side-looking airborne radar (Appendix 1), an infrared/ultraviolet scanner and photographic cameras. Data storage and documentation included a Polaroid camera and digital cassette recorder.

FIGURE 5. FRENCH SUPERCYCLOPE SCANNER SYSTEM



SOURCE: Massin, J. M., 1981: 177

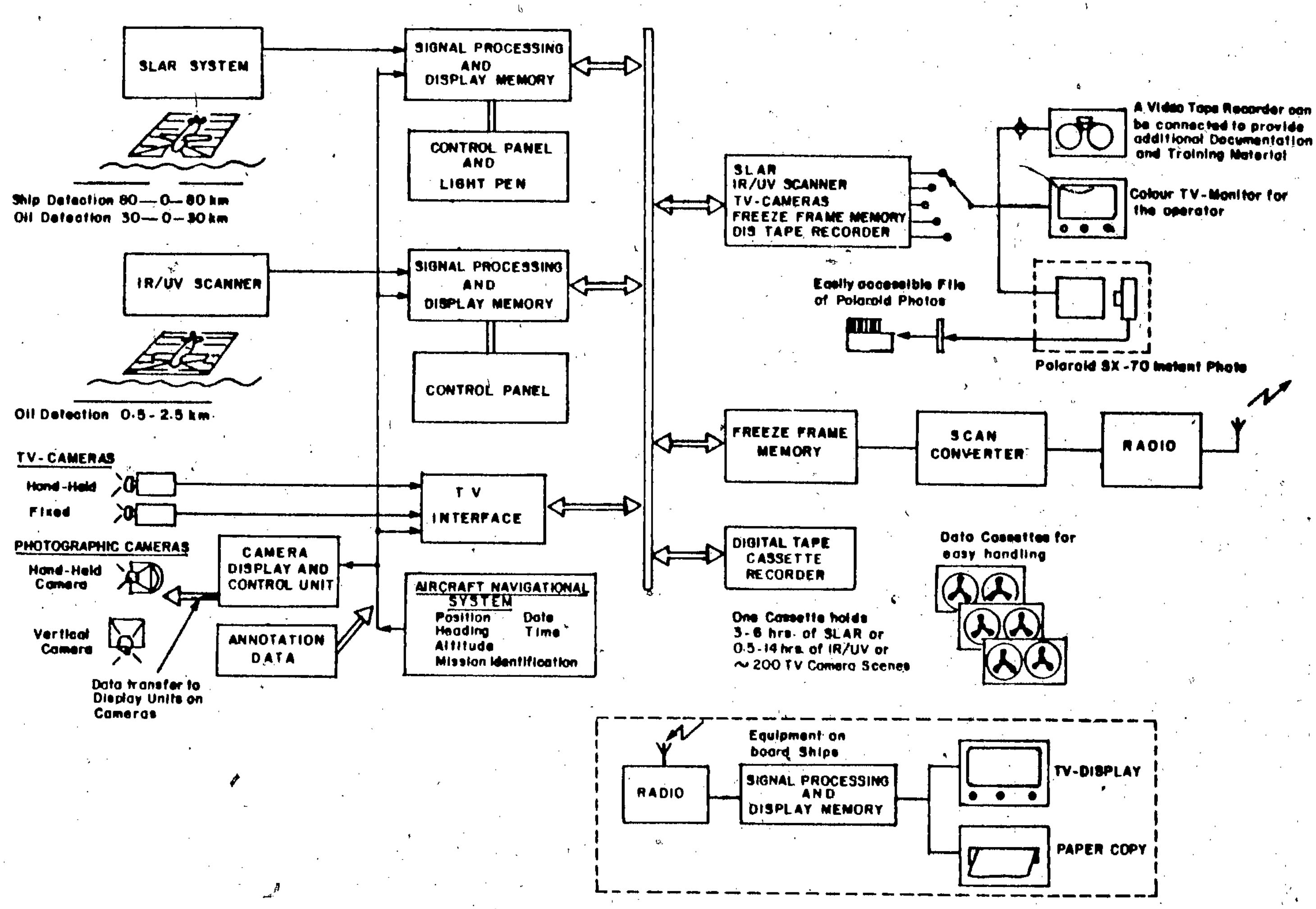
Navigational data were integrated into the system as well. System add-ons included image links to the ground by microwave, a handheld TV camera, a microwave radiometer and a laser fluorosensor (Figure 6).

The Swedish system has been in operational service since 1980 and has been tested in various flight programs for the French and Dutch governments, the European Economic Community and Swedish Coast Guard. Although Backlund and Holmstrom provided no analyses from their experiments, they claimed the system had performed very satisfactorily. The UV channel on the scanner was used successfully to image spill area and the IR channel to indicate relative oil thickness. Unfortunately, they provided no details on thickness discrimination performance. While the authors argued that the Swedish system was low weight, low volume, low in power consumption, reliable and needed only a minimum of service, Backlund (1979) quoted system installation costs at that time as $535,000 U.S., a high sum for most emergency response groups.

Perhaps the most elaborate and technologically advanced oil spill surveillance system is the U.S. Coast Guard's "Aireye" (White and Schmidt, 1983). It was designed to include a side-looking airborne radar, a three-channel infrared/ultraviolet line scanner, an aerial reconnaisance camera, an airborne data adaptation system and a control display and record console. In addition, to identify polluting vessels at night, an active gated television was developed for the Aireye. Each sensor could produce annotated hard copy imagery (Figure 7). As of 1983, the system was to be installed on six U.S. Coast Guard jet aircraft.

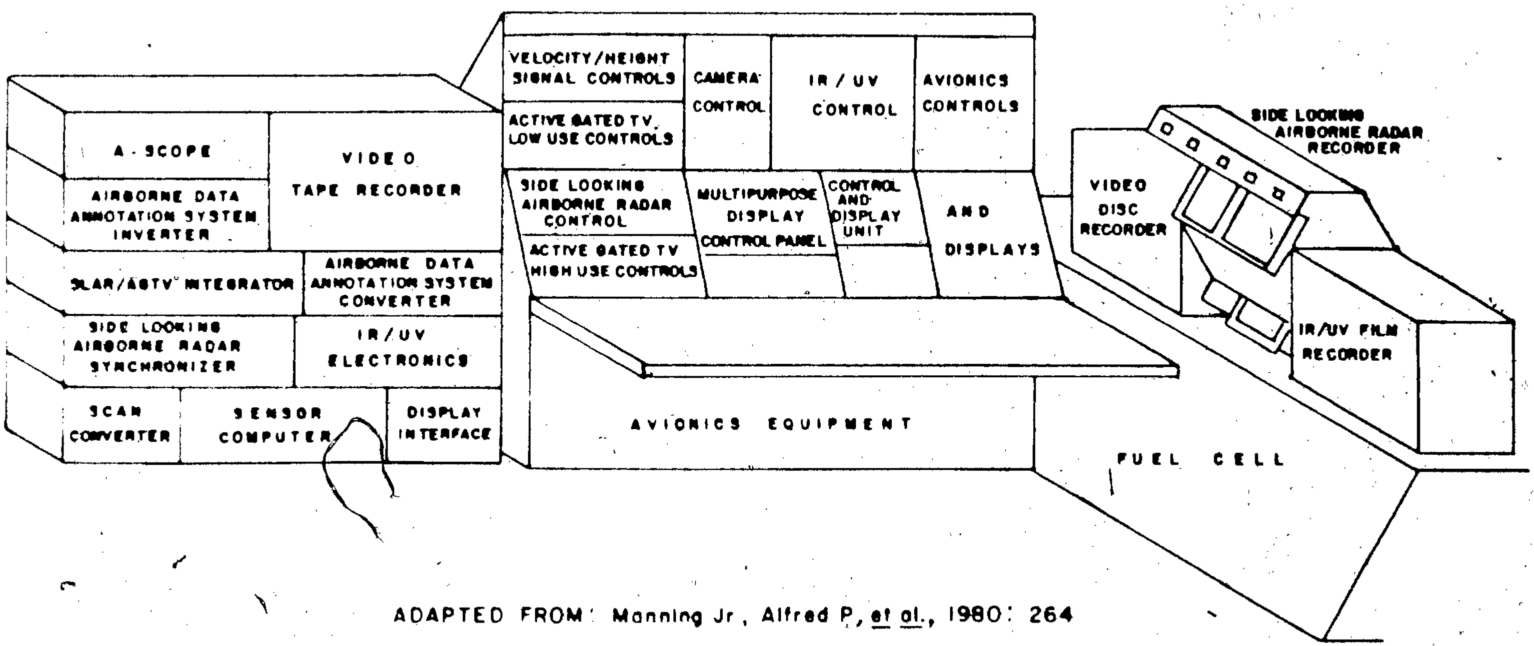
A key feature of the Aireye computer was its onboard image-processing capabilities which included such enhancement functions as spatial

FIGURE 6. SWEDISH MARITIME SURVEILLANCE SYSTEM



SOURCE: Backlund, Lars, and Lars Holmström, 1983: 351

FIGURE 7. U.S. AIREYE SURVEILLANCE SYSTEM



ADAPTED FROM: Manning Jr, Alfred P, et al., 1980: 264

filtering, intensity scaling, frame-to-frame averaging, magnification zoom, high resolution zoom, automatic character generation, graphic overlay and geometric correction. A complex and integrated system, the Aireye was very expensive and required a high degree of sophistication and training for use. It was developed primarily for spill and vessel identification purposes; the literature did not document its ability to measure spill thickness.

The French, Swedish and American systems were developed after extensive research and field training. Although each was claimed to be an integrated package capable of oil detection under virtually any circumstance, problems of poor weather, heavy sea states and false targets have restricted their utility. While sophistication was the reason for their versatility, it was also the cause of their high costs. Moreover, whether they were able to accurately identify spill thickness could not be determined from the literature.

The video system developed for this study is more limited in scope, but much lower in cost. In addition, its performance in measuring thin spill thickness may be superior. Assessing its effectiveness in determining spill thickness is the main objective of this study.

3.2 Experimental Studies

To evaluate the capability and effectiveness of oil spill sensors through experimental studies, it is useful to have a design concept of what might be considered an 'ideal' system. O'Neil et al. (1981) suggested such a system should:

- provide continuous, day and night, all weather, wide area, real-time surveillance
- detect any oil spill that occurs in the marine environment both on and below the surface
- confirm that the detected substance is in fact oil
- map the areal extent of the spill
- obtain the thickness distribution and quantify the amount of oil spilled
- identify the source of pollution and the specific type of pollutant being discharged
- provide precise navigational accuracy for spill and source location and positioning of clean-up vessels
- document all collected data on hard copy records for legal evidence.

This is a demanding list and one not capable of being satisfied by any single sensor. Nonetheless the list can serve as a reference when evaluating existing instrumentation. Table 5 alphabetically lists studies of actual field trials of many different sensors covering much of the electromagnetic spectrum. Some of the studies comparatively evaluated one particular type of sensor such as photographic cameras, while others compared different sensor types such as multispectral scanners and radar. Appendix 1 describes the various instrumentation types referenced in Table 5.

Table 5 shows that sensor evaluation studies historically have occurred in two main time periods - the early 1970's and the 1980's. Research for the first of these periods suggested a heavy emphasis on photographic sensors as well as initial examination of a wide variety of sensors over much of the electromagnetic spectrum. Work in the 1980's has been based on improvements in the electronics of sensing and recording units.

3.2.1. Sensor Systems. Examination of the results presented in Table 5 leads to the following conclusions with respect to sensor systems, spectral bands, oil type and oil thickness.

TABLE 5. SUMMARY OF SENSOR SYSTEM EVALUATION STUDIES

RESEARCHER	SENSOR SYSTEM	WAVELENGTH OR FREQUENCY	RESULTS
Aukland and Trexler (United States, 1970), Aukland et al. (1971) and Catoe and Orthlieb (1971)	Dual 70 mm modified K-24 aerial camera, no filters, Kodak Ektachrome Infrared Aero (8443) and Kodak Ektachrome MS Aerographic (2448) Color film.	Visible and photographic infrared	- Infrared gives slightly sharper oil/water contrast at low sun angles, but both visible and infrared color are useful in spill detection.
	Four lens 70 mm modified K-24 aerial camera, Kodak Wratten 18A and UV to mid-visible filters, Kodak (8403) Tri-X Aerecon Black and White film.	Ultraviolet to middle wavelength visible	- 0.36 to 0.40 μm are most useful wavelengths for hydrocarbon detection, but 0.60 also has potential.
	Bendix TM/LN-2 and Bendix TM/LN-3 infrared line scanners.	4 - 5.5 μm and 8 - 14 μm respectively	- 8 - 14 μm imagery is much superior to 4 - 5.5 μm and is best of all imagery of authors under clear weather conditions.
	Fixed beam, dual polarized microwave radiometers.	Center frequencies of 10.2 GHz and 30 GHz respectively	- Microwave sensors have potential in oil spill detection as an all-weather back-up to other sensors, although microwave sensors can be confused by ships' wakes and sea conditions.

TABLE 5. SUMMARY OF SENSOR SYSTEM EVALUATION STUDIES - Continued

RESEARCHER	SENSOR SYSTEM	WAVELENGTH OR FREQUENCY	RESULTS
	Naval Research Laboratory four frequency dual polarized synthetic apetature radar.	P-band (428 MHz) L-band (1228 MHz) C-band (4455 MHz) X-band (8910 MHz)	- Reliable oil spill detection is possible over wide areas under adverse weather conditions, but there is difficulty in obtaining real-time processing.
Geraci and Caltabiano (1983)	Conventional 35 mm cameras, Kodak Wratten 12 filter, Kodak High Speed and Kodak Ektachrome Infrared Color films.	Photographic infrared from 0.7 to 0.9 μm	- Color infrared photographs can be digitized to determine area coverage of oil spills. - Both infrared photography and thermal infrared imagery are effective in identifying oil on water, but they must be used together to provide accurate data interpretation. - Neither method is capable of determining oil type or thickness.
	Airborne AGA Thermovision System.	Thermal infrared from 2.0 to 5.6 μm	
Goodman and Morrison (1985)	Monochrome LLLTV with a Corning 7-51 filter and polarizer.	Ultraviolet and photographic infrared	- Imagery was combined into a composite monitor image with red for IR, blue for UV and green for position imagery. - Essential oil spill areal information provided in a readily understood format in real-time.
	Barr and Stroud thermal imager.	8 - 14 μm	

TABLE 5. SUMMARY OF SENSOR SYSTEM EVALUATION STUDIES - Continued

RESEARCHER	SENSOR SYSTEM	WAVELENGTH OR FREQUENCY	RESULTS
	Conventional videos for positional and navigational information.	Visible spectrum	- Equipment portable, easily installed, low in maintenance and easy to operate.
Gordon et al. (United States, 1971b) and Munday et al. (1971)	Nine inch Fairchild T-11 cameras with a large variety of filter and film types.	Ultraviolet (0.32 - 0.40 μm) to infrared (0.72 - 0.80 μm)	- Good thin slick detection is provided by UV - blue band photography, thick slick by green band. - Red and photographic infrared bands are not useful for oil detection, but thermal infrared can detect oil. - Both photography and scanner data give good results; photography is cheaper, but scanner can be easily quantified.
	70 mm format cameras with a large variety of filter and film types.		
	Multispectral line scanners with 17 channels each.		
Horvath and Stewart (United States, 1971a)	Multispectral line scanner with 17 channels.	0.32 - 0.38 μm 0.45 - 0.47 μm 0.55 - 0.58 μm 9.3 - 11.7 μm	- Sun angle, hydrocarbon type, and slick thickness can vary the reflectance and thermal information recorded by different channels. - Oil type can not be distinguished by MSS instrumentation, but reflectance regions (UV to IR) define areal extent and, together with thermal data, can approximate spill thickness.

TABLE 5. SUMMARY OF SENSOR SYSTEM EVALUATION STUDIES - Continued

RESEARCHER	SENSOR SYSTEM	WAVELENGTH OR FREQUENCY	RESULTS
Lowe and Hasell (1969)	Multispectral line scanner with 12 channels.	Ultraviolet to thermal infrared	- Both ultraviolet and thermal infrared provide the best contrast against background seawater.
Martec Limited (Canada, 1985)	Hasselblad 500 EL/M, Kodak Wratten 18A filter, Kodak Tri-X Black and White film.	Ultraviolet	- Good results are achievable under adequate light conditions, but system is not capable of real-time operation or determination of oil type or thickness.
	Pentax ME-Super 35 mm, no filters, Kodacolor 200 and Ilford XP1.	Visible	- Visible photography is not as discriminating as UV.
	RCA Model TC1030H Low Light Level Television with a Corning 7-51 filter and horizontal polarizer.	Ultraviolet and near infrared	- Excellent oil-water discrimination results with overcast skies and calm waters. - This system has a wide field of view, is reliable and easy to use.
	Thermal Imaging Ltd. System 8020 Pyro-Electric Vidicon.	Thermal infrared (8 - 14 μm)	- Oil detection capabilities of unit are minimal.

TABLE 5. SUMMARY OF SENSOR SYSTEM EVALUATION STUDIES - Continued

RESEARCHER	SENSOR SYSTEM	WAVELENGTH OR FREQUENCY	RESULTS
	Barr and Stroud IR18 Thermal Infrared Imagery System.	Thermal infrared (8 - 14 μm)	- Oil can be detected, even under night conditions, but numerous false targets are recorded, the field of view is narrow and interpretation is difficult.
	Oilspills Sensor which measures spectral radiance from vapour cloud from slick rather than slick itself.	Thermal infrared (8 - 14 μm)	- This system produces virtually no useful data except under very special conditions of low wind and high evaporation.
Maughan <u>et</u> <u>al</u>. (1973)	An array of three Hasselblad 500EL 70mm cameras, Kodak Wratten 1A filter with Kodak Color SO-397, Kodak Wratten 12 filter with Kodak Aerochrome Color Infrared (2443) and no filter with Kodak Plus-X Panchromatic (2402).	Photographic spectrum	- Only positive color film (SO-397) with Wratten 1A filter can provide adequate imagery quality under less than optimum weather conditions such as cloud or haze.
Millard and Woolever (1973) and Millard <u>et</u> <u>al</u>. (1973)	Video camera with spectral and polarizing filtration.	Photographic spectrum	- Use of a Corning 7-51 filter (above 0.67 μm and below 0.42 μm) on an inexpensive conventional television camera with black and white monitor can greatly enhance detection of oil spills relative to the eye.

TABLE 5. SUMMARY OF SENSOR SYSTEM EVALUATION STUDIES - Continued

RESEARCHER	SENSOR SYSTEM	WAVELENGTH OR FREQUENCY	RESULTS
	Two video cameras with each viewing through a polarization filter oriented 90° to the other.	Photographic spectrum	- The two camera system can minimize the effects of sun glint when operating in a subtractive polarizing fashion.
Neville *et al.* (1979)	LLLTV with a horizontal polarizing filter and Corning 7-51 filter.		- High contrast, real-time dynamic imagery of oil spill possible under various sky conditions. - Night use limited when lights in image or day use in high sea states.
Reinheimer *et al.* (1973) and Rudder *et al.* (United States, 1972)	An array of four Hasselblad 500 EL/M 70mm cameras and a Zeiss RMK 1523 camera, a wide range of filters including Kodak Wratten 18A, 39C, 47B, 32, 35, 65, 75, 98 and 99, Kodak Tri-X Aerographic Black and White (2403), Kodak Ektachrome MS Aerographic Color (2248) and Kodak Aerochrome Color (2443) films.	Ultraviolet, visible and photographic infrared	- Multiband photographs together with color photographs are effective in oil spill detection. - Maximum image contrast enhancement of hydrocarbons is achieved with the following film/filter combinations: 2403/99 and 2403/32 (visible band), 2424/99 and 2424/32 (photographic infrared band).

TABLE 5. SUMMARY OF SENSOR SYSTEM EVALUATION STUDIES - Continued

RESEARCHER	SENSOR SYSTEM	WAVELENGTH OR FREQUENCY	RESULTS
Shimoda *et al.* (1975)	I^2S multi-band camera with infrared aerial films.	Visible to thermal infrared	- Color photography is suitable for determination of slick area, especially with few clouds and low winds. - Thermal images are effective for thick oil slicks only.
	Wild RC-8 aerial camera with color and black and white films.		
	Fujitsu thermal scanner.		
	Daedalus multispectral line scanner.		
Thaman *et al.* (1972)	A variety of cameras, filters and film types.	Ultraviolet to photographic infrared	- Black and white photography and/or scanner imagery give adequate areal information on spills; color films add little except cost. - Tonal variations, which can be representative of oil film thickness, are more easily identified on photographs. - Differential polarization can add contrast between oil and water.
	Ultraviolet scanner.	Ultraviolet	
	Nine channel black and white multispectral scanner.	Ultraviolet to infrared	

TABLE 5. SUMMARY OF SENSOR SYSTEM EVALUATION STUDIES - Continued

RESEARCHER	SENSOR SYSTEM	WAVELENGTH OR FREQUENCY	RESULTS
	Side-looking synthetic aperature radar.	Radar band	- Radar can be useful because of its all-weather, day-night capability, if sea state conditions are high enough to allow oil to have a detectible calming effect.
Thomson and McColl (Canada, 1972)	Vinten 70mm cameras with several film and filter types.	Ultraviolet, visible and photographic infrared	- The best film/filter combination for delineating oil slicks is Kodak Plus-X with Kodak Wratten 39. - The infrared line scanner is useful in oil detection only when there is a significant temperature difference between oil and water.
	Modified Reconofax infrared line scanner.	8 - 14 μm	
Vizy, (1974)	Leica M-3 35mm cameras, Kodak Wratten, 2B, 18A, 39, 89B filters in various combinations with Kodak Plus-X Aerographic Panchromatic Infrared (2424) and Kodak High Speed Ektachrome Color films.	Ultraviolet, visible and photographic infrared	- There is significant detection capability in the ultraviolet and blue bands, less in the infrared and almost none in the green and red. - Best film/filter combinations are either 2424 or 2402 film with either 18A or 39 filters. - Oil type can not be specifically determined, but it may be possible to show oil type differences when more than one type is present.
Worsfield et al. (1975)	Conventional daylight television and LLLTV.	Visible spectrum	- Useful for view of spill during flight and to aid flight line navigation and track recovery.

