Biological Productivity of the Southern Beaufort Sea: phytoplankton and seaweed studies

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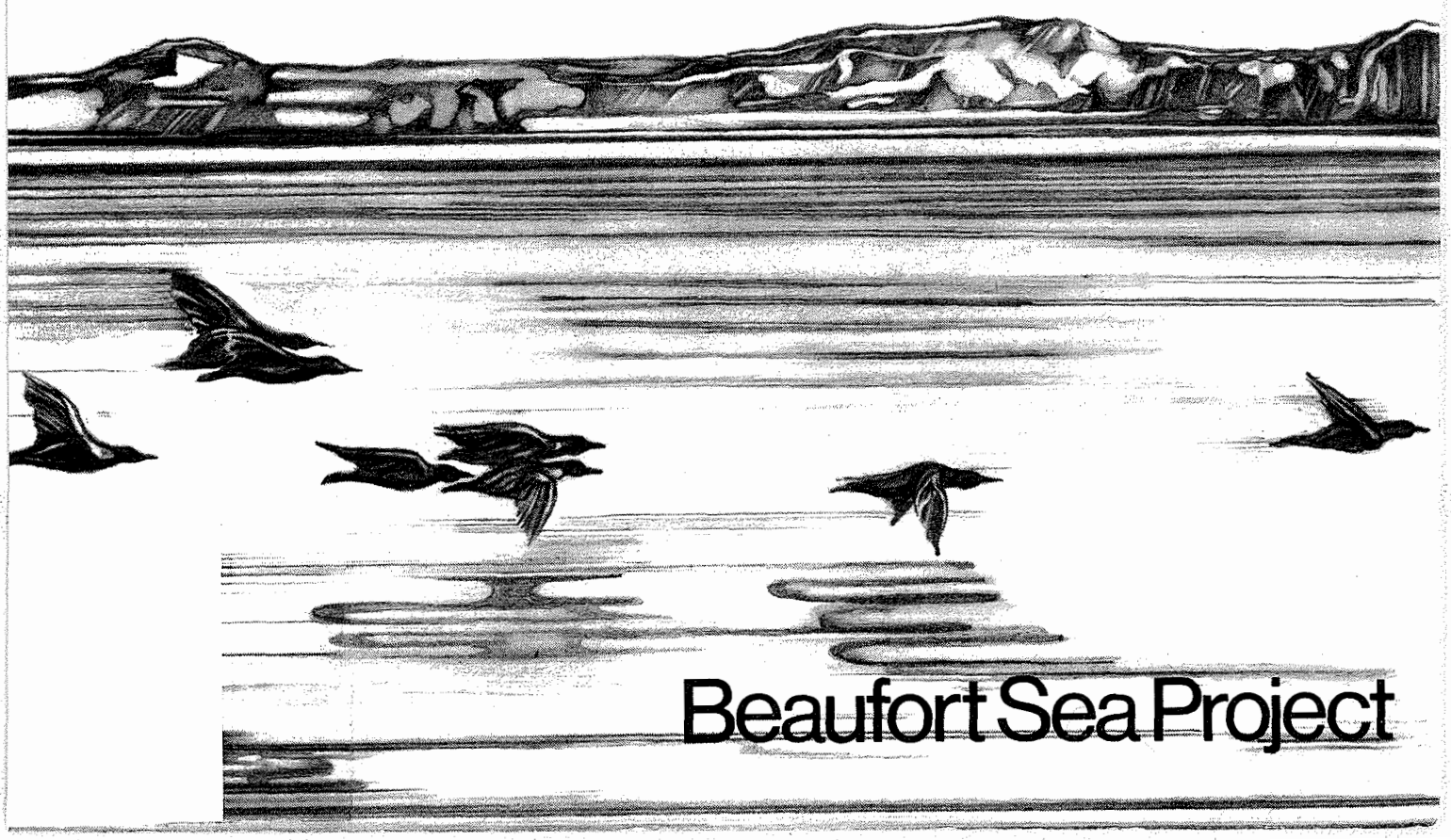

Beaufort Sea Project

BIOLOGICAL PRODUCTIVITY OF THE SOUTHERN BEAUFORT SEA: PHYTOPLANKTON AND SEAWEED STUDIES

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1. SUMMARY

Standing stock and *in situ* primary productivity of the southern Beaufort Sea phytoplankton were determined during the summers of 1973, 1974 and 1975. Average cell numbers were 10 times greater at inshore stations than at offshore stations at corresponding depths while the rate of primary productivity was 2 to 8 times greater at inshore stations. Cell numbers ranged from 2.0 to 4802.0 x 10^3 cells/1, while integrated productivity values averaged 47.45 mg C/m^2/h for inshore stations and 8.82 mg C/m^2/h for offshore stations. Possible reasons for a greater standing stock and primary productivity at inshore stations are discussed.

The largest group represented was the Bacillariophyta with 64 species, followed by the Pyrrophyta with 5 species, the Chrysophyta with 3 species, the Chlorophyta with 2 species and the Euglenophyta and Cyanophyta with 1 species each. There were at least 87 species identified.

The phytoplankton community consisted mainly of diatoms and flagellates. Diatoms dominated the inshore stations and flagellates were more abundant at offshore stations. Possible reasons for this unique distribution are discussed.

Diatoms were more sensitive than flagellates when they were exposed to crude oils, Corexit and crude oil-Corexit mixtures. The toxicity of crude oil-Corexit mixtures on algal photosynthesis and growth was greater than crude oil or Corexit alone. Possible long-term ecological consequences of such differential sensitivity and selective toxicity are discussed.

Primary production of seaweed was severely inhibited by all types of crude oil at relatively low concentrations.

2. INTRODUCTION

Planktonic and attached plants are the primary producers in marine food chains; they transform light energy and fix carbon dioxide into organic matter which can readily be transmitted to higher levels in the food chain. The measurement of the rate of fixation is therefore of the greatest importance to fisheries. In addition, their photosynthetic activity is important in the generation of oxygen needed by all organisms. Standing crops and productivities of marine plants are controlled by environmental factors such as light, temperature, salinity, available nutrients, growth substances, animal grazing and interactions with other organisms. Marked changes in the marine environment may directly or indirectly affect standing crops and productivities, and consequently disturb ecosystems.

In the near future large quantities of crude oil may be available from the Beaufort Sea area. The oil will be transported by tankers or through pipelines to the south for refining. In addition to spillage from tankers, blowouts from offshore wells may cause widespread oil pollution. It is only a matter of time before significant quantities of oil are spilled into the surrounding marine environment.

After a spill, oil starts to dissipate at sea, and is washed on and off the beaches by wind, waves and tidal currents. This means that contamination varies continuously and it is impossible to determine accurately the amount of oil that any one area is exposed to.

Spilled oils are frequently cleaned up by means of spraying chemical dispersants such as Corexit. The dispersant itself may be toxic to marine life.

The best procedure for assessing damage to the environment is a comparison of the ecology and biota of an area before and after an oil spill.

Owing to the complexity of most natural marine communities, and the multiplicity and variability of the environmental factors acting upon them, it is usually difficult to identify and quantify the effects of oils on the entire community or a given species within it. For this reason, it was desirable to carry out bioassays employing laboratory cultures of a single species which could be subjected to changes in concentration individually under controlled conditions. However, the ultimate proof that laboratory-derived culture and bioassay data reflect reality must come from studies of natural marine communities.

The project's objective is to determine the baseline of primary productivity and the potential impact of oil pollution on primary productivity in the Beaufort Sea. This information may provide a greater appreciation of the indirect effects of oil pollution upon higher trophic levels and fish stocks of the Beaufort Sea. Such baseline data are essential for the early detection of deleterious environmental changes resulting from oil exploration and production activities.