TABLE 5. SUMMARY OF SENSOR SYSTEM EVALUATION STUDIES - Continued

RESEARCHER	SENSOR SYSTEM	WAVELENGTH OR FREQUENCY	RESULTS
			- Sensitivity in blue and green makes it preferable to photography, yet inexpensive.
Yuanfu et al. (1982)	Color and multispectral camera systems.	Ultraviolet, visible, photographic and thermal infrared and microwave band	- Ultraviolet is best for detecting thin oil slicks, blue-green is next best, red for thick slicks and photographic infrared not very useful. - Color photography offers tonal differences relative to various oil conditions. - Highest contrast for multispectral photography is during overcast skies, but under no conditions can oil type or thickness be reliably determined. - Thermal infrared and microwave sensing can detect oil during both day and night.
	Thermal infrared scanner.		
	Scanning microwave radiometer.		
Zwick et al. (1981)	LLLTV with a polarizing filter and a spectral filter centered at 0.40 μm and 0.75 μm.	Visible spectrum	- Consistently high oil and water contrast for all oil types but no apparent variation for thickness.

3.2.1.1 **Photographic cameras and multispectral scanners.**

1. These sensors operate best with few clouds, little haze and low winds (Shimoda et al., 1975).
2. Photographic and scanner information both provide fair oil spill detection capability (Munday, 1971; United States, 1971b).
3. Good areal information can be provided by these sensors (Geraci and Caltabiano, 1983; Shimoda et al., 1975); color appears to provide little advantage over black and white (Thaman et al., 1972).
4. Differential polarization can increase oil and water contrast (Thaman et al., 1972).
5. Although limited by a lack of real-time capability, photographic cameras have the advantage of being generally less expensive than scanners (Munday et al., 1971; United States, 1971b).
6. The best film/filter combinations appear to be 2402/18A or 39, 2403/32 or 99, 2424/18A, 32, 39 or 99, and SO-397/1A (Vizy, 1974; Maughan et al., 1973; Reinheimer et al., 1973; Canada, 1972; United States, 1972). This is a wide assortment of film and filter types, but the most preferred bands amongst these appears to be the UV-blue and red (Appendix 2).

3.2.1.2 **Video systems.**

1. With a high level of radiometric resolution, video offers good contrast between oil and water in the photographic spectrum for

areal spill delineation (Canada, 1985; Zwick et al., 1981; Neville et al., 1979).

2. UV and red or IR bands together offer considerable oil/water contrast enhancement (Millard and Woolever, 1973; Millard et al., 1973).

3. Practical advantages of video systems include real-time viewing and recording, portability, ease of installation and operation, low cost, and use in flight line navigation and track recovery (Canada, 1985; Goodman and Morrison, 1985; Neville et al., 1979; Worsfield et al., 1975).

3.2.1.3 LLLTV.

1. Capable of detecting oil on water under night conditions, this sensor type also offers the advantages of real-time data presentation, wide field view and ease of use (Goodman and Morrison, 1985; Neville et al., 1979).

2. May be limited in night use when lights are in image or in day use in high sea states (Neville et al., 1979).

3. No apparent ability to detect thickness (Zwick et al., 1981).

3.2.1.4 Radar.

1. This sensor can detect oil under adverse weather conditions and at night by measuring backscatter differences between oiled and unoiled waters in moderate sea states, but is not capable of real-time processing or detection under calm or severe surface conditions (Thaman et al., 1972; Aukland et al., 1971; Catoe and Orthlieb, 1971; United States, 1970).

3.2.2 Spectral Bands.

3.2.2.1 Ultraviolet.

1. This band is consistently reported to optimize the contrast between oil and water, particularly with respect to thin slicks (Canada, 1985; Yuanfu et al., 1982; Vizy, 1974; Aukland et al., 1971; Catoe and Orthlieb, 1971; Munday et al., 1971; United States, 1971b; United States, 1970; Lowe and Hasell, 1969).

3.2.2.2 Visible.

1. The blue band near the ultraviolet has some capability for oil spill detection (Yuanfu et al., 1982; Vizy, 1974; Munday et al., 1971; United States, 1971b).
2. Some sources reported that the green band is useful for recording thick oil slicks (Munday et al., 1971; United States, 1971b), while another argued for the red band (Yuanfu et al., 1982). Vizy (1974) claimed neither was suitable.

3.2.2.3 Near or photographic infrared.

1. This band by itself has proven of little use in oil spill detection other than for the possible exception of low sun angle conditions (Yuanfu et al., 1982; Aukland et al., 1971; Catoe and Orthlieb, 1971; Munday et al., 1971; United States, 1971b; United States, 1970).

3.2.2.4 Thermal infrared.

1. While several authors report that this portion of the spectrum is suitable for oil spill identification (Yuanfu et al., 1982; Munday et al., 1971; United States, 1971b; Lowe and Hasell, 1969), certain caveats may apply. For example, some thermal sensors are much less effective than others, some image too many false targets (Canada, 1985) and some are only capable of detecting thick slicks in clear weather conditions (Shimoda et al., 1975).

3.2.2.5 Microwave.

1. This portion of the spectrum can be utilized by certain instruments as all-weather backup to other sensors, but existing microwave instrumentation can be confused by boat wakes or sea waves (Aukland et al., 1971; Catoe and Orthlieb, 1971; United States, 1970).

3.2.3 Oil Type.

- No sensor system is apparently capable of accurately identifying types of spilled oil (Canada, 1985; Geraci and Caltabiano, 1983; Yuanfu et al., 1982; Horvath and Stewart, 1971). However, it may be possible to show oil type differences when more than one oil type is present (Vizy, 1974).

3.2.4 Oil Thickness.

- There is reportedly limited potential for remote sensing techniques to identify oil spill thickness. Tonal variations in color photography may indicate thickness differences (Thaman et al., 1972) as might a combination of multispectral bands from ultraviolet to thermal (United States, 1971a).

These conclusions as derived from Table 5 are in agreement with similar summarizations by several other authors including Canada (1984b), Bogorodskii et al. (1975), Canada (1974), Catoe (1973), Estes et al. (1972) and Wobber (1971). Their reviews summarize sensor types and spectral bands, but provide no references from the literature.

3.3 Determination of Study Objective and Sensor System.

The preceding interpretation of Table 5 indicated that reliable areal delineation of oil spills was feasible with a variety of sensors and under a range of environmental conditions. Such was not the case with oil type or thickness. The literature was clear that oil type identification has not been achieved, but there is disagreement over whether spill thickness can be determined.

Canada (1985), Geraci and Caltabiano (1983), Zwick et al. (1981), Shimoda et al. (1975), Thaman et al. (1972) and United States (1971a) have indicated that oil thickness determination by remote sensing techniques is uncertain at best. However, within the visible spectrum, some success at oil thickness identification has been achieved according to Yuanfu et al. (1982), Munday et al. (1971) and United States (1971b) through use of the ultraviolet band for thin slicks and the red or green bands for thick slicks.

In an effort to resolve the matter, a series of tests and a field trial were undertaken in this study with the objective of determining whether oil spill thickness could be determined through selected filtration in the photographic spectrum. It was intended that these experiments examine several oil types and a range of sensor filters from the UV to IR in relation to spill thickness.

Imaging of oil spill thickness can be affected by oil type, optical conditions such as skylight and camera angle, and water conditions such as surface roughness and turbidity. Table 6 lists these conditions, rates their importance and describes how each was dealt with in this study. Owing to the reputed difficulty in accurately sensing oil thickness, most of these variables were eliminated or minimized in order to isolate filter type as the key thickness determinant.

With respect to sensor system selection, Table 5 interpretation suggests very practical reasons for choosing video: real-time viewing and recording, portability, ease of installation and operation and use in flight line navigation and track recovery. Its analog to digital characteristics allow rapid and accurate computer enhancement and analysis. Video also has satisfactory sensitivity in the blue and green bands for optimum use in light overcast conditions. The financial constraints of most emergency response organizations also argue strongly in favor of video because of its low cost. With these advantages, video consequently became the primary system of choice.

TABLE 6. CONDITIONS RELATED TO REMOTE SENSING OF OIL SPILL THICKNESS

CONDITIONS		IMPORTANCE	HOW DEALT WITH IN STUDY
Optical Conditions	Sunlight	Major	Near vertical sun angles tested.
	Skylight	Moderate	Testing done with overcast skies.
	Camera angle	Major	Look angle constant at vertical.
Oil Type	Crude oil Waste oil 10W30 oil Diesel oil Gasoline	Major	Each oil type separately imaged with a variety of filters.
Water Conditions	Surface roughness	Major	Sea state can greatly affect reflectivity; only calm conditions imaged.
	Turbidity	Major	Filtration in the red band tested.
	Marine vegetation	Moderate	This can be a factor near-shore; no nearshore areas imaged.
	Temperature Salinity Dissolved oxygen	Minor	These are not of sufficient importance to influence results.

CHAPTER 4. METHOD DEVELOPMENT AND CONTROLLED TESTS

Commencing in the summer of 1986, a series of controlled experiments were carried out to test the hypothesis that selected video filtration can determine relative spill thickness. These initial experiments were controlled to limit the variables affecting the optical-thickness relationship. For example, environmental conditions such as surface roughness and turbidity could be eliminated, while appropriate weather conditions could be used when they became available. In addition, the experiments permitted selective testing of various video cameras and filters prior to actual field use.

The controlled tests progressively improved on one another until a reliable data set was acquired. Data were collected for each experiment in the series, but digital data compilation and analysis were completed only for the final test.

4.1 Method of Data Collection

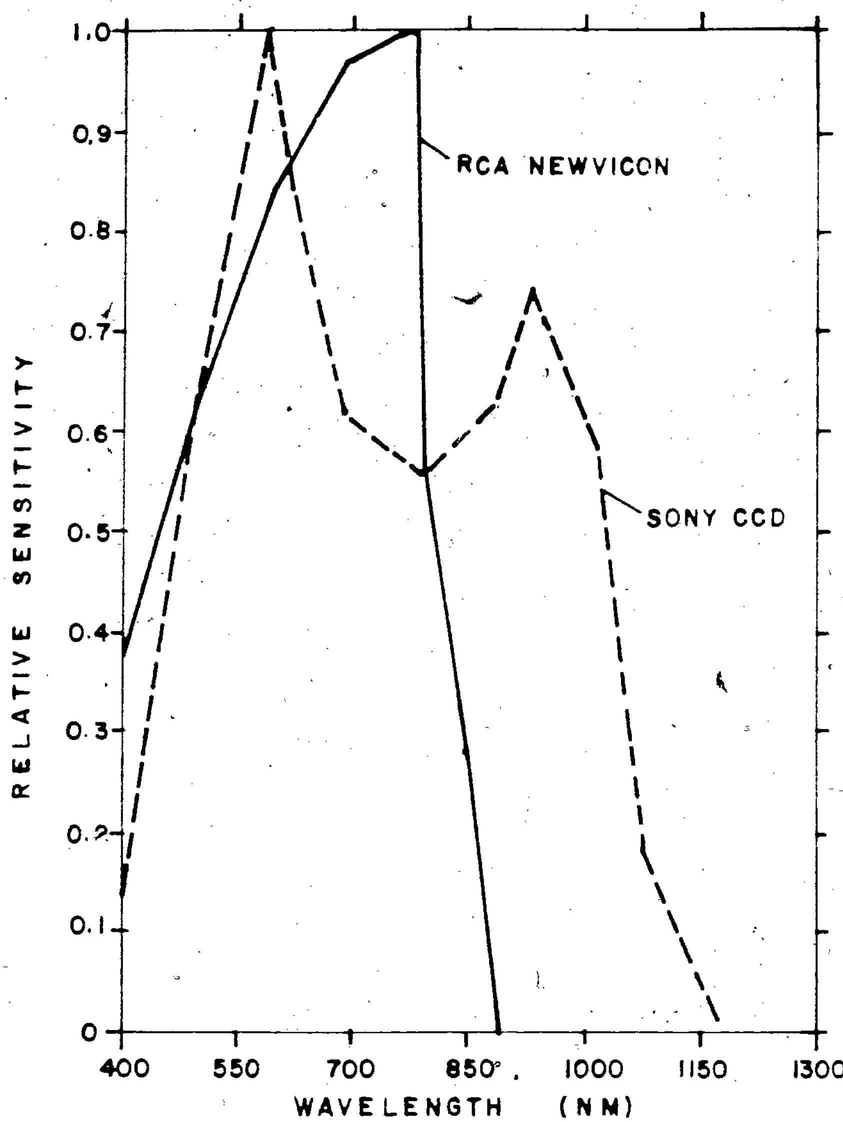
4.1.1 Pilot Test.

On 15 August 1986, a pilot test was undertaken at Simon Fraser University for a brief simplified look at whether thickness differences could be observed. Sixteen ten-liter white buckets were filled with freshwater. Fifteen of these were introduced with varying quantities (one drop to 500 ml) of waste oil, diesel oil and gasoline. The other was left with only freshwater as a control (Figure 8). A Sony CCD video camera with a spectral sensitivity from the UV to the IR (Figure 9) was utilized to image the cluster of buckets under both direct sunlight and full shade

FIGURE 8. ARRANGEMENT OF PILOT TEST BUCKETS, SIMON FRASER UNIVERSITY REMOTE SENSING LABORATORY, 15 AUGUST 1986

Note: This 35 mm photograph shows shadow and sun lit areas in the white buckets. The video imagery used for evaluation purposes in the test was collected under full sun conditions initially and then under full shade conditions to limit exposure problems from sun-shade contrast.

FIGURE 9. SPECTRAL SENSITIVITY OF THE RCA NEWVICON AND SONY CCD VIDEO CAMERAS



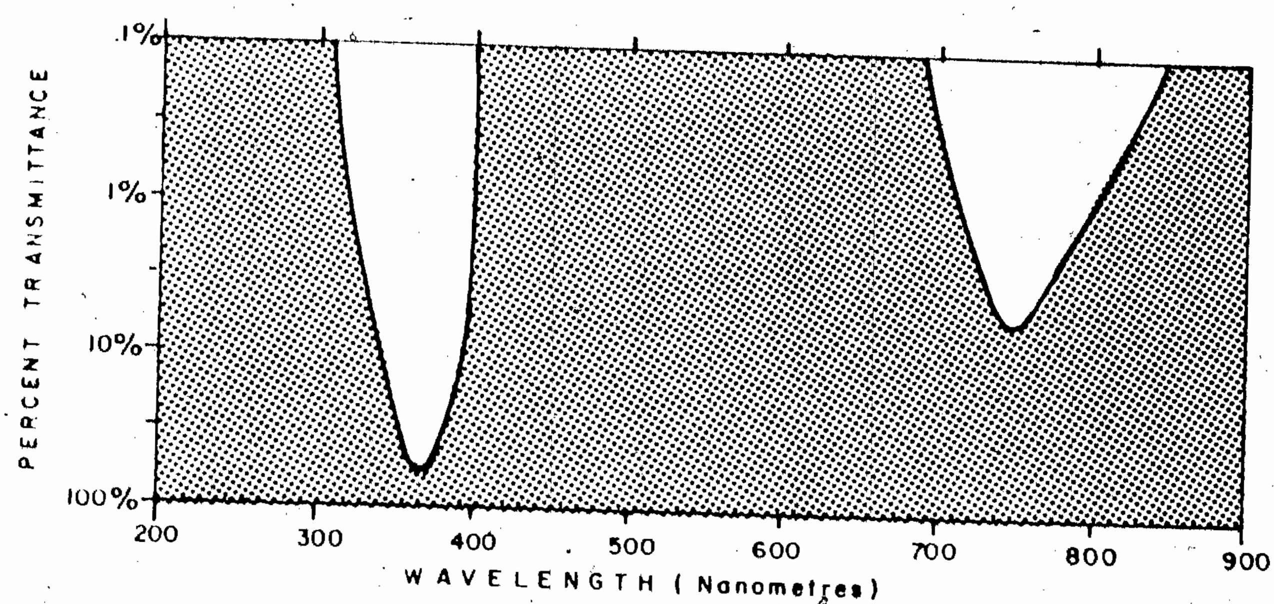
SOURCE: Roberts, A., and D.J. Evans, 1986:732

conditions. Six different filter types (18A, 88A, 400nm, 450nm, 500nm and 600nm) were separately mounted in front of the camera lens to provide specific wavelength coverage within the photographic spectrum. The transmittance characteristics of the 18A glass filter is shown in Figure 10 by way of example. Appendix 3 shows the transmittance ranges of all of the filters used in the pilot test.

The resulting recorded imagery was displayed on a monochrome monitor in the lab and examined visually without enhancement. No digital or statistical analyses were undertaken. At this simple level of examination, the test succeeded in demonstrating that it was possible to visually discriminate amongst thick layers (greater than 100 μm) and oil types such as crude oil and gasoline, but not amongst thinner layers (less than 100 μm). However, it was considered a possibility that digital enhancement and analysis would be able to either provide this discrimination and/or set discrimination limits for thinner layers. One potential cause of the poor thin layer discrimination was the translucence and white color of the buckets which would have significantly increased light levels (albedo) from bottom reflectance. In the "thin layer" buckets this would have added to the non-oil reflectance and masked the weaker oil reflectance. A second test was therefore planned to eliminate this background albedo problem.

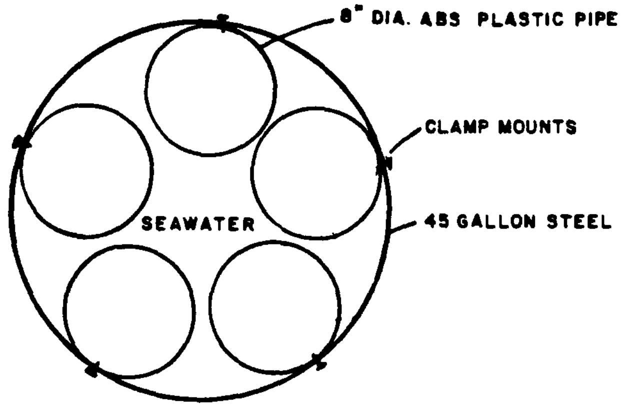
4.1.2 **Shellburn Refinery Test.** Arrangements were made with Shellburn Refinery, Burnaby, B.C., for use of its dock and foreshore for the second test in the series. In each of five 45 gallon drums donated by Shell Canada Limited, five eight-inch diameter ABS plastic pipe cylinders one foot in length were clamped vertically (Figure 11). A sixth 45 gallon drum was to be

FIGURE 10. TRANSMITTANCE SIGNATURE OF 18A GLASS FILTER

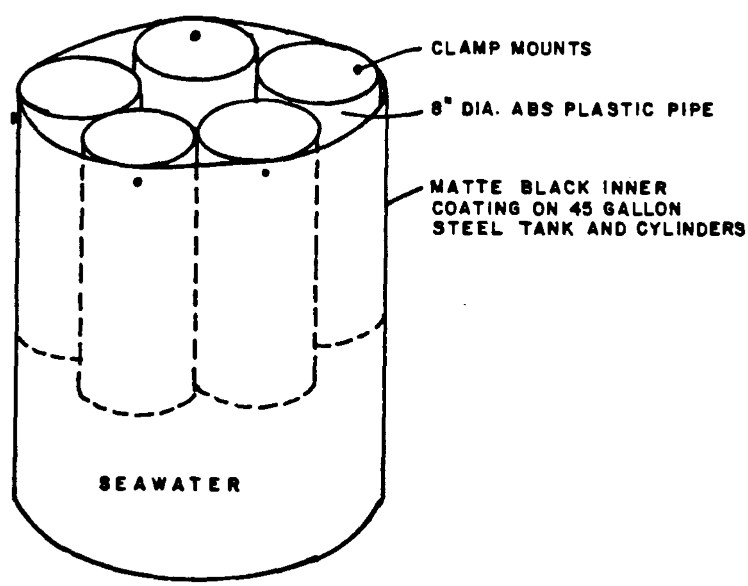


SOURCE: Eastman Kodak Company, 1970: 63

FIGURE 11. DESIGN OF PIPE CYLINDERS IN 45 GALLON DRUM



TOP PLAN



OBLIQUE CUTAWAY VIEW

used as a control and therefore had nc clamped cylinders. All of the cylinders and the interior of every drum was painted matte black to reduce the background albedo.

The six drums were positioned in an exposed area adjacent to the Shellburn dock where seawater was pumped to within two inches of the top of each drum. Diesel oil, gasoline, bunker fuel, waste oil and crude oil were each introduced into different drums in five quantities ranging from 0.0324 cc to 32.4 cc (Figures 12 and 13).

The quantities of hydrocarbon placed in the cylinders in each drum were originally intended to simulate five different thicknesses ranging from 1 to 10000 μm. Unfortunately pooling of the smaller hydrocarbon quantities (when the entire surface within each cylinder was not covered) resulted in some uncertainty as to exact thin layer thicknesses. Calculations of quantities for the purpose of representating thicknesses were as follows:

Inside area of each cylinder $= \pi r^2 = 3.1416\ (10.16\ \text{cm})^2 = 324\ \text{cm}^2$

If $1\ \mu\text{m} = 0.001\ \text{mm}$, then $10000\ \mu\text{m} = 10\ \text{mm} = 1\ \text{cm}$

Therefore, to cover an area of $324\ \text{cm}^2$ to a thickness of $10000\ \mu\text{m}$, 324 cc ($324\ \text{cm}^2 \times 1\ \text{cm}$) were required.