3. RESUME OF CURRENT STATE OF KNOWLEDGE

As early as 1936, Galtsoff found that crude oil was toxic to the growth of the diatom, *Nitzschia closterium*. Mommaerts-Billiet (1973) reported that growth of the marine nannoplankton, *Platymonas tetrathele* was inhibited more in a mixture of crude oil and emulsifier than in crude oil alone. Strand *et al*. (1971) developed toxicity test procedures

to evaluate the relative toxicity of oil, chemical dispersants, and oil-dispersant mixtures to marine phytoplankton grown in pure culture. Nuzzi (1973) showed that soluble constituents of #2 fuel oil had an inhibitory effect on the growth of *Chlamydomonas* sp., *Chlorella* sp. and *Sceletonema costatum* in axenic cultures and also impaired natural populations of phytoplankton. Pulich *et al.* (1974) used the same fuel oil to test the growth and photosynthesis of Texan Marine microalgae. They found that the diatom *Thalassiosira pseudonana* was very sensitive to #2 fuel oil. Gordon and Prouse (1973) demonstrated that 3 types of oil inhibited phytoplankton photosynthesis and that the degree of inhibition depended upon oil type and concentration. Kauss *et al.* (1973) found that the toxicity of crude oil to freshwater algae varied from inhibition to stimulation of growth. They explained this as probably due to the interaction of biological and physical variables.

Alexander *et al.* (1972) found that primary productivity was significantly depressed and seasonal succession of algal species was reduced in an oil-polluted small pond in Alaska. Hellebust *et al.* (1975) monitored an experimental crude oil spill on a small subarctic lake in the Mackenzie Valley. They found that the presence of crude oil had no significant effects on phytoplankton composition or abundance throughout the growth season, but had a marked inhibitory effect on most members of the periphyton. They also noted a considerable stimulation of growth of the blue-green alga *Oscillatoria angustissima*.

Any seaweed species will be killed if completely covered by a thick layer of crude oil for a long period of time (Smith, 1970). Craigie and McLachlan (1971) observed that the brown fucoid seaweeds, *Fucus serratus*, *F. vesiculosus* and *Ascophyllum nodosum*, considerably polluted by Bunker C oil following the "Arrow" incident did not exhibit any noticeable toxic effects in mature or juvenile stages.

Holmes (1969) found that oil strongly adhered to the red algae *Endocladia* and *Porphyra* spp., and resulted in death of these species. Similar observations were made following the "Torrey Canyon" accident (Smith, 1970). Total primary productivity in kelp beds following the "Torrey Canyon" accident was greatly reduced in heavily polluted areas (Bellamy and Whittick, 1968). Shiels *et al.* (1973) found that the concentrations of crude oil in seawater necessary to cause a specific degree of photosynthetic inhibition apparently changes seasonally depending on physical and chemical factors and on the species composition and relative abundances. They also found that photosynthetic inhibition occurred in *Laminaria saccharina*, *Cladophora stimpsonii* and *Ulva fenestrata* at 7 ppm Prudhoe Bay crude oil, whereas other species were not significantly affected at this concentration.

More recently, Walker *et al.* (1975) isolated a petroleum-degrading achlorophyll alga, *Prototheca jopfii* from Colgate Creek in Chesapeake Bay.

4. MATERIALS AND METHODS

4.1 Study areas and algal collection

4.1.1 Phytoplankton

Water samples containing natural populations of phytoplankton were collected with a van Dorn sampler from different depths at various locations in the Beaufort Sea and Eskimo Lakes (Fig. 1).

Live phytoplankton subsamples were concentrated on 0.45 μ Millipore membrane filters, and placed in 6-oz Aladdin insulated thermos jars with a small amount of seawater at low temperature (about 2°C). The thermos jars were packed in a styrofoam box with ice packs and shipped back to the Arctic Biological Station for culture studies.

4.1.2 Seaweeds

The sporophytes of *Laminaria* sp. and *Phyllophora* sp. were respectively collected by SCUBA divers from station 560 in Liverpool Bay and station 561 in the Eskimo Lakes (Fig. 1). They were placed in a bucket with seawater and transported to the field laboratory. Prior to the experiments, they were kept in a cage with a float and suspended at 2 metres depth near the field camp (69°25'N, 131°16'W).

Some plants were wrapped with seawater-moistened paper in a styrofoam box with ice packs and transported to Ste. Anne de Bellevue where they were maintained under continuous light at an intensity of 100 lux, at a temperature of 1°C and a salinity of 16 °/₀₀ in a recirculating seawater tank until use.

4.2 Culture medium and conditions

The culture medium used was an artificial seawater, ASP 2 (Provasoli *et al.*, 1957) with the addition of 0.126 mg $Na_2Mo_4 \cdot 2H_2O$ and 19.2 mg $NaHCO_3$ per 100 ml. The pH was adjusted to 7.8. When it was used for carbon-14 uptake experiments, the unlabelled $NaHCO_3$ was omitted.