Corresponding thicknesses for other cylinders were:

1000 μm - 32.4 cc

100 μm - 3.24 cc

10 μm - 0.324 cc

1 μm - 0.0324 cc

Imaging was done under sun and shade conditions with a Sony CCD video camera set on a pedestal mount beside the Shellburn dock approximately

FIGURE 12. SCHEMATIC OF 45 GALLON DRUM LAYOUT, SHELLBURN REFINERY TEST, 15 SEPTEMBER 1986

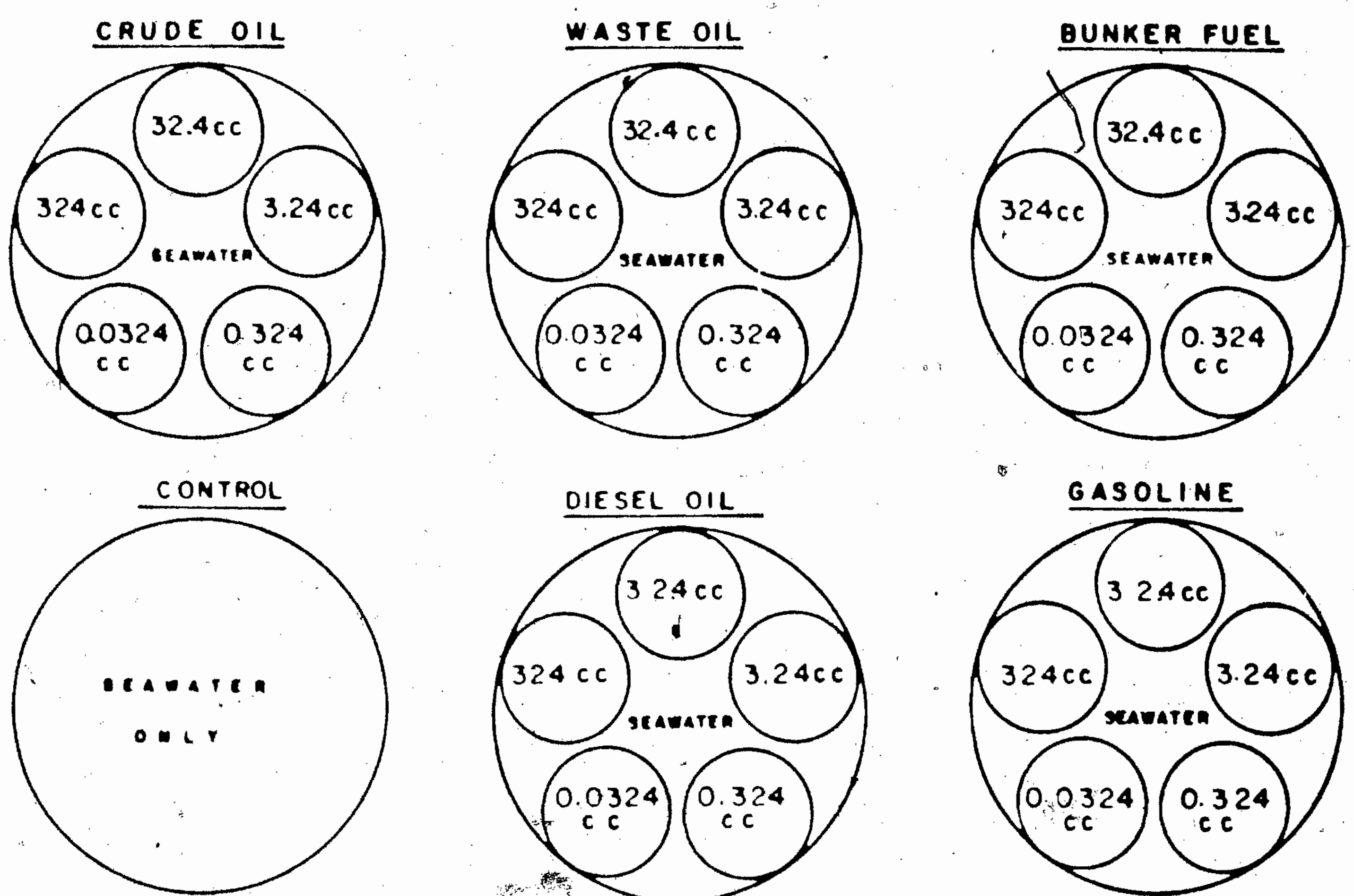


FIGURE 13. ARRANGEMENT OF 45 GALLON DRUMS, SHELLBURN REFINERY TEST, 15 SEPTEMBER 1986

above the drums positioned on the foreshore. Filters used in the test were 18A, 87B, 88A, 450nm, 550nm and 650nm (Appendix 3).

On visually reviewing the video imagery later on a monochrome monitor, it was discovered that, although some variations in oil type and thickness were discernable, too large an area appeared in each image. This meant that individual cylinders were too small for proper viewing or digitizing. In addition, the non-vertical sun angle caused direct sun and deep shade contrasts in the drums which resulted in a too wide exposure range that made accurate reflectivity measurements very difficult. Consequently, it was necessary to design a third and final controlled test.

4.1.3 Final Controlled Test. The setup for the final controlled test (05 October 1986) at Simon Fraser University was similar to the Shellburn Refinery test except that the drums were positioned in a straight line and imaged individually from a near vertical position. The water control was in the centre of each drum between cylinders rather than in a separate drum. Hydrocarbon types were crude oil, waste oil, 10W30 oil, diesel oil and gasoline. Hydrocarbon quantities were again 0.0324 cc to 324 cc to represent thicknesses ranging by order of magnitude between one and 10000 μm (micrometers or microns). However, pooling of the smaller quantities (0.0324 - 3.24 cc) made accurate determination of these thicknesses impossible.

The camera setup was identical to that of the pilot test except that an RCA Newvicon rather than a Sony CCD video camera was used. Filtration included no filter, 18A, 88A, 650nm, 550nm, 450nm, 301A/92 combination, 50 and 301A/46 combination (Appendix 3). (No filter implied full transmittance throughout the photographic spectrum according to the spectral sensitivity of the camera - Figure 9.) A ten-second duration hydrocarbon image and a separate five-second labelled image were recorded on a Sony 8mm video cassette recorder (VCR) for each hydrocarbon type under both direct sun and full shade conditions.

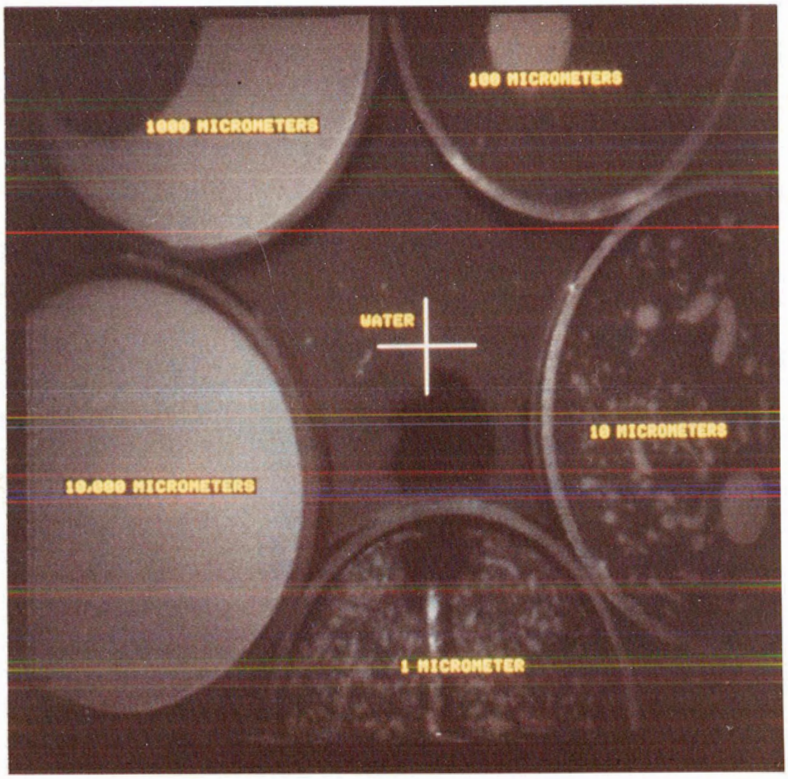
4.2 **Data Compilation**

The imagery acquired in the final controlled test was first examined for completeness and clarity. The five-second labelled images preceding the ten-second hydrocarbon images were used to identify tape counter readings on the VCR for each filter for each hydrocarbon for sun and shade conditions. Within each ten-second hydrocarbon image interval (approximately 300 video frames), the clearest portion was selected for digitization.

Digitization was carried out on the Simon Fraser University VAX 11/750 IIS image analysis system using a waveform monitor and time base corrector. The latter two pieces of hardware were included in the system to adjust the peak voltage for each image to ensure proper exposure and to provide image synchronization for the video digitizer in the analysis system. An example of a digitized image of diesel oil using a 301A/46 combination filter under full shade conditions and varying thicknesses is provided in Figure 14.

Following digitization, the individual image frames were visually examined. It was noticed that a number of direct sun condition images were overexposed or degraded because of overvoltage flare from specular reflectance. Final analyses for this controlled test were therefore

FIGURE 14. EXAMPLE OF A DIGITIZED IMAGE - DIESEL OIL, 301A/46 COMBINATION FILTER, SHADE - SHOWING NOMINAL THICKNESSES FROM 1 MICRON TO 10000 MICRONS



restricted to shade conditions only, because of the difficulty of dealing with these distorted high contrast images.

Using the IIS System 500 software (International Imaging Systems Inc., 1980), several data examination procedures were run on each image. Profiles and graphs of radiometric values, as illustrated in Figure 15, were first used for selected target reflectance cross-sections to determine if digital brightness levels (also known as reflectivity or grey levels) increased in relation to hydrocarbon quantity (i.e., approximate thickness). This appeared to be the case, so another software routine (blotch) was used to measure grey levels in designated areas or blotches.

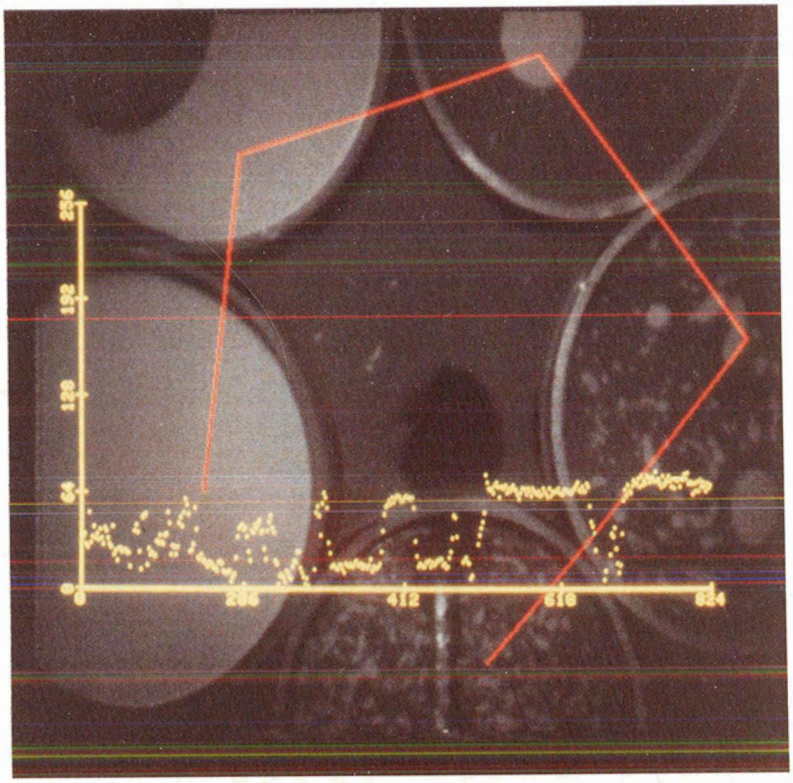
Finally, for each selected target area, each pixel was individually examined to record pixel-specific grey level values (8 bit resolution: 0-256 levels).

In each image for each quantity (or approximate thickness), 12 grey level points were sampled and averaged across the slick area. An adjacent water area was also sampled 12 times, averaged and subtracted from the hydrocarbon mean grey level to reduce any bias caused by radiometric camera lens distortions such as light fall-off. The resulting values were defined as adjusted mean grey levels (or reflectivity levels) and were recorded by hydrocarbon type and filter type (Table 7). These data provided the basis for subsequent statistical calculations.

4.3 Data Analysis and Interpretation

The data compilation in Table 7 was graphed by hydrocarbon type using STATPRO software (Penton Software Inc., 1985) on an IBM-AT microcomputer (Figures 16-20). In all five graphs there appeared to be an

FIGURE 15. EXAMPLE OF A PROFILED AND GRAPHED IMAGE - DIESEL OIL, 301A/46 COMBINATION FILTER, SHADE



X-axis: Number of pixels along selected red profile
Y-axis: Reflectivity or grey level where
0 = full darkness and
256 = full brightness

TABLE 7. HYDROCARBON THICKNESS AND ADJUSTED MEAN GREY LEVEL BY HYDROCARBON TYPE AND FILTER TYPE IN SHADE CONDITIONS IN FINAL CONTROLLED TEST

HYDROCARBON TYPE	OIL THICKNESS (μm)	ADJUSTED MEAN GREY LEVEL BY FILTER TYPE								
		No Filter	18A	88A	650nm	550nm	450nm	301A/92	50	301A/46
CRUDE OIL	1	31	11	13	22	28	36	8	10	29
	10	32	12	17	23	35	43	11	12	33
	100	39	14	28	26	40	46	11	14	36
	1000	41	17	33	27	41	48	11	15	37
	10000	42	*	34	27	41	49	9	15	37
WASTE OIL	1	32	5	44	16	23	25	13	26	24
	10	33	13	45	21	27	34	20	27	24
	100	35	17	47	22	30	36	21	27	25
	1000	41	14	48	23	35	37	21	27	29
	10000	42	18	48	22	36	41	22	21	30
10W30 OIL	1	28	18	25	26	22	32	21	20	11
	10	46	23	28	30	49	48	23	28	22
	100	53	28	47	35	59	49	30	34	35
	1000	53	29	49	37	60	49	37	34	35
	10000	44	26	49	37	51	40	37	34	32
DIESEL OIL	1	40	7	32	28	34	35	14	14	23
	10	42	7	36	30	37	44	15	18	30
	100	44	8	43	37	*	50	21	29	39
	1000	48	10	50	43	47	51	22	30	39
	10000	50	14	51	45	50	52	22	30	41
GASOLINE	1	35	22	11	13	18	20	7	5	2
	10	39	24	12	23	24	30	8	*	5
	100	45	40	14	38	43	44	25	27	42
	1000	49	57	18	45	45	45	32	28	44
	10000	51	59	29	46	45	44	33	28	42

* Missing datum

FIGURE 16. PLOT OF ADJUSTED MEAN GREY LEVEL VERSUS HYDROCARBON THICKNESS BY FILTER TYPE FOR CRUDE OIL

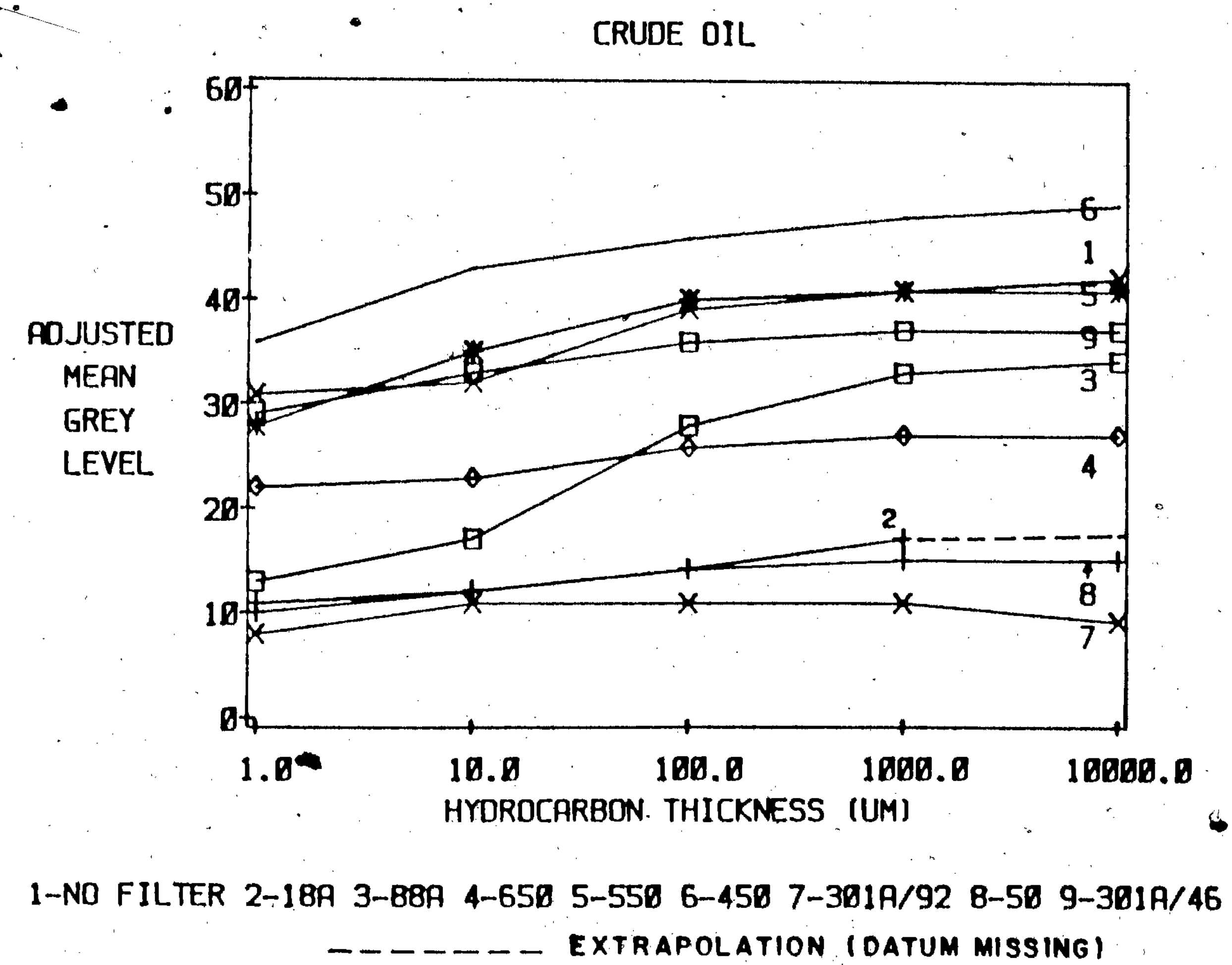


FIGURE 17. PLOT OF ADJUSTED MEAN GREY LEVEL VERSUS HYDROCARBON THICKNESS BY FILTER TYPE FOR WASTE OIL

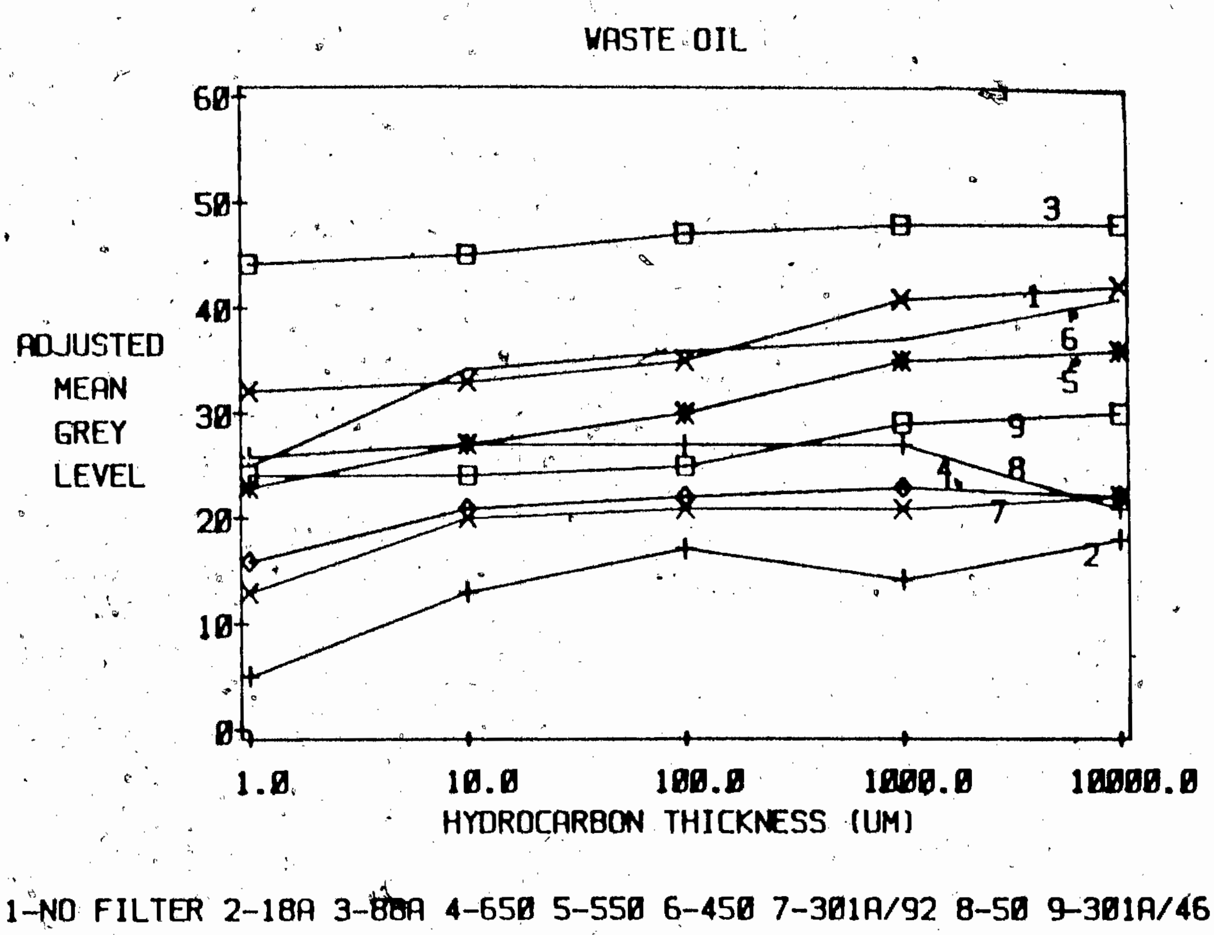
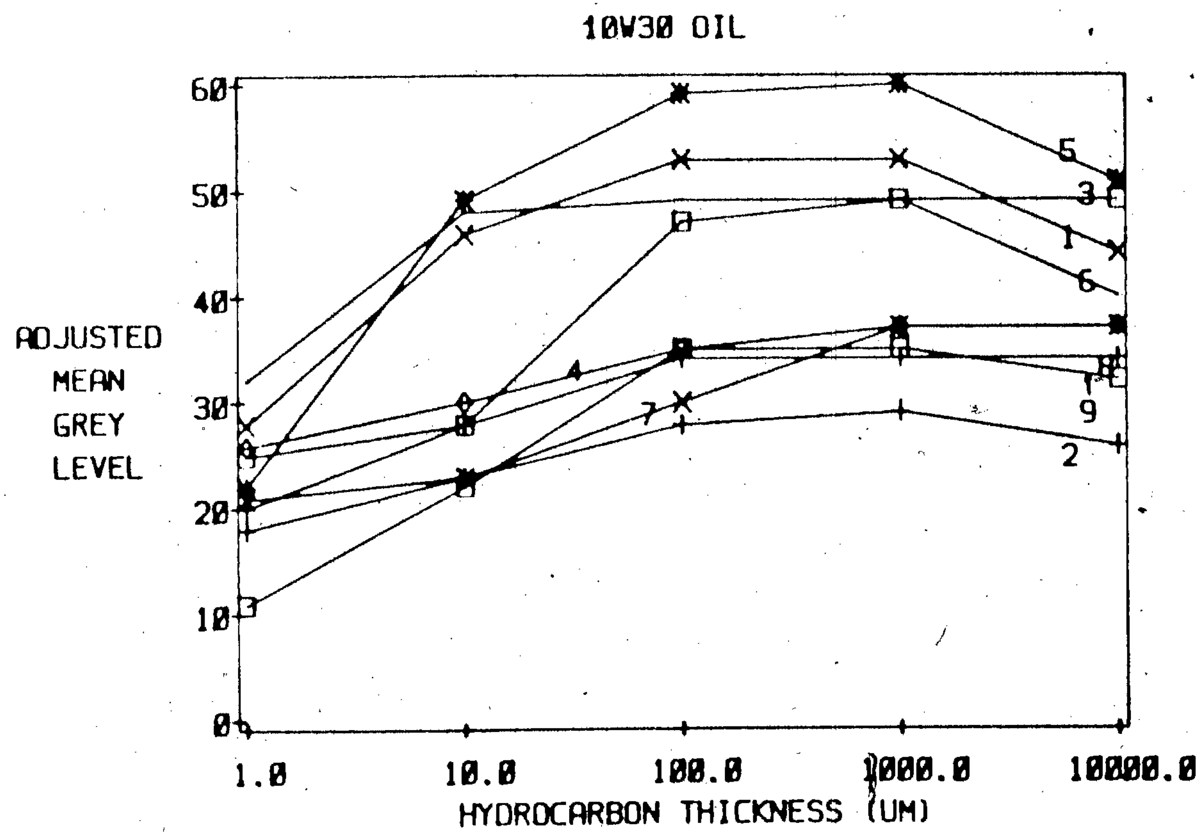
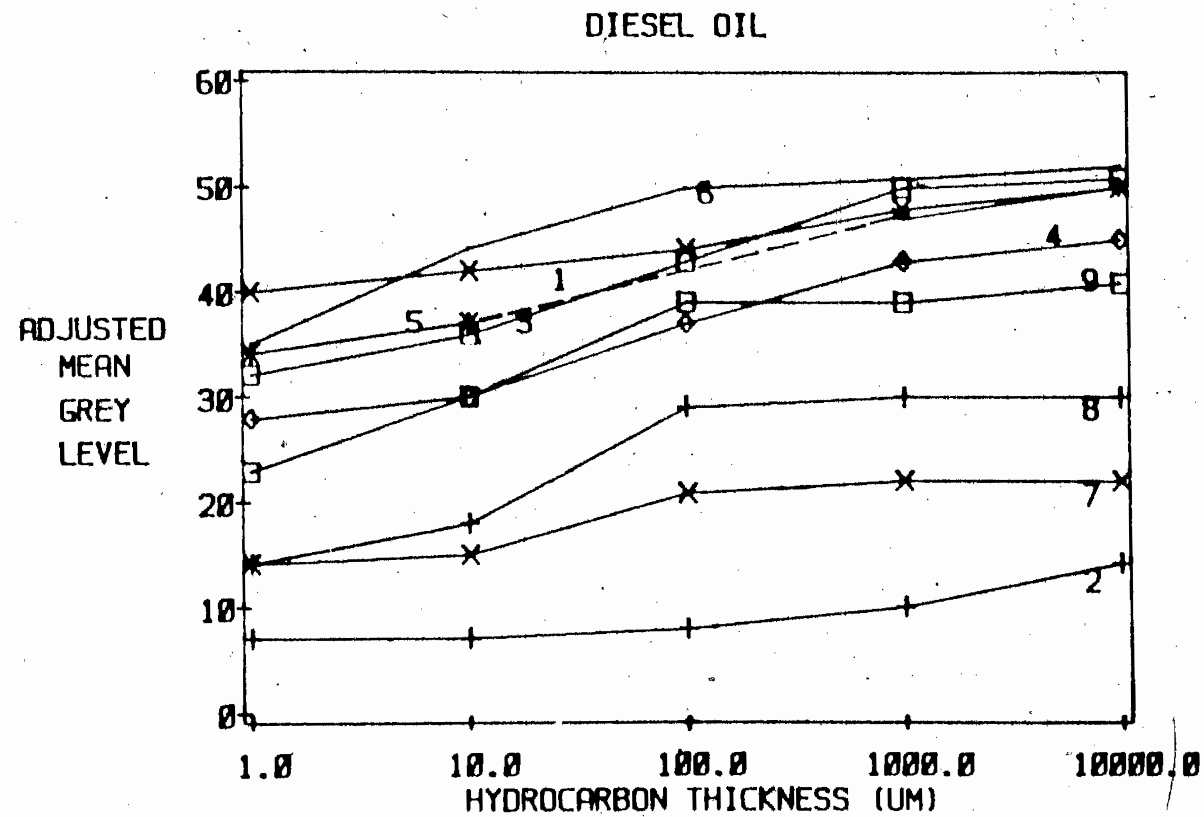


FIGURE 18. PLOT OF ADJUSTED MEAN GREY LEVEL VERSUS HYDROCARBON THICKNESS BY FILTER TYPE FOR 10W30 OIL



1-NO FILTER 2-18A 3-88A 4-650 5-550 6-450 7-301A/92 8-50 9-301A/46

FIGURE 19. PLOT OF ADJUSTED MEAN GREY LEVEL VERSUS HYDROCARBON THICKNESS BY FILTER TYPE FOR DIESEL OIL

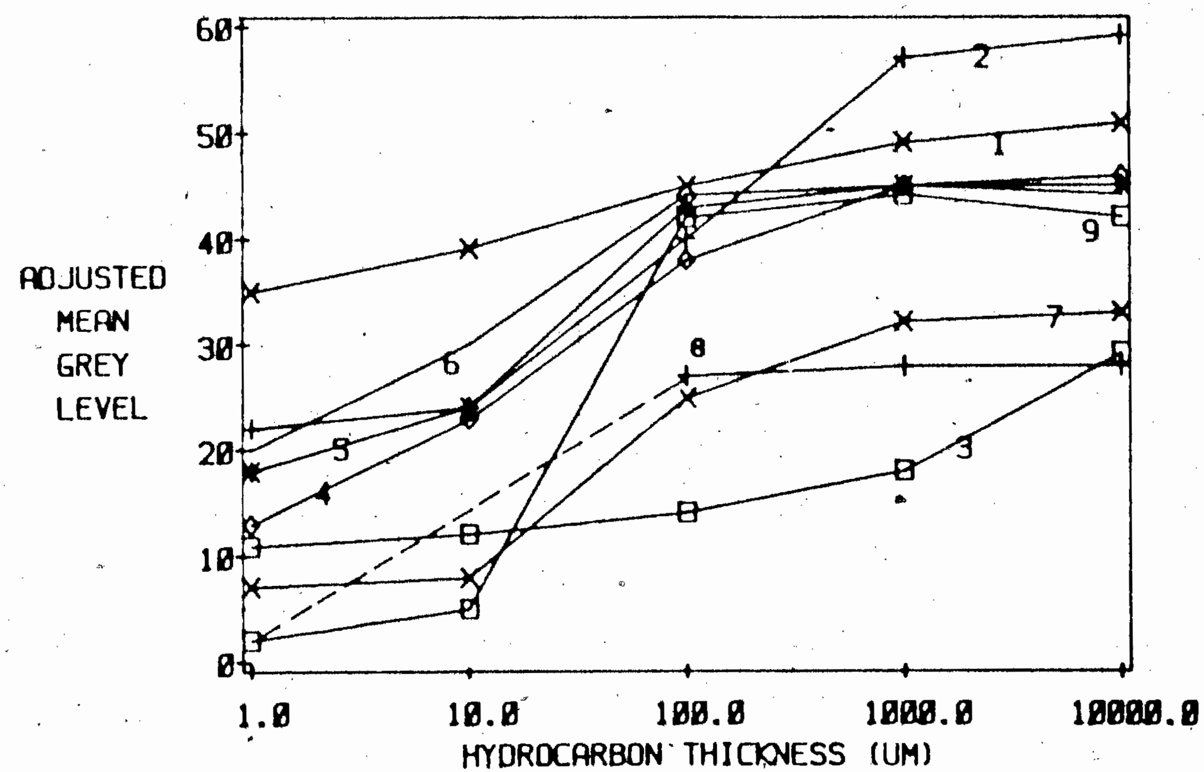


1-NO FILTER 2-18A 3-88A 4-650 5-550 6-450 7-301A/92 8-50 9-301A/46

------- INTERPOLATION (DATUM MISSING)

FIGURE 20. PLOT OF ADJUSTED MEAN GREY LEVEL VERSUS HYDROCARBON THICKNESS BY FILTER TYPE FOR GASOLINE

GASOLINE



1-NO FILTER 2-18A 3-88A 4-650 5-550 6-450 7-301A/92 8-50 9-301A/46

------ INTERPOLATION (DATUM MISSING)

increase in adjusted mean grey level (or reflectivity level) with an increase in hydrocarbon quantity or approximate thickness up to 1000 microns. However, the adjusted mean grey level between 1000 and 10000 microns did not follow this trend. Instead, values (line slopes) over 1000 microns were more or less neutral with no general positive trend apparent.

Analyzed by hydrocarbon type, line slopes between 1 and 1000 microns appeared steeper for the translucent hydrocarbons such as 10W30 oil, diesel oil and gasoline. In the more opaque crude and waste oils, they did not show as much reflectance differential. This could have been a consequence of a lower capacity of the crude and waste oils to permit passage through them of internally reflected light within the cylinders and therefore these curves "flattened out" sooner.

There was also a relatively consistent pattern in adjusted mean grey levels for different filter types. For example, the 18A filter usually had the lowest of overall grey levels, while the 650nm and "no filter" filters demonstrated relatively higher adjusted mean grey levels. This was a function of exposure levels (voltage) within the camera; these levels were a function of the transmission characteristics of each filter and the spectral sensitivity of the camera as well as f-stop and light level.

A series of statistical analyses were also carried out on the data in Table 7 using SHAZAM (White, 1984) software on a Callan Unistar microcomputer. The first analysis was a combined filter multiple regression for each hydrocarbon type in which oil thickness was set as the independent variable and each grey level set as the dependent variable. Resulting regression slope, T-ratio and R^2 values for both linear and logarithmic series are presented in Table 8. These values clearly showed the

TABLE 8. RESULTS OF LINEAR AND LOGARITHMIC COMBINED REGRESSIONS OF FINAL CONTROLLED TEST DATA BY HYDROCARBON TYPE

HYDROCARBON TYPF	NUMBER OF OBSERVATIONS	OUTPUT FROM LINEAR REGRESSION			OUTPUT FROM LOGARITHMIC REGRESSION		
		REGRESSION SLOPE	T-RATIO	R^2	REGRESSION SLOPE	T-RATIO	R^2
CRUDE OIL	44	0.48084E-03	2.9883	0.9186	0.99632	8.0961	0.9649
WASTE OIL	45	0.41947E-03	2.9467	0.8952	0.84446	6.6697	0.9424
10W30 OIL	45	0.52555E-03	1.4952	0.5131	1.8337	6.0083	0.7450
DIESEL OIL	44	0.88683E-03	4.2935	0.8793	1.6262	12.794	0.9680
GASOLINE	44	0.16226E-02	3.5918	0.5250	3.2493	10.445	0.8443

Notes: The independent variables are hydrocarbon thickness (μm), eight dummy variables and a constant; the dependent variable is adjusted mean grey level.

Logarithmic regression refers to the linear dependent variable (adjusted mean grey level) regressed against the natural logarithm of thickness.

Regression slope is the estimated coefficient for thickness.

T-ratio = (regression slope)/(standard error).

relationship of adjusted mean grey level to hydrocarbon thickness to be logarithmic rather than linear. Logarithmic regression slopes implied a distinct trend of increasing albedo or grey level with increasing thickness, supporting the study hypothesis that video imagery can detect differences in spill thickness. T-ratios for the logarithmic regressions were also consistently higher, indicating a greater degree of significance than for the linear, while R^2 values demonstrated that the logarithmic regressions had a better overall fit than the linear estimations. Logarithmic regression slopes for the lighter hydrocarbons, 10W30 oil, diesel oil and gasoline, were steeper than for crude or waste oil, confirming a similar observation noted earlier in relation to Figures 16 - 20. The coefficients of the logarithmic regressions all exhibited a high statistical significance. Standard errors and f-statistics from the SHAZAM output also were examined; in all cases the f-statistics indicated significance of the equations as a whole.

The second analysis applied to Table 7 data was a logarithmic multiple regression of adjusted mean grey level against hydrocarbon thickness by hydrocarbon type and filter type (Table 9). In each case, the adjusted mean grey level of a particular filter was set as the dependent variable and oil thickness as the independent variable. In terms of regression slope, T-ratio and R^2 values, Table 9 confirms the earlier observation that discrimination of hydrocarbon thickness by video imagery was greater for lighter hydrocarbons than for the more opaque crude and waste oils. Filters with the most meaningful and consistent values for regression slope, T-ratio and R^2 were "no filter", 88A, 550nm, 450nm and 301A/46 respectively. This was particularly so for diesel oil and gasoline. It should be noted though that the lens used with the 18A glass filter resulted in underexposures and

TABLE 9. RESULTS OF LOGARITHMIC MULTIPLE REGRESSIONS OF ADJUSTED MEAN GREY LEVELS AGAINST HYDROCARBON THICKNESSES BY HYDROCARBON TYPE AND FILTER TYPE FOR FINAL CONTROLLED TEST DATA

HYDRO-CARBON TYPE	TYPE OF OUTPUT	FILTER TYPE								
		NO FILTER	18A	88A	650nm	550nm	450nm	301A/92	50	301A/46
CRUDE OIL	REGRESSION SLOPE	1.1292	0.63867E-01	1.7372	0.86859E-01	0.69487	3.7784	-0.86859E-01	-1.0857	0.56458
	T-RATIO	13.000	0.81850E-01	3.0739	0.28868	3.1789	2.2466	-0.65465	-1.2322	2.7107
	R^2	0.9826	0.0022	0.7590	0.0270	0.7711	0.6272	0.1250	0.3360	0.7860
WASTE OIL	REGRESSION SLOPE	1.2160	1.1726	0.47772	0.60801	1.4766	1.5200	0.82516	-0.43429	0.7383
	T-RATIO	5.8812	2.6021	5.7446	2.2913	10.410	4.4331	2.5166	-1.3207	4.4903
	R^2	0.9202	0.6930	0.9167	0.6364	0.9731	0.8676	0.6786	0.3676	0.8705
10W30 OIL	REGRESSION SLOPE	1.6937	0.95545	2.9966	1.2595	2.9966	0.7383	1.9978	1.4766	2.3886
	T-RATIO	1.3080	2.1855	3.7220	5.0483	1.7346	0.66458	6.3791	3.0867	2.6270
	R^2	0.3632	0.6142	0.8220	0.8947	0.5007	0.1283	0.9313	0.7605	0.6970
DIESEL OIL	REGRESSION SLOPE	1.1292	0.73830	2.2583	2.0412	1.8240	1.7806	0.9988	1.9109	1.9543
	T-RATIO	13.0	3.8334	8.6667	8.9355	14.849	3.9033	4.0038	3.8492	4.3102
	R^2	0.9826	0.8305	0.9616	0.9638	0.9910	0.8355	0.8424	0.8316	0.8610
GASO-LINE	REGRESSION SLOPE	1.8240	4.6470	1.8240	3.8218	3.2572	2.7361	3.3006	2.5810	5.1681
	T-RATIO	10.967	6.3831	3.7123	6.0439	3.8903	3.4116	5.0332	2.8337	3.1363
	R^2	0.9757	0.9314	0.8212	0.9241	0.8346	0.7951	0.8941	0.8006	0.7663

Note: All values are based on five observations except for crude oil/18A, diesel oil/550nm and gasoline/Wratten 50 for which data were missing.

that a gelatin filter or lens with a larger aperature would have provided better results as would have gain control adjustments within the video camera itself.

In summary, analysis of the final controlled test data showed that video imagery with selected filtration could provide order of magnitude comparisons of hydrocarbon thicknesses up to 1000 microns (1 mm) based on reflectance measurements. Thicknesses greater than 1000 microns showed no discernable increase in reflectance values. The ability of video systems to discriminate relative oil thicknesses appeared to be greater for translucent hydrocarbons such as 10W30 oil, diesel oil and gasoline in contrast to crude or waste oils. For these lighter hydrocarbons, filters which appeared to provide the greatest reflectance differences, as defined by regression slope, T-ratio and R^2, were "no filter", 88A, 550nm, 450nm and 301A/46.

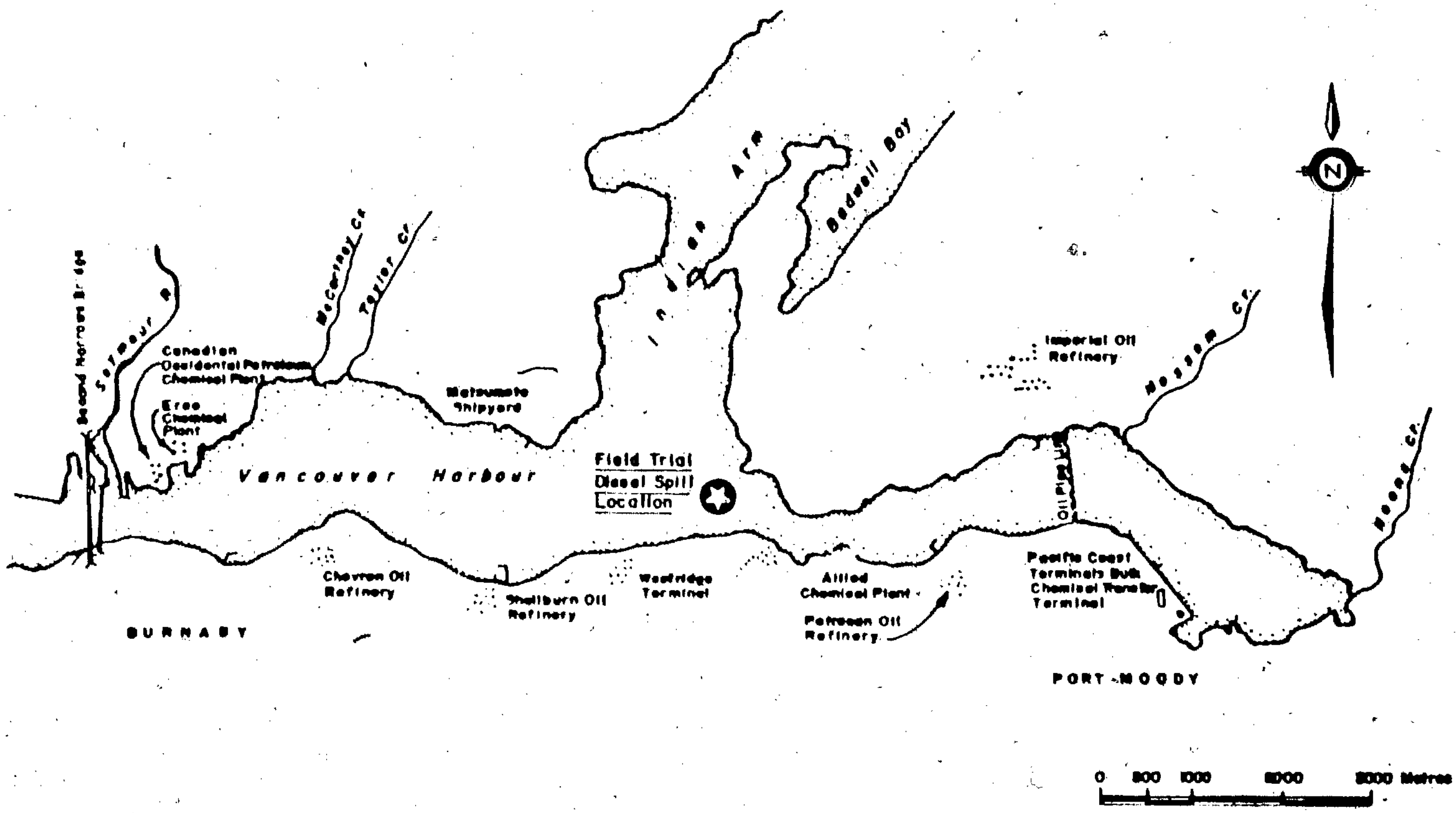
CHAPTER 5. FIELD TRIAL

One of the problems encountered in the controlled test situation was "pooling" of the hydrocarbons on the surface of the cylinders. A field trial was therefore planned to provide a large surface area to reduce this difficulty. The field trial also offered an opportuntity to investigate the effects of certain environmental parameters as well as to test the remote sensing equipment under operational conditions.