All experiments were carried out under unialgal culture conditions, and incubation took place in controlled environment incubator shakers (New Brunswick Scientific Co.). These were continuously illuminated with eight 20W Westinghouse F24T12 high output, coolwhite fluorescent tubes at an intensity of 1650 lux, and were shaken continuously at a speed of 200 rpm.

Experiments on the effect of temperature were carried out at 0°, 5°and 10°C.

4.3 Phytoplankton isolation and unialgal cell suspension

The concentrated phytoplankton cells on Millipore membrane filters were grown in 100 ml of ASP 2 in 125 ml Erlenmeyer flasks in a Percival Plant Growth Chamber (Model 1-60 LVL). The flasks were kept at 10°C and continuously illuminated with cool white fluorescent tubes at a light intensity of 1650 lux. After 2 weeks, all flasks were examined for live phytoplankton. Samples of the phytoplankton were then streaked on an agar surface of ASP 2 medium (solidified with 1.5% agar) in a petri dish. After 2 weeks incubation, a variety of colonies formed; several colonies were selected for identification. By repeated subculturing and streaking on agarized ASP 2 medium, unialgal cultures of 5 dominant species, *i.e.* *Chlamydomonas* sp., *Chaetoceros* sp., *Navicula* sp., *Nitzschia* sp. and *Thalassiosira* sp. were obtained. All unialgal isolates were finally transferred to agar slants in test tubes. These cultures were maintained under continuous illumination at an intensity of 100 lux and 1°C and were then routinely transferred once every 4 weeks.

All species of phytoplankton used for laboratory experiments were obtained during the exponential growth phase of unialgal cultures which were grown in ASP 2 liquid medium for 7 to 10 days. Unialgal cell suspensions were adjusted with ASP 2 medium to 4.8×10^5 cells/ml. Twenty ml of this suspension were added to each flask containing 180 ml of oil- and/or Corexit-treated media, and thus all experiments were started with a concentration of 4.8×10^4 cells/ml.

4.4 Preparation of oil- and Corexit-treated seawaters, and oil-Corexit mixtures

4.4.1 Oil- and Corexit-treated seawaters

Corexit 8660 and four different types of crude oil were used in this study and were applied to the phytoplankton and seaweed in two ways; emulsion and oil slick.

4.4.1.1 Oil-seawater emulsion

Three concentrations of oil-seawater emulsions used in the field were prepared as described by Percy and Mullin (1975).

4.4.1.2 Oil slick and Corexit addition

Five different quantities (0, 2, 20, 200 and 2000 µl) of crude oil or Corexit were taken by Pipetman p20, p200, p1000 and p5000 (Gilson Co., France), and were directly added to 180 ml of ASP 2 medium in the 250 ml screw-capped Erlenmeyer flasks.

4.4.2 Oil-Corexit mixtures

Two µl of oils and Corexit were each added to a 250 ml screw-capped Erlenmeyer flask containing 180 ml of ASP 2 medium; the disposable pipette tips were rinsed with the medium 15 times.

4.5 Measurements of primary production

4.5.1 Standing stock determination

Standing stock was measured by cell counts. The methods of phytoplankton preservation, identification and enumeration are described by Foy and Hsiao (1976).

4.5.2 Carbon-14 method

4.5.2.1 Phytoplankton

The method for carbon-14 uptake generally followed procedures outlined by Strickland and Parsons (1968). For in situ experiments, one ml of 10 µCi of $NaH^{14}CO_3$ (NEN Canada) was added to each 300 ml BOD light and dark bottle with a phytoplankton sample of known total carbonate content. Duplicate bottles were set up, well stoppered and suspended on a line which was anchored by 2 heavy lead weights and buoyed vertically by a float. The bottles were placed at predetermined sampling depths or in a seawater-cooled water bath for 4-6 hours under natural sunlight and temperature. After incubation, the in situ labelled phytoplankton was killed by adding 1 ml of 40% formaldehyde neutralized with calcium carbonate. As soon as the labelled samples were shipped back to the field camp, they were filtered through Millipore HA type 47 mm diameter filters.