5.1 Method of Data Collection

The study area identified for field testing of the results acquired from the controlled tests was in Burrard Inlet (Figure 21). This area was selected because of its usually calm, clear waters, its proximity to an airport and cleanup equipment depot, and its concentration of potential oil spill sources including freighter anchorages, four refineries, three chemical plants and some chemical transfer terminals. Environmental Protection Service (EPS) records (Canada, 1986d) indicated that seven medium-sized oil spills occurred in Burrard Inlet in 1985, approximately one every two months. With this frequency it was originally anticipated that a convenient spill of opportunity would be likely for undertaking a field trial. Environmental Emergencies Branch of EPS agreed to provide notification in the event of any medium-sized spill in Burrard Inlet and, as well, several aircraft spill searches were made. Between October 1986 and early March 1987, only one spill of sufficient size occurred in the area. Unfortunately, the remote sensing aircraft to be used in the study was under repair at the time.

FIGURE 21. FIELD TRIAL STUDY AREA

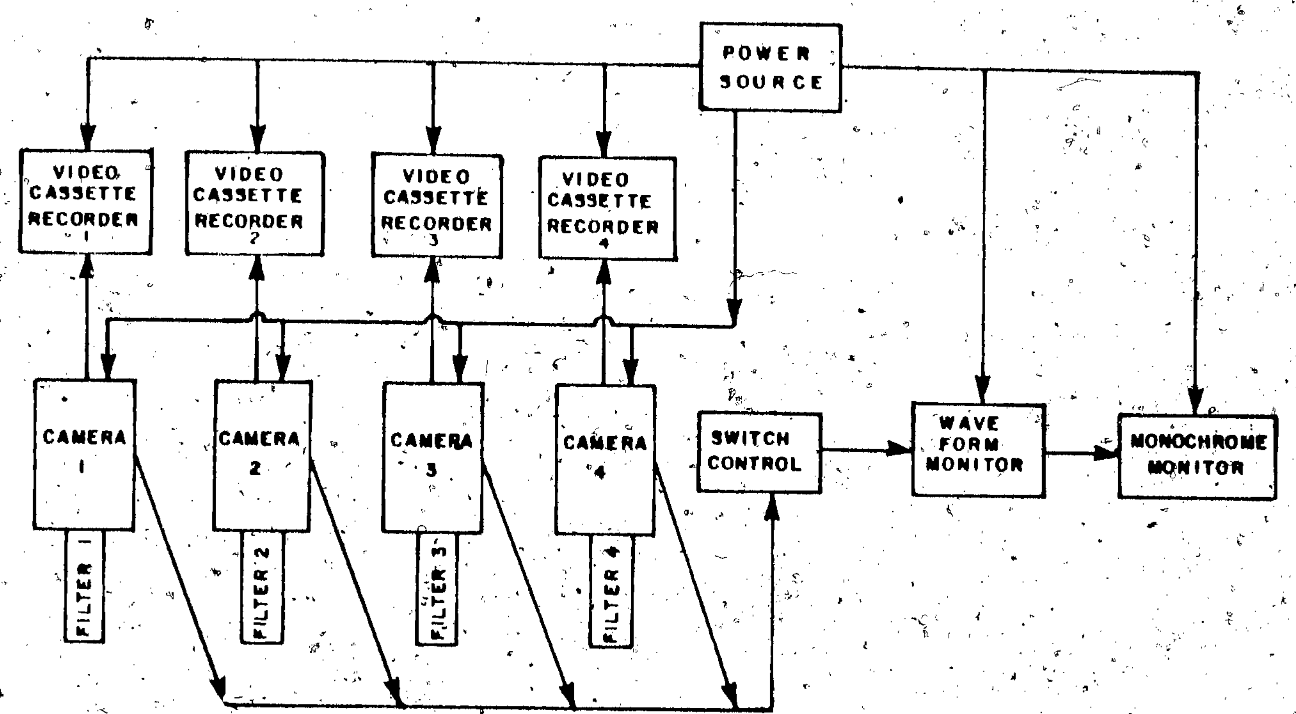


Without a spill of opportunity, it became necessary to obtain permission to create a field trial spill specifically for the study. Application was made to the Ocean Dumping Approval Process (ODAP) for this purpose (Appendix 4). Agencies such as the Canadian Coast Guard, Department of Fisheries and Oceans, Canadian Wildlife Service and Port of Vancouver were notified. Concern was expressed by some of the environmental agencies, but approval eventually was granted based on the extensive involvement of Burrard Clean Limited, a spill cleanup contractor which assumed responsibilty for spill control and cleanup.

The video package developed for the field trial, consisted of a four camera array with each camera having its own 8mm video cassette recorder and selected optical filter, a waveform monitor and a monochrome monitor (Figure 22). A switch control was included for camera selection for display on the monochrome monitor. The cameras consisted of three Sony CCD monochromes and an RCA Newvicon black and white. The video cameras were sensitive in the ranges shown in Figure 9. The hydrocarbon chosen was diesel because it had demonstrated good thickness reflectance in the final controlled test and was approvable under ODAP. The filters selected were 18A, 500nm, 600nm and 88A (Appendix 3). In spite of some of the difficulties experienced with the 18A filter in the final controlled test, it was nonetheless chosen because of its well documented high oil to water contrast. The remaining three filters each represented a band selection which had proven promising in the final controlled test.

In addition to the video equipment, two Nikon 35 mm photographic cameras with 24 mm Nikkor lenses were utilized in the field trial. One of the cameras was loaded with Kodak 2443 Aerochrome Infrared film and fitted

FIGURE 22. SCHEMATIC OF VIDEO SYSTEM IN AIRCRAFT FOR FIELD TRIAL



with a Nikon 056 (Wratten 22) filter to eliminate the blue and blue-green spectral regions. The other camera contained Kodak 5037 Ektachrome Tungsten film and used an 85B filter. The two cameras combined to provide full photographic spectrum imaging. (The spectral sensitivity of the two film types is shown in Figure 23.)

The aircraft used in field trial data collection was a Cessna 185 with 9 inch and 18 inch photography ports, a 1000 mile range and 30000 feet altitude capability. This aircraft is relatively inexpensive to produce and operate, yet has practical performance characteristics for operational use.

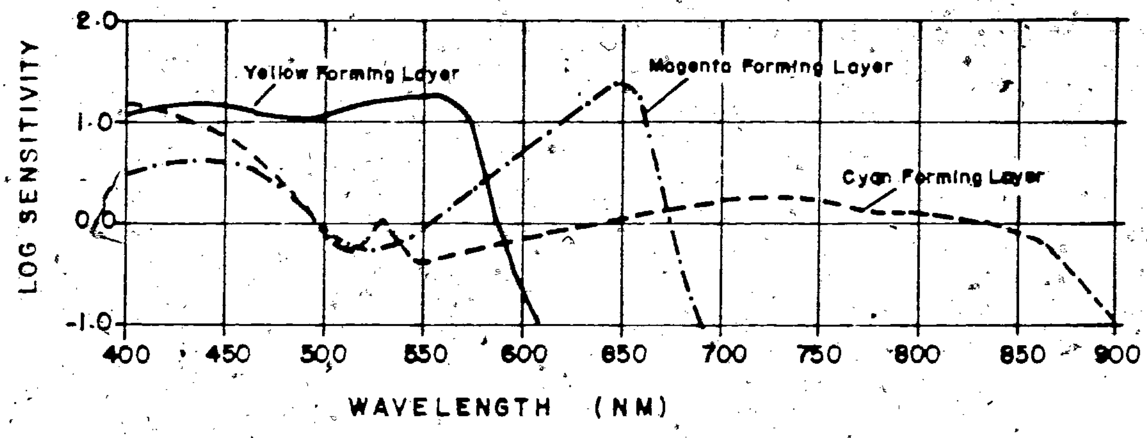
Reference measurements of spill thickness for correlation with video and photographic imagery obtained from the aircraft were collected through surface sampling from a boat using a Ross-Belore sampler (Figure 24). The sampler was designed to be dropped onto a spill surface so that its bottom edge could trap and absorb that area of the spill with a specially designed absorbent pad. After each field trial sample was obtained, the absorbent was removed and placed into a numbered, time-referenced sampling jar which was sealed for later laboratory analysis.

On 10 January 1987, a preliminary sortie was made over Burrard Inlet to check the video system under real-time conditions. All components worked successfully except that the sensitivity of the lens on the Newvicon camera was not high enough for the relatively high opacity of the 18A filter. This was later rectified prior to the actual field trial through use of a different lens with an additional f-stop.

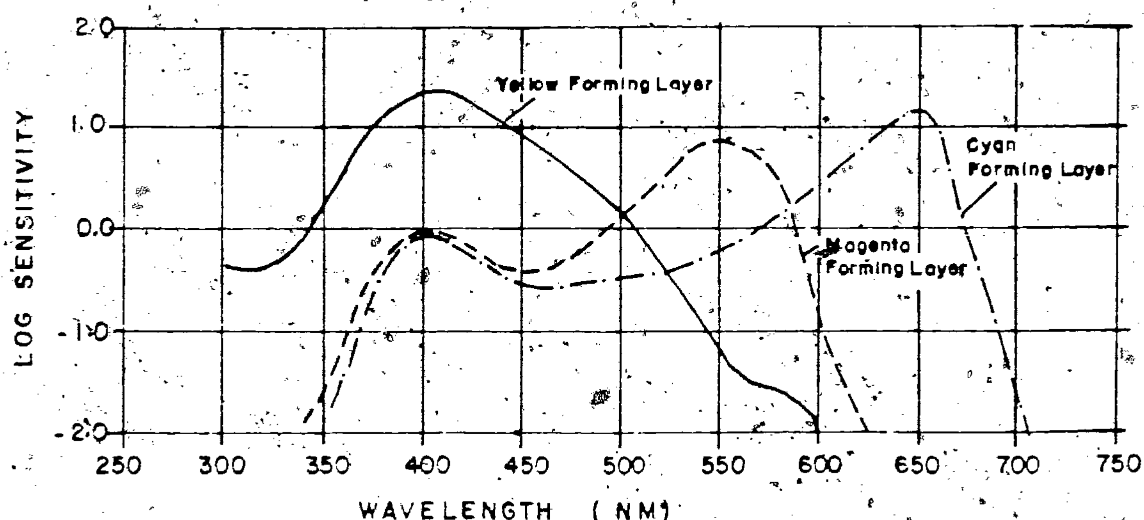
The field trial took place on 18 March, 1987 in Burrard Inlet (Figure 25) as approved under ODAP. A series of consecutive passes at 1500, 1000 and 500 foot elevations were made between 1118 hours and 1200 hours

FIGURE 23. SPECTRAL SENSITIVITY OF FILMS USED IN FIELD TRIAL

KODAK 2443 AEROCHROME INFRARED FILM

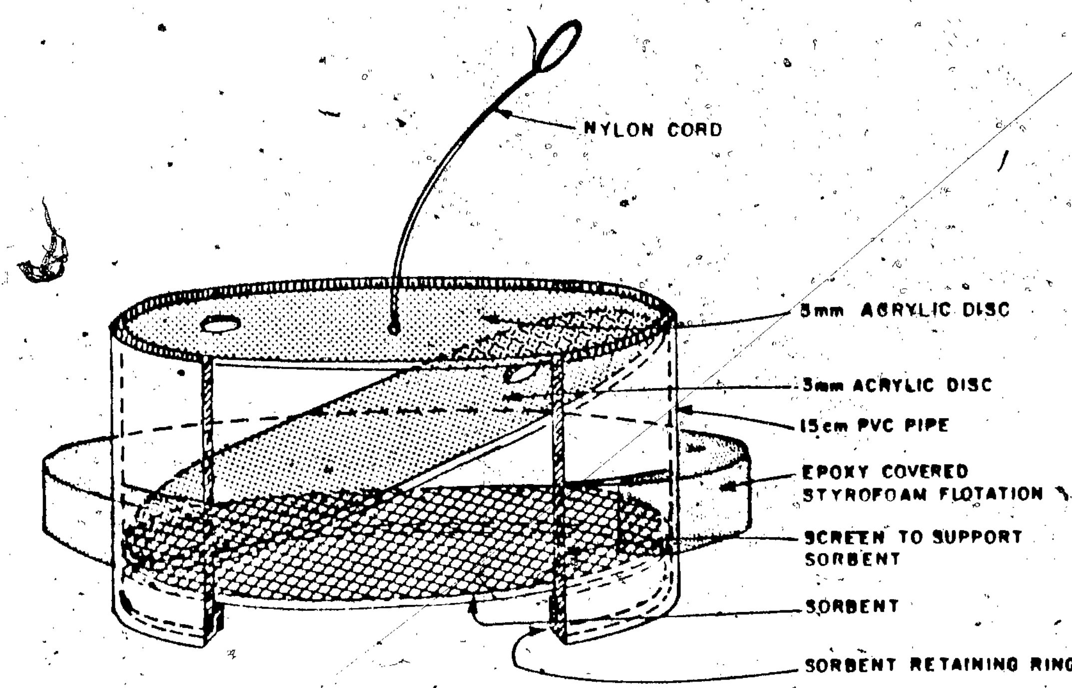


KODAK 5037 EKTACHROME TUNGSTEN FILM



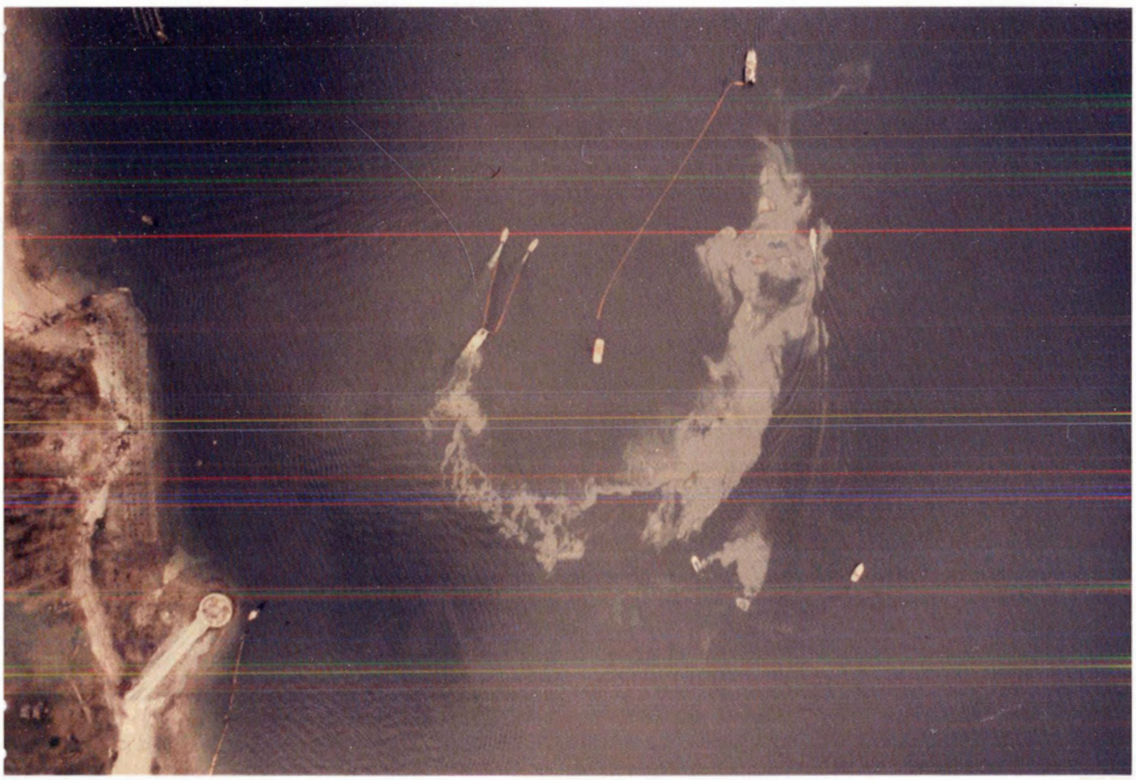
SOURCE: Eastman Kodak Company, 1972: D-23 and D-30

FIGURE 24. DIAGRAM OF ROSS - BELORE OIL THICKNESS SAMPLER



(NOT TO SCALE)

FIGURE 25. AERIAL VIEW OF FIELD TRIAL, BURRARD INLET, 18 MARCH 1987



Pacific Standard Time. Surface sampling was carried out simultaneously with the overhead passage of the aircraft; watch synchronization between the field sampler and camera operator made it later possible to match the laboratory results from the surface samples with the video and photographic imagery. A total of 18 passes were made of which four were later dropped from analysis because two were only for equipment adjustment, one had no surface samples and one did not include the sampling boat in the video imagery. The camera with the infrared film malfunctioned near the start of operations and therefore prevented collection of color IR photographs. This resulted in lack of photographic corroboration of video IR results.

Environmental conditions during the field trial were optimum in terms of limiting the potential variables identified in Table 6. The sea was calm and clear, while the spill site was sufficiently offshore for marine vegetation not to be a factor. The sun was at a near vertical angle and there was a consistent, moderately thick cloud cover at 2,000 feet which minimized the sun glare problem. These conditions plus the full functioning of the video equipment onboard the aircraft and the surface sampler on the boat provided 14 flight lines of useful data. Apart from the loss of one additional flight line with the color photographic camera, excellent color photographs were acquired for all other flight lines.

5.2 Data Compilation

5.2.1 Surface Samples. Surface samples collected during the field trial were quantitatively analyzed in the West Vancouver Analytical Laboratory of Environment Canada. Detailed procedures for the quantification of the diesel oil collected in each sorbent pad are presented in Appendix 5. A Perkin-Elmer Model 882 Infrared Spectrophotometer provided the analytical results. The value obtained for each sample from the chemical analysis was expressed in mg. The method for translating weight to thickness for each sample was as follows:

$$\text{Thickness (T)} = \frac{\text{Volume of Diesel Sample (V)}}{\text{Area of Ross-Belore Sample Pad (A)}}$$

Knowing Weight (W) = Density (D) x Volume (V)

Then V = W/D

and T = (W/D)/A

Now W is known in mg for each sample by laboratory analysis,
D is known by laboratory quality control for the diesel oil used in the field trial (0.8625 gm/cc),
A is derived by $A = \pi r^2 = 3.142 \times 7.7^2 = 186.3\ cm^2$,
So T can be calculated in cm or μm.

Weight and converted thickness values for each flight line sample are presented in Table 10. Thickness values are included in reflectance/thickness correlations described later in this chapter.

5.2.2 **Imagery.** For meaningful data compilation of field trial imagery, it was first necessary to identify which flight lines showed surface sampling actually occurring, in order to be able to correlate imagery measurements with surface thicknesses. For the 14 video flight lines fitting this category, the imagery was again reviewed with counter readings on the video cassette recorder noted where the sampling boat appeared near the center or nadir of the lens. Each of the counter readings was used as a reference for image digitization on the VAX11/750 IIS image analysis system using a waveform monitor and time base corrector.

For the color photography, images which showed surface sampling near the nadir were selected for VAX 11/750 IIS digitization. Digitization

TABLE 10. SAMPLE WEIGHTS DETERMINED BY CHEMICAL ANALYSIS AND CORRESPONDING CALCULATED SAMPLE THICKNESSES

FLIGHT LINE NUMBER	SAMPLE WEIGHT (mg)	SAMPLE THICKNESS (μm)
1	5150	321
2	19	1
3	31800	1979
4	6	1
5	29	2
6	65	4
7	20	1
8	55	3
9	9	1
10	13	1
11	17	1
12	9	1
13	44	3
14	42	3

was carried out by securing each selected color 35 mm frame on a light table and imaging it with a video camera regulated by a waveform monitor. Each frame was sequentially imaged with Wratten 25 (red), 58 (green) and 47 (blue) filters in conjunction with a 301A filter (for elimination of near infrared energy) so as to create a digitized color composite image.

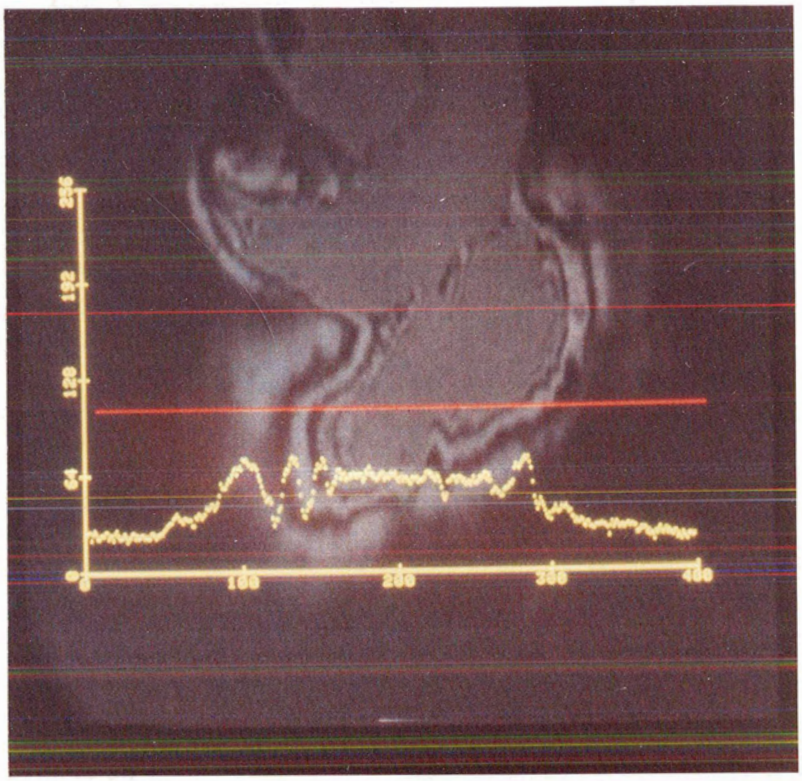
The first examination of the 14 digitized video images (Figure 26) was used to determine target reflectivity across a transect. This profiling and graphing confirmed spill thickness variations so that a second routine (points) was used to determine adjusted mean grey levels (brightness levels) in a manner identical to that used for the final controlled test. Table 11 shows adjusted mean grey levels by filter type and diesel oil thickness (as derived in the preceding section) on a flight line basis as well as altitude and time of sampling.

With respect to the digitized red, green and blue bands acquired from the 35 mm color photography, the adjusted mean grey level for each band of the selected image for each flight line was determined using the points procedure. The resulting values were ratioed one to another by flight line and are shown in Table 12 along with measured diesel oil thicknesses. It should be noted that certain flight lines are missing from Table 12 as explained in more detail in the next section.

5.3 Data Analysis and Interpretation

Table 11 data were presented in two graphs (Figures 27 and 28). Figure 27 portrayed a complicated plot of adjusted mean grey level versus diesel oil thickness in the lower hydrocarbon thicknesses (less than 25 μm). Higher thicknesses up to 1979 microns suggested an increase in adjusted mean grey level, or reflectivity, with an increase in hydrocarbon thickness. The

FIGURE 26. EXAMPLE OF A PROFILED AND GRAPHED IMAGE - FIELD TRIAL, BURRARD INLET, 18 MARCH 1987



X-axis: Number of pixels along selected red profile
Y-axis: Reflectivity or grey level where
0 = full darkness and
256 = full brightness

TABLE 11. MEASURED DIESEL OIL THICKNESSES AND ADJUSTED MEAN GREY LEVELS BY FILTER TYPE IN FIELD TRIAL

FLIGHT LINE	ELEVATION (FEET)	SAMPLING TIME (PST)	MEASURED DIESEL OIL THICKNESS (μm)	ADJUSTED MEAN GREY LEVEL BY FILTER TYPE			
				18A	500nm	600nm	88A
4	1000	1130	1	16	3	2	2
9	500	1141	1	42	29	34	24
12	500	1148	1	21	8	10	12
10	500	1144	1	20	15	18	14
11	500	1146	1	8	6	6	4
2	1500	1127	1	17	15	18	8
7	1000	1137	1	14	9	8	8
5	1000	1133	2	31	19	27	22
14	1500	1156	3	14	9	4	3
13	1000	1151	3	13	6	5	3
8	500	1139	3	43	22	23	21
6	1000	1135	4	19	15	9	8
1	1500	1125	321	36	28	30	17
3	1500	1128	1979	44	29	28	24

TABLE 12. MEASURED DIESEL OIL THICKNESSES AND BAND RATIOS FROM FIELD TRIAL 35 MM COLOR PHOTOGRAPHY

FLIGHT LINE	MEASURED DIESEL OIL THICKNESS (μm)	BAND RATIO					
		RED/GREEN	GREEN/RED	RED/BLUE	BLUE/RED	GREEN/BLUE	BLUE/GREEN
12	1	220	183	202	121	219	133
10	1	181	232	201	125	223	127
11	1	230	151	193	145	211	212
2	1	198	163	230	91	233	134
7	1	235	178	211	112	229	139
14	3	208	166	191	143	176	159
13	3	209	175	223	109	224	132
6	4	214	180	175	123	190	151
1	321	207	176	250	96	255	124
3	1979	196	180	226	102	237	133

Note: Flight lines 5, 8 and 9 excluded because of anomalous surface sampling; flight line 4 excluded because of camera malfunction.

FIGURE 27. PLOT OF ADJUSTED MEAN GREY LEVEL VERSUS HYDROCARBON THICKNESS BY FILTER TYPE FOR ALL FIELD TRIAL FLIGHT LINES

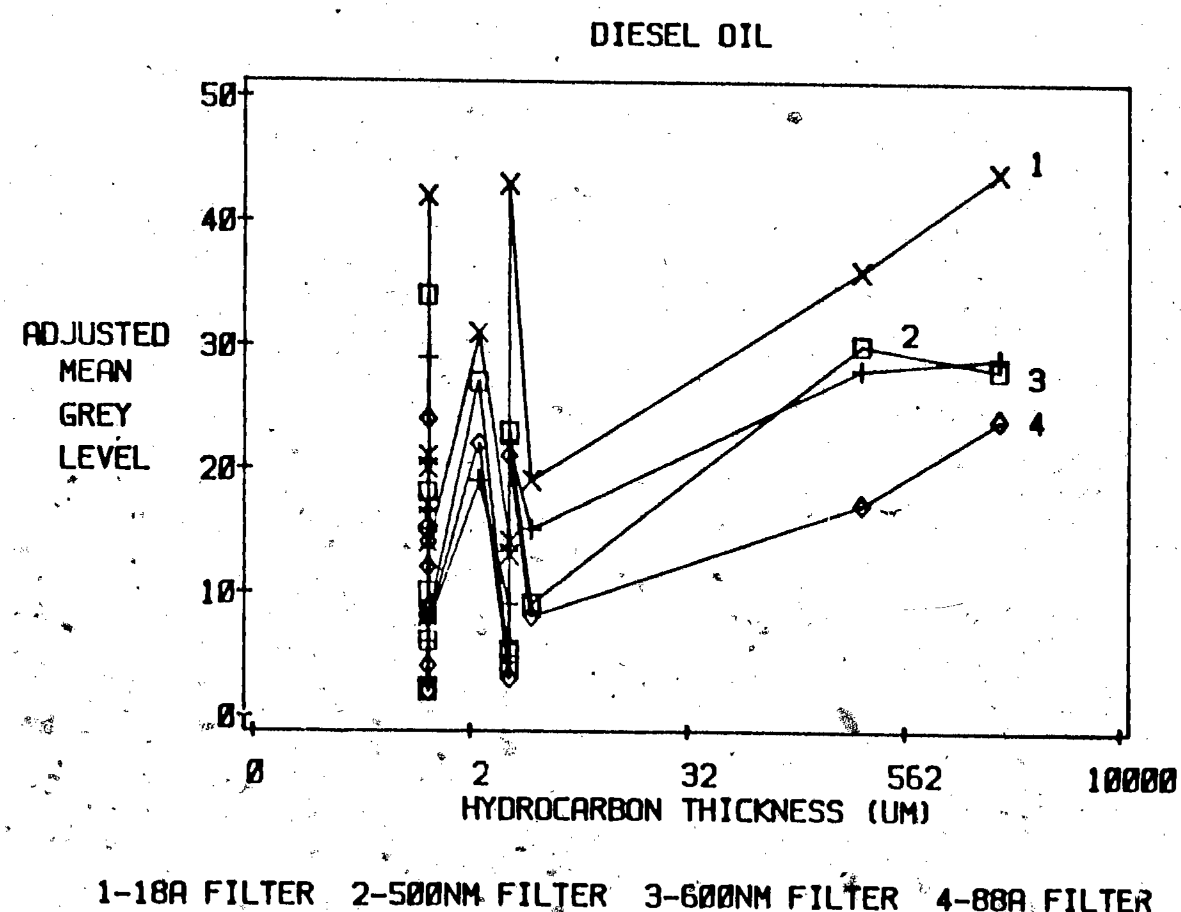
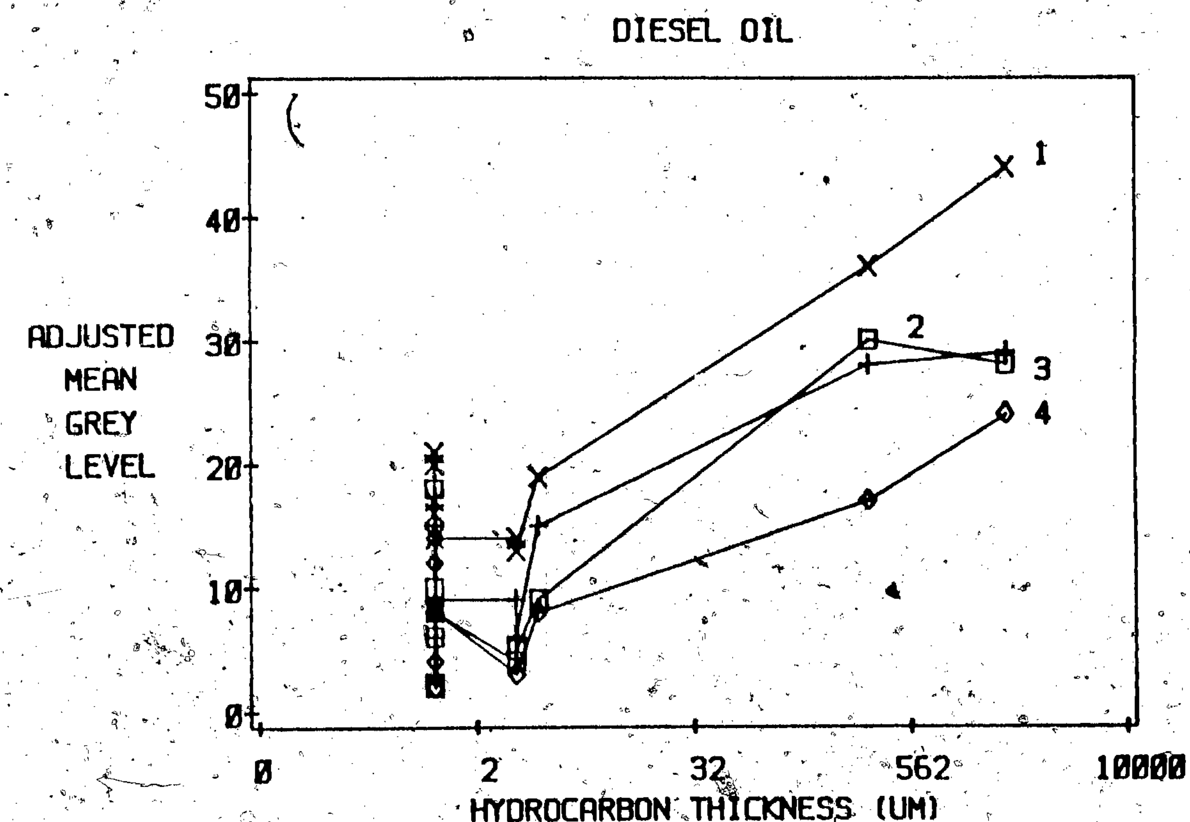


FIGURE 28. PLOT OF ADJUSTED MEAN GREY LEVEL VERSUS HYDROCARBON THICKNESS BY FILTER TYPE WITHOUT FIELD TRIAL FLIGHT LINES 5, 8 AND 9



1-18A FILTER 2-500NM FILTER 3-600NM FILTER 4-88A FILTER anomalies in the lower thickness range could possibly be explained by examination of Table 11 which showed that adjusted mean grey levels for flight lines 5, 8 and 9 for all filter types were comparatively high. Re-examination of the digitized images for these flight lines indicated that sampling uncertainties were likely the cause. That is, either exact sampling points during surface sampling were difficult to identify or the sampling boat was in an area in which thickness variations were close together.

Owing to these constraints, Table 11 figures were re-plotted without flight lines 5, 8 and 9 (Figure 28). The plot in this figure showed a considerably improved correlation between adjusted mean grey level and hydrocarbon thickness through the range of hydrocarbon thickness values considered. In other words, these selected field data confirmed the earlier final controlled test results which indicated higher reflectivity values with higher spill thickness.

Again using the data in Table 11, statistical analyses were carried out. The first analysis was a combined filter multiple regression for the diesel oil in which the thickness of the diesel was set as the independent variable and each grey level set as the dependent variable. Resulting regression slope, T-ratio and R^2 values for both linear and logarithmic series were derived and are presented in Table 13. These values indicated that the relationship of adjusted mean grey level to hydrocarbon thickness was statistically better represented in logarithmic rather than linear fashion, and that excluding flight lines 5, 8 and 9 considerably enhanced the results. Logarithmic regression slopes for both data sets suggested that grey level increased with thickness as *per* the study hypothesis. T-ratios for the logarithmic regressions indicated a high degree of significance and R^2 values (without flight lines 5, 8 and 9) had the

TABLE 13. RESULTS OF LINEAR AND LOGARITHMIC COMBINED REGRESSIONS OF FIELD TRIAL DATA

TYPE OF ANALYSIS	TYPE OF OUTPUT (FOR ALL 14 FLIGHT LINES)			TYPE OF OUTPUT (WITHOUT FLIGHT LINES 5,8 & 9)		
	REGRESSSION SLOPE	T - RATIO	R^2	REGRESSION SLOPE	T - RATIO	R^2
LINEAR	0.65916E-02	2.6132	0.4011	0.89453E-02	5.456	0.6932
LOGARITHMIC	1.7691	3.0119	0.4238	2.4718	7.3392	0.7737

Notes: The independent variables are hydrocarbon thickness (μm), three dummy variables and a constant; the dependent variable is adjusted mean grey level.

Logarithmic regression refers to the linear dependent variable (adjusted mean grey level) regressed against the natural logarithm of thickness.

Regression slope is the estimated coefficient for thickness.

T-ratio = (regression slope)/(standard error) best overall fit. Standard errors and f-statistics from the SHAZAM output indicated significance of the equations as a whole (without lines 5, 8 and 9).

Table 14 displays the results of linear and logarithmic multiple regressions of adjusted mean grey levels against diesel oil thicknesses for the four filter types for two data sets - all flight lines, and all flights lines except 5, 8 and 9. In each case the adjusted mean grey level of a particular filter was set as the dependent variable and oil thickness as the independent variable. Again the outputs showed that the logarithmic regressions were more meaningful than the linear. In terms of regression slope, T-ratio and R^2 values, increases in hydrocarbon thickness appeared to correlate with reflectance values for all filter types. Omitting flight lines 5, 8 and 9 improved the correlation outputs. Filters providing the most meaningful statistical values for regression slope, T-ratio and R^2 were 18A and 500nm. This was only in partial agreement with the final controlled test in which the 18A did not produce strong statistical results, although the literature clearly supported the usefulness of 18A filters in enhancing oil and water contrast (Vizy, 1974). However, the reasons for this were recognized during the controlled test; corrective camera and lens adjustments were made prior to the field trial which led to the improved results.

With respect to the 35 mm color photography, statistical analyses were undertaken on Table 12 data. Linear and logarithmic multiple regressions were calculated for band ratios against thicknesses for the flight lines shown in that table. Resulting regression slopes, T-ratios and R^2 values appear in Table 15. The band ratio with the best statistical results was the red-blue which was in agreement with Aukland and Trexler (United States, 1970) and Catoe and Orthlieb (1971).

TABLE 14. RESULTS OF LINEAR AND LOGARITHMIC MULTIPLE REGRESSIONS OF ADJUSTED MEAN GREY LEVELS AGAINST DIESEL OIL THICKNESSES BY FILTER TYPE FOR FIELD TRIAL DATA

FLIGHT LINES INCLUDED (NUMBER OF OBSERVATIONS)		TYPE OF OUTPUT	FILTER TYPE			
			18A	500nm	600nm	88A
All (14)	LINEAR	REGRESSION SLOPE	0.95960E-02	0.63759E-02	0.47551E-02	0.56395E-02
		T - RATIO	1.4995	1.4356	0.8289	1.2761
		R^2	0.3065	0.3596	0.2754	0.2345
5, 8, & 9 Omitted (11)	LINEAR	REGRESSION SLOPE	0.12573E-01	0.79514E-02	0.72772E-02	0.79798E-02
		T - RATIO	3.7746	2.3708	1.7862	2.9263
		R^2	0.7652	0.6424	0.5741	0.6243
All (14)	LOGARITHMIC	REGRESSION SLOPE	2.5308	1.9281	1.4072	1.2102
		T - RATIO	1.7071	1.9456	1.0515	1.1381
		R^2	0.3397	0.4343	0.3004	0.2137
5, 8, & 9 Omitted (11)	LOGARITHMIC	REGRESSION SLOPE	3.3463	2.4590	2.2168	1.8651
		T - RATIO	5.5367	4.2189	2.6[illegible]36	2.7931
		R^2	0.8649	0.8112	0.6798	0.6062

TABLE 15. RESULTS OF LINEAR AND LOGARITHMIC MULTIPLE REGRESSIONS OF BAND RATIOS AGAINST DIESEL OIL THICKNESSES FOR FIELD TRIAL 35 MM PHOTOGRAPHY

TYPE OF ANALYSIS	TYPE OF OUTPUT	BAND RATIO					
		RED/GREEN	GREEN/RED	RED/BLUE	BLUE/RED	GREEN/BLUE	BLUE/GREEN
LINEAR	REGRESSION SLOPE	-0.68734E-02	0.18942E-02	0.40601E-02	-0.24691E-03	0.32294E-02	-0.20452E-02
	T - RATIO	-0.66549	0.13187	0.33550	-0.31097E-01	0.27174	-0.12432
	R^2	0.1066	0.0055	0.3556	0.5898	0.4130	0.1315
LOGARITHMIC	REGRESSION SLOPE	-1.5101	-0.63449E-02	2.4653	-0.85291E-01	1.0074	-1.3610
	T - RATIO	-0.57861	-0.17587E-02	0.84583	-0.42826E-01	0.33891	-0.33202
	R^2	0.0934	0.0031	0.4060	0.5898	0.4164	0.1431

A similar approach using video data was also undertaken by ratioing adjusted mean grey levels for different filter pairs (Table 16). These data were multiply regressed against diesel oil thicknesses both linearly and logarithmically (Table 17). The regression slope, T-ratio and R^2 values suggested the importance of the 18A filter relative to the others.

In summary, field trial data analysis, both graphically and statistically, showed that video imagery with selected filtration could identify relative spill thicknesses in the order of two to three orders of magnitude based on reflectance measurements under specific environmental conditions. Because of some uncertainty over sampling accuracy, thin slick results for the field trial were confusing. However, deletion of suspect flight lines led to analytical results which strongly suggested that 18A and 500nm filters were useful in identifying relative diesel thicknesses under limited environmental conditions. Additional analyses of band and filter ratios further confirmed this result. The field trial results were for experimental purposes only; development of an operational system would require additional field trials under different conditions.

Field trial data represented several photographic bands and, in that sense, were multispectral. However, no special combinations of filters showing potential for thickness discrimination such as the 18A together with the 500nm were tested. In addition, the statistical tests examined only a simple relationship between a particular filter and oil thickness. Multivariate analysis could extend these results by identifying useful band or filter combinations. This is a promising direction for refining the filter-thickness relationship documented in this study.

TABLE 16. MEASURED DIESEL OIL THICKNESSES AND FILTER RATIOS FROM FIELD TRIAL VIDEO IMAGERY

FLIGHT LINE	MEASURED DIESEL OIL THICKNESS (μm)	FILTER RATIO					
		18A/500nm	18A/600nm	18A/88A	500nm/600nm	500nm/88A	600nm/88A
12	1	2.63	2.10	1.75	0.80	0.67	0.83
10	1	1.33	1.11	1.43	0.83	1.07	1.29
11	1	1.33	1.33	2.00	1.00	1.50	1.50
2	1	1.13	0.94	2.13	0.83	1.88	2.25
7	1	1.56	1.75	1.75	1.13	1.13	1.00
14	3	1.56	3.50	4.67	2.25	3.00	1.33
13	3	2.17	2.60	4.33	1.20	2.00	1.67
6	4	1.27	2.11	2.38	1.67	1.88	1.13
1	321	1.29	1.20	2.12	0.93	1.65	1.76
3	1979	1.52	1.57	1.83	1.04	1.21	1.17

Note: Flight lines 5, 8 and 9 excluded because of anomalous surface sampling; flight line 4 excluded for compatability with Table 12.

TABLE 17. RESULTS OF LINEAR AND LOGARITHMIC MULTIPLE REGRESSIONS OF FILTER RATIOS AGAINST DIESEL OIL THICKNESSES FOR FIELD TRIAL VIDEO IMAGERY

TYPE OF ANALYSIS	TYPE OF OUTPUT	FILTER RATIO					
		18A/500nm	18A/600nm	18A/88A	500nm/600nm	500nm/88A	600nm/88A
LINEAR	REGRESSION SLOPE	0.16284E-03	0.22174E-03	0.47689E-04	0.36397E-04	-0.16105E-03	-0.25723E-03
	T - RATIO	0.64446	0.57196	0.73194E-01	0.12641	-0.37509	-1.0603
	R^2	0.3637	0.4716	0:2642	0.1421	0.0530	0.2631
LOGARITHMIC	REGRESSION SLOPE	0.41595E-01	0.11327	0.13731	0.44951E-01	0.31599E-01	-0.43713E-01
	T - RATIO	0.65698	1.2612	0.88558	0.63956	0.29224	-0.68903
	R^2	0.3651	0.5493	0.3378	0.1876	0.0456	0.1991

CHAPTER 6. DISCUSSION AND CONCLUSIONS

The objective of this study was to evaluate whether hydrocarbon spill thickness could be estimated by measuring light reflectance differences using multispectral video remote sensing. As the literature on the subject was contradictory, a series of controlled tests and a field trial were undertaken to investigate this possibility. The video and photographic systems selected for use were intended to be experimental only; an operational system would require further testing and modification.

Graphical and statistical analyses of final controlled test data showed that video imagery collected with specific filters could provide comparative estimates of hydrocarbon thickness up to 1000 microns (1 mm). Oil thickness discrimination was better for translucent hydrocarbons such as 10W30 oil, diesel oil and gasoline than for crude or waste oils. The most effective filters were determined to be 88A, 550nm bandpass and 301A/46.

Field trial video imagery, also analyzed graphically and statistically, confirmed that it was possible to identify relative spill thickness from reflectance measurements, although not with the same statistical significance as in the final controlled test. Depending on how the field trial data were interpreted, there was some uncertainty over estimating thin slick (less than 25 μm) thicknesses. Filters proving most effective were 18A and 500nm bandpass under the specific environmental conditions encountered.

In comparing the results of the final controlled test and the field trial, there was agreement that relative estimation of hydrocarbon thickness to two or three orders of magnitude was possible through measurement of reflectance differences using a multispectral video remote sensing system. It is important to note that estimation was relative; no attempt was made to ascribe specific thicknesses to specific grey levels on a predictive basis. Instead, the imagery was analyzed for grey levels in relation to known hydrocarbon thicknesses. Relative thickness determination appeared to be possible up to 1000 microns. Beyond that there was no discernable increase in reflectance values. Statistical analyses of the two independent tests (controlled and field) suggested that for both the reflectance to thickness relationship appeared to be logarithmic.

In the final controlled test, oil type seemed to be a factor in the ability to resolve differences in hydrocarbon thickness. Diesel showed good reflectance/thickness relationships; this was confirmed by the field trial. Further studies would be needed to better understand the requirements for hydrocarbon type identification and full multispectral evaluations. For example, filters representing different bands could be combined physically in the camera setup or digitally on the computer to provide actual multispectral imaging. In addition, multivariate analysis could be run on the resulting data to identify optimal combinations for identifying spill thicknesses.

With respect to the filters used with the video cameras, only those in the blue-green band (500nm and 550nm) were effective under both the final controlled test and field trial conditions. However, the 18A filter showed the best results in the field trial after proper exposure levels were achieved. The final controlled test imagery of the 18A was poor because of underexposure. Filter results from the video imagery accorded with Munday <u>et al</u>. (1971) and United States (1971b) which reported that good thin slick detection was provided by using UV and blue band photography, and thicker slick detection, the green band. It also concurred with Yuanfu et al. (1982) in terms of the UV and blue-green, but disagreed in the use of the red band for thicker slicks. However, analyses of digitized photographic imagery suggested the importance of the red and blue bands in imaging spill thickness, as per Yuanfu et al. (1982). This was confirmed in the controlled test for thicknesses greater than 100 microns for the light oils and gasoline (Figures 18-20).

In summary, the conclusions drawn from the experiments undertaken in this study are as follows:

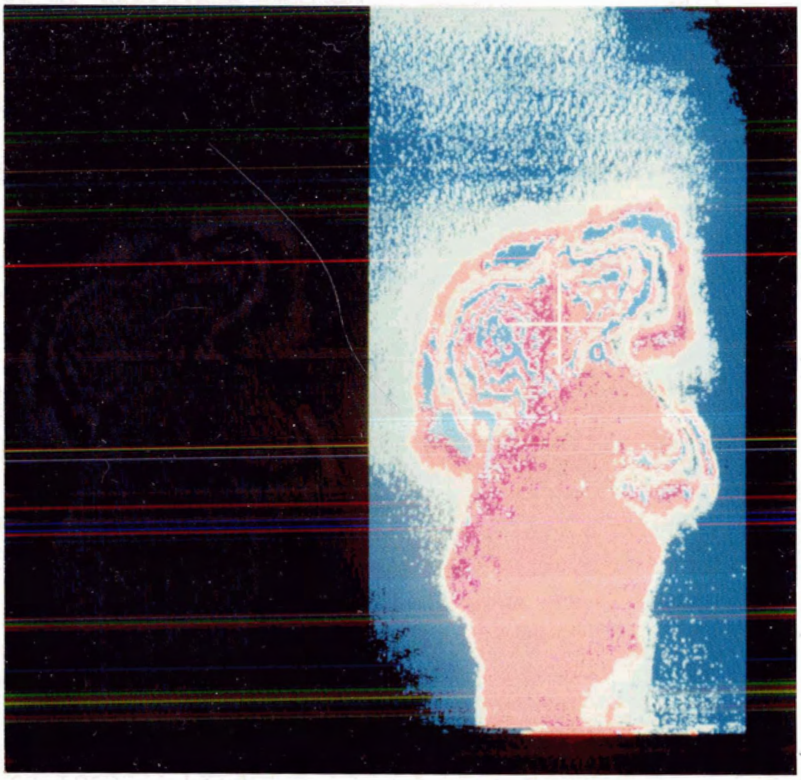
1. Hydrocarbon spill thickness can be relatively estimated in the order of two to three orders of magnitude by measuring light reflectance differences using multispectral video remote sensing.
2. Reflectance measurements for comparing oil thicknesses are only effective in spill thicknesses less than 1000 microns.
3. Blue-green and ultraviolet band video filtration is best for showing relative hydrocarbon thickness in slicks less than 100 microns thick.
4. Some of the experiments suggested that the red band may be useful under limited conditions such as only translucent hydrocarbons greater than 100 microns.
5. Translucent hydrocarbons such as 10W30 oil, diesel oil and gasoline allow better thickness determination than do opaque hydrocarbons such as crude or waste oils.

Experiments by others have focused on the potential for remote sensing techniques to identify absolute hydrocarbon spill thicknesses. This study dealt with the question of whether determination of relative thickness was possible and concluded that it was. This is important with respect to focusing oil spill cleanup efforts, knowing that thick regions of spills contain more than 90 percent of total oil in less than ten percent of the spill area (Hollinger, 1974). The experimental video system developed for the field trial therefore could be of practical use in assisting cleanup efforts under similar environmental conditions. However, a fully operational system would require more testing with respect to sunlight - skylight, weather and sea state, turbidity, near shoreline vegetation conditions and camera corrections.

Future testing could also include use of a larger aperature lens with an 18A filter under controlled conditions, and more extensive surface sampling in field trials to provide a larger data set. Of course, such trials are logistically complex and may be very costly. They must be designed for very efficient data collection. Flight elevations at 500 feet are recommended because the resulting larger imagery permits more precise identification of spill sampling locations. Altitude appeared to have no bearing on the ability to determine thickness through reflectance differences. However, all observations were made at relatively low altitude; atmospheric effects could be important at greater heights.

In spite of some of the uncertainties associated with the multispectral video remote sensing system used in the field trial, data analysis clearly demonstrated that the system was capable of estimating relative hydrocarbon spill thicknesses to two or three orders of magnitude on the basis of light reflectance differences under certain environmental conditions. This was shown through grey level quantification of digitized imagery and subsequent statistical analyses. Further computer treatments of the data would likely produce improved resolution through supervised classification procedures and related multivariate techniques; resulting classified images can be pseudo-colored and displayed with split imaging for illustrating the identified differences in hydrocarbon thickness (Figure 29). Application of such techniques to the hydrocarbon spill thickness method developed in this study should prove of considerable benefit in improving oil spill cleanup operations.

FIGURE 29. EXAMPLE OF A PSEUDO-COLORED SPLIT IMAGE - FIELD TRIAL, BURRARD INLET, 18 MARCH 1987



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APPENDIX 1. DESCRIPTION OF REMOTE SENSING INSTRUMENTATION

DESCRIPTION OF REMOTE SENSING INSTRUMENTATION

According to Intera Environmental Consultants Ltd. (Canada, 1984a: 9):

> To the eye, the appearance of an oil slick is extremely variable, depending on illumination conditions, oil type and thickness, relative locations of the slick and the observer, environmental conditions prevailing at the time, and the physical and mental state of the observer. Even under ideal conditions, the water to oil contrast is subtle in the visible portion of the spectrum, straining anyone's visual acuity.

It is owing to these limitations of the human eye within the visible spectrum as well as its total inability below and above the visible that a variety of oil spill sensor systems have been developed. They are discussed in this appendix relative to the portions of the spectrum within which they operate. More detailed summaries of remote sensing equipment are provided by Canada (1984b) and Lillesand and Kiefer (1979).

Visible, Near Visible and Infrared Sensors

Photographic Sensors. There is a wide range of photographic cameras available for oil spill remote sensing from 35 mm reflex to large format with corresponding low to high cost. Magazine capacity, cycle rate, lens optics, resolution and shutter speed can vary considerably. In addition, there are many color and black and white film types which differ in speed, resolution and wavelength sensitivity. There are also numerous filters available which can further isolate portions of the electromagnetic spectrum.

Photographic cameras offer high resolution and can provide stereoscopic coverage and multispectral imaging. General availability of many lenses, films and filter types is also an advantage. However, photographic systems are not real-time and some systems are very costly.

Radiometers. A radiometer is a passive non-imaging device which measures the absolute value of the energy emitted and/or reflected from an object. Typical airborne radiometers provide point measurements along an aircraft's flight path. Incoming radiation is transduced into an electrical current which is then recorded. Radiometer sensitivity can range from the ultraviolet to the far infrared depending on the type of sensing element incorporated in the instrument. (Radiometers which detect between 0.3 and 1 m are known as photometers). In addition, energy in specific spectral bands can be detected through use of filters or a diffraction grating.

Line Scanners. While radiometers generate a one-dimensional profile along a flight line, scanners create a two-dimensional record for a swath beneath the aircraft. In effect, a line scanner is a radiometer which sweeps from side to side as the aircraft moves above the ground creating a series of cross-profiles. Scanner system components include a collection system consisting of a mirror which oscillates on a shaft oriented parallel to the flight line and a solid state detector or detector array where received energy is converted into electrical impulses and recorded on an electromagnetic tape. Scanners sense the photographic and thermal portions of the electromagnetic spectrum, although some are also capable of sensing the microwave band. In the case of multispectral scanners, incoming energy is split into smaller bands by a prism or diffraction grating. It is possible to develop a composite color picture by designating a different energy band (i.e., color) to each channel and superimposing channel images.

Another type of scanner is the pushbroom scanner in which, rather than an oscillating mirror, terrain radiance is recorded through repeated sampling by a solid state sensor array. Aircraft forward motion again provides the scan direction. Pushbroom scanners generally have a higher resolution than standard multispectral scanners because of the precise geometry of their sensor array, greater signal power from the large area of their focal plane and minimum mechanical disturbances because they lack a moving mirror.

Video Systems. Video or television systems consist of an optics package which collects incoming radiation and focuses it on an image tube or solid state detector. Solid state detectors utilize photodetector arrays and silicon chips. Different integrated circuit technologies are available including the charge couple device (CCD), the charge injection device (CID) and metal on silicon (MOS) (Meisner, 1986). Video output can be achieved by a cathode ray tube showing a real-time image, recorded on a videotape or digitized in a freeze-frame image. Both color and black and white systems are available; higher resolution is attainable with black and white. It is important that the monitor and recorder are compatible with the camera owing to the "weakest link" rule. This rule states that the resolution, S/N ratio, and distortion of the entire system will never exceed that of the weakest component, whether camera, recorder or monitor (White, 1983).

Resolution and sensitivity of video systems can vary as a function of electron beam diameter across the cathode ray tube screen, imperfect electro-optics and detection-induced noise, but they have the advantage of operating in real-time at relatively low cost. Spectral sensitivity can range from ultraviolet to thermal but most cameras are limited to the photographic spectrum. Selective filtration is readily achievable using a variety of optical filters.

Video cameras commonly create an image which is geometrically distorted by 1 - 2 percent depending on camera aperature and timing relationships. One key component of video cameras is the lens; focal length and aperature diameter determine field of view and amount of available light, two important factors for adequate remote sensing of oil spills.

One important variable amongst video cameras is the ability to produce images under low light conditions as is the case with low light level television (LLLTV). In these systems image-forming electrons are electrostatically accelerated before being focused on a fluorescent phosphorus screen. Usually capable of operating in the same electromagnetic range as conventional TV's, they have the added advantage of being usable under starlight, moonlight, dawn or dusk conditions, but are expensive relative to standard videos.

Forward-Looking Infrared (FLIR) Devices. FLIRs are basically line scanners which operate in the thermal infrared portion of the spectrum. The main components of a FLIR are a scanner, a detector array and electronic components including output devices. One common scanning technique is contiguous scanning which is a combination of high speed horizontal scanning with oscillating vertical scans. Detector arrays require supercooling to 77° K., usually through the use of liquid nitrogen. The most common display unit is that of a standard television monitor with the option of videotape or single frame recorders. While capable of recognizing small targets over ranges of several miles, FLIRs are correspondingly constrained by a limited field of view.

Fluorosensors. Fluorescence radiation is created when a molecule absorbs a photon and subsequently emits another photon with less energy but greater wavelength. Most fluorosensors operate in the ultraviolet portion of the spectrum through detection of natural fluorescence or artifically stimulated fluorescence, depending on the sensor system. With fluorescence-induced systems, pulsed or continuous wave lasers (light amplification by stimulated emitted radiation) create the fluorescence. Fluorescence is usually recorded on a magnetic tape via a telescopic receiver.

Active Gated Television (AGTV) Sensors. One of the generation of new combined sensor systems, the active gated television combines a low light level television with a laser. In its passive mode, the system functions as an LLLTV capable of night sensitivity; in the active mode, a pulse laser is transmitted to the target. The camera intensifier in the LLLTV is then gated on 'to act as a receiver'. This approach provides high target readability under limited light conditions with a reduced field of view.

Fraunhaufer Line Discriminators. Fraunhaufer dark lines in the solar spectrum are caused by selected absorption of light by gases in the upper atmosphere with the strongest lines occurring in the ultraviolet and infrared bands of the spectrum during daylight hours. The Fraunhaufer line discriminator records luminescence through comparison of sky and target radiance on a selected Fraunhaufer line in the solar spectrum. Mechanically the system consists of one telescope looking skyward and another towards the ground, a chopper wheel alternating between them, filters, a photo-multiplier, a light collector and electronic components including a mini-computer which calculates luminescence and reflectance values.

Microwave/Radar Sensors

Passive Microwave Systems. Passive microwave systems operate in a fashion similar to thermal radiometers and scanners and therefore are capable of either flight path profiles or wider scan lines along the length of a flight path. The main difference between passive microwave sensors and radiometers is that the former utilize antennas rather than photon detection elements. Energy collected via an antenna is amplified and compared to an internal calibration temperature reference signal. The difference between the two is electronically detected and recorded in such output recorders as a synchronized film recorder.

Passive microwave sensors record energy in the microwave portion of the electromagnetic spectrum from a variety of emission sources. These may include not only target temperature and instant radiation, but also emitted, reflected or transmitted energies from other sources such as the sky or atmosphere. Owing to the variety of sources, passive microwave energy yields a noisy signal which can be difficult to interpret. This is particularly critical with respect to oil spill detection for which microwave systems attempt to discriminate between open water waves and surface water calmed by oil.

Side-Looking Airborne Radar (SLAR) Systems. Radar stands for radio detection and ranging. It is basically an active microwave system which uses radio waves to detect objects and determine their range through transmission of short bursts of microwave energy and recording their return or backscatter reflections.

One particular type of radar, side-looking airborne radar or SLAR, uses an antenna under an aircraft to propagate microwave energy to a target. A synchronizer switch varies the antenna between transmitting and receiving mode. Received energy is processed to produce an amplitude/time video signal which is recorded on a film recorder. Each image line on the film is a total representation of the signal strength from a single radar pulse. A strip image is created in the film recorder through a series of such pulses.

Synthetic Aperature Radar (SAR) Systems. Whereas SLAR systems are known as real aperature sensors because they depend on the actual physical length of their antenna, synthetic aperature radar or SAR systems depend on modified data recording and processing techniques to synthesize the effect of a long antenna. SAR's record both the amplitude and frequency of target returns as compared to only amplitude for SLARs. Frequency information from a target is compared to a control frequency reference signal generated internally with the resulting pattern recorded photographically or on magnetic tape. These signal films must be interpreted in turn by a laser optical processor. SAR is very complex and requires dependable performance from its many system components.

APPENDIX 2. PREFERRED FILM AND FILTER TYPES FOR REMOTE SENSING OF OIL SPILLS

PREFERRED FILM AND FILTER TYPES FOR REMOTE SENSING OF OIL SPILLS

FILM	DESCRIPTION
2402	Kodak Plus-X Aerographic (Black and White) Panchromatic with extended red sensitivity
2403	Kodak Tri-X Aerographic (Black and White) Panchromatic with extended red sensitivity
2424	Kodak Infrared Aerographic (Black and White) Infrared, visible and ultraviolet (weak between 500-600 nm)
SO-397	Kodak Ektagraphic EF Aerographic (Color reversal) Sensitive multilayer balanced

FILTER	WAVELENGTH (μm)
1A	380 - 1100
18A	310 - 400 and 700 - 800
32	300 - 520 and 600 - 1100
39	300 - 500 and 680 - 1100
99	520 - 590 and 740 - 1100

APPENDIX 3. TRANSMITTANCE RANGES OF FILTERS USED IN CONTROLLED TESTS AND FIELD TRIAL

TRANSMITTANCE RANGES OF FILTERS USED IN CONTROLLED TESTS AND FIELD TRIAL

FILTER	TRANSMITTANCE RANGE (μm)
18A	310 - 400 and 700 - 800
50	430 - 480 and 750 - 1100
87B	830 - 1100
88A	720 - 1100
301A/46	400 - 520
301A/92	620 - 690
400 nm	375 - 425
450 nm	425 - 475
500 nm	475 - 525
550 nm	525 - 575
600 nm	575 - 625
650 nm	625 - 675

APPENDIX 4. DOCUMENTATION FROM OCEAN DUMPING APPROVAL PROCESS

APPLICATION

Government of Canada | Gouvernement du Canada

Environmental Protection
Conservation and Protection

MEMORANDUM **NOTE DE SERVICE**

TO / À: B. A. Heskin
Regional Director, Pacific & Yukon

Attention: H. Nelson - Ocean Dumping

SECURITY - CLASSIFICATION - DE SÉCURITÉ

OUR FILE — N / RÉFÉRENCE

YOUR FILE — V / RÉFÉRENCE

DATE March 11, 1987

FROM / DE: Bob Sherwood
Senior Physical Scientist
Referral and Impact Analysis
Pacific & Yukon Region

SUBJECT / OBJET: Oil Spill Remote Sensing Experiment

Attached is an application for approval under the Ocean Dumping Control Program for an oil spill remote sensing experiment on March 18, 1987 in Burrard Inlet. The intent of the experiment is to test an array of video cameras and filters on board a Cessna 185 for thickness detection of a diesel spill of known quantity. In addition, the experiment will provide an opportunity for Burrard Clean to improve its spill response capability.

All precautions will be taken to ensure that no escape of product, nor any form of environmental degradation occurs. EP personnel will be present during all releases of the diesel fuel and can call a halt to the work at any time. Only sea conditions in which the fuel can be realistically expected to be recovered will be worked. Oil containment barriers, a skimmer and sorbents will be utilized in cleanup following the aircraft overflights. A small runabout with outboard will be used to keep birds away from the area prior to and during cleanup.

I recognize the extremely tight timeframe in which approval is being sought and thank you for your efforts in this regard.

Should additional information be required, please contact me at 666-5925.

Bob Sherwood

Environment Canada Environnement Canada

APPLICATION FOR A PERMIT TO DUMP AND/OR TO LOAD SUBSTANCES FOR DUMPING AT SEA
DEMANDE D'AUTORISATION D'IMMERSION OU DE CHARGEMENT DE SUBSTANCES À IMMERGER

PART A BASIC INFORMATION / PARTIE A RENSEIGNEMENTS GÉNÉRAUX

1 NAME OF APPLICANT / Nom du requérant: SIMON FRASER UNIVERSITY — BOB SHERWOOD
TEL. Nº / Nº de tél.: 666-5925

ADDRESS / Adresse: C/O ENVIRONMENT CANADA, KAPILANO 100 - PARK ROYAL, WEST VANCOUVER BC V7T 1A2

2 TYPE OF BUSINESS / Type d'entreprise: RESEARCH AND DEVELOPMENT

3 NAME(S) OF INDIVIDUAL(S) RESPONSIBLE FOR LOADING AND DUMPING ON BEHALF OF APPLICANT / Nom de la personne chargée du chargement et de l'immersion au nom du requérant

NAME(S) / Nom(s)	TITLE(S) / Titre(s)	TEL. Nº(S) / Nº(s) de tél.
BOB SHERWOOD	SENIOR PHYSICAL SCIENTIST	666-5925

4 SUBSTANCE (Give chemical, common, trade, or other name) / Substance (donner l'appellation chimique, commune, commerciale ou autre): DIESEL

FORM / Forme: ☐ SOLID / Solide ☐ SLUDGE / Boue ☐ GASEOUS / Gaz ☒ LIQUID / Liquide
OTHER (specify) / Autre (préciser):

TOTAL Q'TY TO BE DUMPED / Quantité totale à immerger: 5 IMP. GALS.

5 SOURCE OF SUBSTANCE / Source de la substance: PETROLEUM REFINERY

NAME OF FIRM (if applicable) / Nom de la société (s'il y a lieu): SIMON FRASER UNIVERSITY

ADDRESS / Adresse: AS ABOVE IN (1)

TYPE OF BUSINESS / Type d'entreprise: UNIVERSITY

TEL. Nº / Nº de tél.: 666-5925

DESCRIBE PREVIOUS DISPOSAL METHODS / Décrire les méthodes d'élimination utilisées auparavant: THIS IS AN EXPERIMENT TO TEST A REMOTE SENSING SYSTEM AND SPILL RESPONSE CAPABILITY

6 DESCRIBE ACTIVITY FROM WHICH SUBSTANCE ORIGINATES / Décrire l'activité responsable de la formation de la substance: PETROLEUM INDUSTRY

7 WHY IS IT NECESSARY TO DUMP SUBSTANCE AT SEA? / Pourquoi est-il nécessaire d'immerger la substance en mer? TO SIMULATE ACTUAL SPILL CONDITIONS

PART B CARRIER INFORMATION / PARTIE B RENSEIGNEMENTS SUR LE TRANSPORTEUR

	NAME	ADDRESS / Adresse	TEL. Nº / Nº de tél.
8 NAME OF CARRIER COMPANY / Nom de la compagnie de transport	BURRARD CLEAN	SUITE 1004 KAPILANO 100 - PARK ROYAL WEST VANCOUVER BC V7T 1A2	926-7431
9 NAME OF CARRIER OWNER / Nom du propriétaire du transporteur	BURRARD CLEAN	SUITE 1004 KAPILANO 100 - PARK ROYAL WEST VANCOUVER BC V7T 1A2	926-7431
10 NAME OF CARRIER'S AGENT (if applicable) / Nom de l'agent du transporteur (s'il y a lieu)			

11 NAME(S) OF INDIVIDUAL(S) RESPONSIBLE FOR LOADING AND DUMPING ON BEHALF OF CARRIER / Nom de la personne chargée du chargement et de l'immersion au nom du transporteur

NAME(S) / Nom(s)	TITLE(S) / Titre(s)	TEL. Nº(S) / Nº(s) de tél.
AS NOTED IN (3) ABOVE	—	—

12 TYPE OF CARRIER / TYPE DE TRANSPORTEUR

(a) SHIPS / Bateaux

NAME OF SHIP / Nom du bateau	NAME OF MASTER / Nom du capitaine	PORT OF REGISTRY / Port d'attache
BURRARD CLEANER #1	BURRARD CLEAN PERSONNEL	NA

OFFICIAL NUMBER / Numéro officiel	OVERALL LENGTH / Longueur hors-tout	EXTREME BREADTH / Largeur au fort	DEADWEIGHT TONNAGE / Chargement en lourd
NA	42 FEET	11 FEET	14 TONS

(b) AIRCRAFT / Aéronefs

TYPE / Type	MODEL / Modèle	SERIAL NUMBER / Numéro de série	NATIONALITY / Nationalité

REGISTRATION MARKS / Marques d'immatriculation	MAX. GROSS WEIGHT AS AUTHORIZED BY CERTIFICATE OF AIRWORTHINESS / Poids brut max. autorisé par le certificat de navigabilité	NAME OF PILOT IN COMMAND / Nom du pilote commandant de bord

(c) UNREGISTERED CARRIERS OR OTHER STRUCTURES / Transporteurs non immatriculés et autres ouvrages

DESCRIBE CARRIER OR OTHER STRUCTURE / Décrire le transporteur ou l'ouvrage: NONE

NAME OR NUMBER (if any) / Nom ou numéro (s'il y a lieu)	OVERALL LENGTH / Longueur hors-tout

EXTREME BREADTH / Largeur au fort	DEADWEIGHT TONNAGE / Chargement en lourd

NAME OF MASTER, PILOT, OR OTHER INDIVIDUAL IN COMMAND / Nom du capitaine, pilote ou autre commandant de bord:

13 PORT OF DEPARTURE / Port de départ
VANCOUVER

14 PROPOSED LOADING DATE(S) / Date(s) proposée(s) pour le chargement
FROM / de: MAR 18/87 — TO / À: MAR 18/87

15 METHOD OF LOADING AND STOWAGE PROPOSED / Méthode proposée de chargement et d'arrimage
LOADING IN 10 GAL DRUMS AND STORING IN SAME.

16 PROPOSED DATE(S) OF DUMPING / Date(s) proposée(s) de l'immersion
MAR 18/87

QUANTITY PER DUMPING / Quantité immergée par opération
50 IMP. GALS

17 WHERE 16 DOES NOT APPLY STATE / Si 16 ne s'applique pas, indiquer
NA

REQUIRED DURATION OF PERMIT / Durée nécessaire de l'autorisation
FROM / de: — TO / À:

TOTAL QUANTITY / Quantité totale
50 IMP GALS.

FREQUENCY AND RATE OF DUMPING / Fréquence et cadence des opérations
10 GALS/MIN

18 DESCRIBE ROUTE FROM LOADING SITE TO DUMP SITE / Décrire le trajet du point de chargement au lieu d'immersion
DIRECT FROM BURRARD CLEAN DEPOT IN VANCOUVER HARBOUR TO OPEN WATER AREA OFF OF CATES PARK NEAR THE MOUTH OF INDIAN ARM.

19 METHOD OF DISPOSAL / MÉTHODE D'ÉLIMINATION

(a) FORM OF PACKAGING OR CONTAINERIZATION / Méthode d'emballage et de conditionnement
POURED FROM 10 GAL DRUMS

(b) SPEED OF CARRIER DURING DISCHARGE / Vitesse du transporteur au cours du déchargement
0 TO 1 KNOT

(c) DISCHARGE RATE / Cadence de déchargement
10 GALS/MIN

(d) DEPTH OF DISCHARGE *(Below sea surface or altitude above sea surface if applicable)* / Profondeur du déchargement (sous le niveau de la mer ou altitude au-dessus du niveau de la mer s'il y a lieu)
SURFACE ONLY

(e) DESCRIBE CARRIER TRACK WHILE DUMPING / Décrire le trajet du transporteur au cours de l'immersion
EAST AND WEST.

PART D DUMP SITE INFORMATION / PARTIE D RENSEIGNEMENTS SUR LE LIEU D'IMMERSION

20 GEOGRAPHICAL COORDINATES OF DUMPSITE / Coordonnées géographiques du lieu d'immersion
LAT: 49°17.8 — LONG: 122°57.5

21 DEPTH OF SEA AT PROPOSED DUMPSITE / Profondeur de la mer au lieu d'immersion
22 METRES

22 REASON FOR SELECTION OF PROPOSED SITE / Raisons du choix du lieu proposé
LOGISTICALLY APPROPRIATE IN BURRARD INLET. LESS BIOLOGICALLY SENSITIVE THAN OTHER AREAS. IN PROXIMITY TO COUNTERMEASURES DEPOT AND BASE OF OPERATIONS.

PARTIE E PROPERTIES OF SUBSTANCES TO BE DUMPED / PARTIE E PROPRIETES DE LA SUBSTANCE A IMMERGER

NOTE: In carrying out any necessary tests the analyst should follow documented procedures and be prepared to describe these procedures in detail.

NOTE: Pour effectuer les essais nécessaires, l'analyste doit suivre les méthodes indiquées et être prêt à les décrire en détail.

23 PHYSICAL PROPERTIES / PROPRIÉTÉS PHYSIQUES

(a) LIQUIDS / Liquides	SPECIFIC GRAVITY / Poids spécifique	VAPOUR PRESSURE / Tension de vapeur	MISCIBILITY WITH SEAWATER / Miscibilité avec l'eau de la mer	VISCOSITY / Viscosité	ODOUR / Odeur	COLOUR / Couleur
	0.82 – 0.98	4.5	LESS THAN 50 ppm	2-2000 CS	LITTLE	LIGHT YELLOW

(b) SOLIDS SOLUBLE IN WATER / Solides solubles dans l'eau	SPECIFIC GRAVITY / Poids spécifique	SOLUBILITY IN SEAWATER / Solubilité dans l'eau de mer	ODOUR / Odeur	COLOUR / Couleur

(c) SOLIDS INSOLUBLE IN WATER / Solides insolubles dans l'eau	PARTICLE SIZE DISTRIBUTION AND SETTLING RATE IN SEAWATER / Grosseur des particules et taux de sédimentation dans l'eau de mer	ODOUR / Odeur	COLOUR / Couleur

24 CHEMICAL AND BIOCHEMICAL PROPERTIES / PROPRIÉTÉS CHIMIQUES ET BIOCHIMIQUES

(a) ARE SUBSTANCES NAMED IN SCHEDULES I AND II OF THE ACT PRESENT? / Y a-t-il des substances mentionnées aux annexes I et II de la Loi
☒ YES / Oui ☐ NO / Non

IF YES, IN WHAT CONCENTRATIONS / Si oui, dans quelles concentrations

(b) CHEMICAL STABILITY / Stabilité chimique

OXIDATION REDUCTION POTENTIAL / Potentiel d'oxydoréduction	CHEMICAL OXYGEN DEMAND / Demande chimique d'oxygène
NA	VARIABLE – GENERALLY LOW

REACTIVITY WITH SEAWATER / Réactivité avec l'eau de mer	CHANGE ON EXPOSURE TO ATMOSPHERE AND SUNLIGHT / Changement au contact de l'atmosphère et de la lumière du soleil
NA	OXIDATION AND EVAPORATION

(c) BIOCHEMICAL BEHAVIOR / Comportement biochimique	BIOCHEMICAL OXYGEN DEMAND AT 20° / Demande biochimique d'oxygène à 20°	BIOTRANSFORMATION / Biotransformation
	LOW AND VARIABLE	NONE KNOWN
	SOLUBILITY IN ANIMAL OR PLANT LIPIDS / Solubilité dans les lipides animaux et végétaux	IF SUBSTANCE IS A PESTICIDE, GIVE PCP REGISTRATION NO. OR COMMON NAME / S'il s'agit d'un pesticide, donner le numéro d'enregistrement des produits antiparasitaires ou le nom commun
	HIGH	NA

25 BIOACCUMULATION BY MARINE ORGANISMS / BIO-ACCUMULATION PAR LES ORGANISMES MARINS

(a) CONCENTRATION FACTOR FOR FISH, MACROINVERTEBRATES AND PLANKTON / Facteur de concentration pour le poisson, les macro-invertébrés et le plancton	(b) RATE OF UPTAKE AND RETENTION *(biological half life)* / Taux d'ingestion et de rétention *(demi-vie biologique)*
NA	NA

(c) TAINTING, COLOUR CHANGE AND OTHER UNDESIRABLE CONTAMINANT EFFECTS ON SEAFOOD
Coloration, changement de couleur et autres effets de contamination indésirables sur les fruits de mer

POSSIBILITY OF TAINTING OF SESSILE MARINE LIFE

26 TOXICITY TO MARINE ORGANISMS *(96 hour LC_{50} in mg/l)*
Toxicité pour les organismes marins *(CL_{50} après 96 heures, en mg/l)*

APPROXIMATELY 100 mg/l 96 LC_{50} TO TROUT
NOTE: SORBENTS, SKIMMERS AND BOOMS WILL BE ON STANDBY IN IMMEDIATE VICINITY TO RECOVER SPILL.

27 DESCRIBE HAZARD TO HUMAN HEALTH BY / Décrire les dangers pour la santé humaine par

(a) ORAL INTAKE *(LD_{50} in mg/kg)* / Ingestion orale *(DL_{50} en mg/kg)*	(b) SKIN CONTACT / Contact avec la peau
MODERATE HAZARD	SLIGHT IRRITATION

(c) INHALATION / Inhalation

LITTLE HAZARD

When the applicant is a corporation, give the title or capacity and telephone number of the person signing this application.
Si le requérant est une société, donner le titre ou la fonction et le numéro de téléphone du signataire de la demande.

MAR 11/87		SENIOR PHYSICAL SCIENTIST
DATE	SIGNATURE OF APPLICANT / Signature du requérant	TITLE / Titre

66 - 5925
TEL. NO. / N° de tél.

APPROVALS

Environment Canada / Environnement Canada
Environmental Protection / Protection de l'environnement

Conservation and Protection
3rd Floor, Kapilano 100, Park Royal
West Vancouver, B.C. V7T 1A2

Your file / Votre référence

Our file / Notre référence

March 17, 1987

4543-2-02173

Mr. Bob Sherwood
Environment Canada
Conservation and Protection
3rd Floor, Kapilano 100
Park Royal, West Vancouver, B.C.
V7T 1A2

Dear Mr. Sherwood:

Re: Ocean Dumping Control Program, File No. 4543-2-02173
Simon Fraser University, Burnaby, B.C.

Your proposal has been reviewed pursuant to subsection 33.1(1) of the Fisheries Act. Attached are the conditions covering your application to conduct loading and ocean dumping. Your attention is directed in particular to Conditions 3, 5, 8 and 9.

With reference to Condition 3, the prescribed activity will be restricted to the date requested by the Proponent, ie: March 18, 1987. Any activities outside of this date will be subject to further review. With reference to conditions 9.2, 9.3, and 9.4, you are requested to ensure that extreme caution and dilligence is exercised to ensure no adverse impact on the environment.

Please be advised that it is the responsibility of the Proponent to ensure that all contractors involved in the loading/dumping activity are made aware of any restrictions and/or conditions.

It is understood that the Proponent has obtained all necessary permits/approvals, etc., from other regulatory agencies in respect of the project(s) described herein.

If you have any questions, please contact Mr. H. Nelson at 666-2947 or Mr. D. Brothers at 666-2990.

Yours truly,

B.A. Heskin, P. Eng.
Director
Pacific and Yukon

DEPARTMENT OF THE ENVIRONMENT
OCEAN DUMPING CONTROL PROGRAM

CONDITIONS FOR OCEAN DISPOSAL FILE NO. 4543-2-02173

1. PROPONENT

Simon Fraser University

2. TYPE OF ACTIVITY

To dump and/or load substances for dumping at sea for experimental purposes. Diesel oil will be spilled to test remote sensing equipment and oil containment and recovery capabilities.

3. TERM

Valid from March 18, 1987 to March 17, 1988. Loading and dumping will be restricted to periods which will not impose a threat to biological resources. These periods will be specified by this office.

4. LOADING SITE(S)

Vancouver Harbour;
49°17.42'N, 123°03.50'W

5. DUMP SITE(S)

Burrard Inlet;
49°17.75'N, 122°56.50'W
at a depth of not less than 20 metres.

6. EQUIPMENT AND METHOD OF DUMPING

Diesel oil will be poured from 10 gallon drums.

7. TOTAL QUANTITY TO BE DUMPED

Not to exceed 50 imperial gallons.

8. MATERIAL TO BE DUMPED

Diesel oil.

9. MONITORING REQUIREMENTS AND TIMING RESTRICTIONS

9.1 The Proponent should notify this office a minimum of five working days prior to loading and dumping. The notification should include the following information:

i) load site and dump site
ii) nature and quantity of the material to be dumped
iii) proposed date(s) on which the loading and dumping will take place.

.....2

9.2 The Proponent shall ensure minimal impact to the marine environment and living resources at the experiment site. The experiment shall be conducted at a time when wind and wave action allow the necessary control of equipment to ensure adequate recovery of oil.

9.3 Equipment on-site to ensure containment and recovery of spilled oil shall include: oil containment barriers; a skimmer; and sorbents. The oil containment barriers must be deployed prior to any release of oil.

9.4 No dumping of oil shall take place until an Ocean Dumping Inspector is present on-site and has approved commencement of the experiment.

9.5 The Proponent should report to the Director, Environmental Protection, Pacific Region, within 30 days of expiry of the Approval, the nature and quantity of material disposed of pursuant to the Approval and the date(s) on which the activity occurred.

B.A. HESKIN, P. ENG
Director
Environmental Protection
Conservation and Protection
Pacific Region
March 17, 1987

Environment Canada / Environnement Canada
Environmental Conservation / Conservation de l'environnement

DEPOSIT OIL INTO BURRARD INLET FOR SCIENTIFIC PURPOSES
permis de/pour — permit to/for

BRITISH COLUMBIA
dans la (les) province(s) — in the province(s)

MBCA BC 87/01
permis n° — permit no.

4'1
délivré en vertu de l'article — issued under section

Migratory Birds Convention Act
de — of

nom et adresse — name and address

Bob Sherwood
Senior Physical Scientist
Enviromental Protection
Conservation & Protection
Pacific and Yukon Region

16 March 1987
date d'émission — date of issue

30 March 1987
date d'expiration — date of expiry

signature du détenteur — signature of holder

pour le ministre — for the minister

conditions spéciales — special conditions

PURSUANT TO SECTION 4'1 and 35'2 OF THE MIGRATORY BIRDS CONVENTION ACT AND REGULATIONS, THIS PERMIT AUTHORIZES THE DEPOSIT OF UP TO 50 GALLONS OF DIESEL FUEL INTO BURRARD INLET NEAR GATES PARK FOR THE PURPOSES OF TESTING REMOTE SENSING EQUIPMENT AND CLEANUP CAPABILITIES.

061-1708 (03-82)

Canada

7469

FOLLOWUP

Government of Canada | Gouvernement du Canada
Environmental Protection
Conservation and Protection

MEMORANDUM **NOTE DE SERVICE**

TO / A
Hal Nelson
Ocean Dumping
Pacific & Yukon Region

SECURITY - CLASSIFICATION - DE SÉCURITÉ

OUR FILE — N / RÉFÉRENCE
4543-2-02173

YOUR FILE — V / RÉFÉRENCE

FROM / DE
Bob Sherwood
Senior Physical Scientist
Referral and Impact Analysis
Pacific & Yukon Region

DATE March 27, 1987

SUBJECT / OBJET: Ocean Dumping Control Program - Simon Fraser University

The test spills proposed for March 18, 1987 in Burrard Inlet were successfully executed as planned. Video and photographic remote sensing data of the spills were collected and are now being analyzed.

Environmental conditions were optimal-wave heights minimal, winds light and cloud cover 10/10 at 2000'. Burrard Clean controlled and cleaned up the oil very efficiently and even took the opportunity to mop up some adjacent unrelated slicks.

I would like to thank you, Duane Brothers and all those involved in the Ocean Dumping approval process for your considerate and expeditious review and comments.

Bob Sherwood

APPENDIX 5. LAB PROCEDURES FOR QUANTIFICATION OF DIESEL OIL COLLECTED IN EACH SORBENT PAD DURING FIELD TRIAL. SURFACE SAMPLING

LAB PROCEDURES FOR QUANTIFICATION OF DIESEL OIL COLLECTED IN EACH SORBENT PAD DURING FIELD TRIAL SURFACE SAMPLING

1. Cut up sorbent pads to fit 100 ml centrifuge tube.
2. Add glass beads to fit 100 ml centrifuge tube.
3. Add cut-up pad to 100 ml centrifuge tube.
4. Add 2 ml concentrated sulfuric acid.
5. Cover with screw cap and centrifuge at 3500 RPM for 10 minutes.
6. Remove pad.
7. Extract liquid on bottom of centrifuge into 100 ml volumetric flask and flush tube with freon 113.
8. Put pad back into centrifuge tube.
9. Add 10 ml freon 113 on top of pad.
10. Repeat steps 5 - 9. At this point pad has all organics removed and in the volumetric flask.
11. Volumize 100 ml volumetric flask.
12. Check the freon 113 as indicated in the Standards Procedures set out on next page.
13. Acidify a 250 ml sample in a 500 ml separatory funnel to less than pH 2 with concentrated sulfuric acid, usually 250 ul is adequate.
14. Extract with 30 ml of freon 113, letting the sample sit five minutes between extractions.
15. Drain each freon extract into a 50 ml volumetric flask by filtering through a small funnel with a GF/C paper and five gm anhydrous sodium sulfate.
16. Rinse funnel and sodium sulfate with freon 113 and make solution to exactly 50 ml.
17. Measure the absorbance at 4000 and 2935 cm-1 on a Perkin-Elmer Model 882 Infrared Spectrophotometer, using appropriate dilutions on samples to fall within the range of the calibration linearity.
18. Using 20 ml of the decanted solution from the Oil and Grease Quantitation (steps 14 - 17), add three gm silica gel and shake for 30 minutes.
19. Centrifuge at 2000 RPM for ten minutes, then carefully decant into five cm cylindrical cell. Measure the absorbance at 4000 and 2935 cm-1 on a Perkin-Elmer Model 882 Spectrophotometer to obtain Hydrocarbon Quantitation values.

STANDARDS PROCEDURES

1. Make a "Standard Oil" with exactly 15 ml hexadecane, 15 ml iso-octane, and 10 ml chlorobenzene. Determine the density by weight, normally around 0.823 gm/ml.
2. Prepare a stock solution using 2500 mg "Standard Oil" made up to exactly 50 ml with freon 113 (50,000 mg/l).
3. Prepare an intermediate stock solution by diluting 1 ml of the above to 100 ml (500 mg/l).
4. Prepare standard solutions of 100, 75, 50, 25, and 10 mg/l by appropriate dilutions and a freon 113 blank.
5. Measure the absorbance at 4000 and 2935 cm-1 against air on an Infrared Spectrophotometer. Typical five cm cell values obtained are as follows:

Concentration (in freon, mg/l)	Absorbance (2935-4000 cm-1)
0	0.36920
10	0.46290
25	0.59750
50	0.81790
75	1.0415
100	1.2633

Slope = 0.1/839
Offset = 7.4443
Correlation = 0.99999

6. Plot the standard curve and perform regression analysis on the Infrared Spectrophotometer. The linear coefficient of correlation should be at least 0.99995.
7. Unless there is a change in the absorbance of the freon 113, then recalibration will be necessary only periodically. Each bottle of solvent should be checked as a sample against the standard curve. If any bottle gives a reading equivalent to more than +/-0.1 mg/l in the freon, then the standard curve must be redone. More than 1 mg/l indicates probable contamination and the freon should not be used.

CALCULATIONS

1. Plot values obtained from "Standard Oil" vs concentrations of sample.
2. Determine the freon concentration of the unknowns.
3. For Oil and Grease Concentrations
   (freon concentration x 50 ml)/(sample volume in ml) = mg/l
4. For Hydrocarbon Concentration
   Calculate as above. In this case, the resulting value represents the quantity of diesel oil in a sorbent pad in mg.