In laboratory experiments, the 250 ml screw-capped Erlenmeyer flasks containing 200 ml of test culture medium and phytoplankton species were held in controlled environment incubator shakers at the standard culture conditions for a 30 to 60 min period of equilibration prior to addition of 100 µl of 10 µ Ci $NaH^{14}CO_3$. Following the addition of radioactive carbon, triplicates of 5 ml of labelled phytoplankton samples were taken after incubating for 4, 8, 12, 24, 48, 72 and 96 hours. They were immediately filtered through Millipore HA type 25 mm diameter filters.

Both in situ and laboratory labelled samples were filtered under a vacuum of 380 mm Hg, and rinsed with 5 ml of 0.001 N HCl made with prefiltered natural seawater or ASP 2, to remove inorganic radioactive bicarbonate solution

retained on the filter. The wet filters were transferred to glass scintillation vials containing 15 ml of liquid scintillation cocktail, Aquasol-2, and well agitated, and then counted for 10 min with a Nuclear Chicago Isocap 300 liquid scintillation system. After counting, 10-100 µl of carbon-14 labelled liquid toluene standard was added to each sample, and all vials were recounted.

4.5.2.2 Seaweeds

For in situ experiments, both *Laminaria* sp. and *Phyllophora* sp. blades were cleaned with Kimwipes to remove epiphytes. Then discs of *Laminaria* blades were cut from meristematic tissues with a cork borer (size #6). *Phyllophora* blades were cut with a razor blade at the end of the 1st dichotomy and pieces with a length of about 2.0 cm were selected. Eight discs of *Laminaria* or 4 pieces of *Phyllophora* were carefully selected and placed with the oils to be tested into 300 ml BOD light and dark bottles filled from a single batch of Millipore prefiltered natural seawater. One ml of 10 µ Ci $NaH^{14}CO_3$ was added to each bottle. The bottles were stoppered and then held vertically on the line at 2 metres depth for 4 to 8 hours at station 507 under natural sunlight and temperature. After incubation, all bottles were injected with 1 ml of 40% formaldehyde neutralized with calcium carbonate to kill the plants, and thus stop photosynthesis. The bottles from in situ experiments were kept in a light-proof box, and transported to the field camp. All blades were removed from the bottles then rinsed with 0.001 N HCl made with Millipore prefiltered natural seawater or ASP 2, blotted dry with Whatman filter paper, and then placed on aluminium trays to dry in an oven overnight at a temperature of 70°to 80°C.

The dried *Laminaria* and *Phyllophora* pieces were placed in tightly capped vials and stored in a desiccator in a freezer until radioassay. Using a metal spatula, the dried seaweeds were crushed to very fine pieces to facillitate weighing out approximately 20 mg subsamples.

To make algal tissue soluble for scintillation counting, Lobban's method (1974) was generally followed. The dried, crushed subsamples of ^{14}C labelled *Laminaria* and *Phyllophora* were first rewetted with 0.2 ml of distilled water in the scintillation vials for 2 hours.

0.2 ml of 60% perchloric acid was then added and swirled, followed by the addition with swirling of 0.4 ml of 30% hydrogen peroxide. The vials were capped tightly and the samples were placed in an oven at 70°to 80°C for 2 hours with agitation every 15 minutes. After digestion, the vials were allowed to cool to room temperature. Sample preparation was completed by addition of 6 ml of 2-ethoxyethanol and 10 ml of cocktail containing 6 g PPO (2,5-diphenyloxazole) per liter of toluene. The vials were recapped and shaken thoroughly several times, then placed in the scintillation counter for 3 x 10 minute counts for each sample. After counting, 50 µl of ^{14}C-toluene standard was added to each sample, and all vials were recounted.

All counts were corrected for efficiency by the internal standardization method of Schindler (1966). The counting efficiency was calculated as follows:

$$\text{Counting efficiency } E = \frac{C^1 - C}{S}$$

where C^1 = the number of cpm measured after addition of the toluene standard.

C = the number of cpm of the sample alone.

S = the actual radioactivity of toluene standard added in disintegrations per minute.

$$\text{Corrected carbon - 14 uptake (dpm)} = \frac{C}{E}$$

Carbon-14 measured photosynthesis

$$P = \frac{(R_L - R_D) \times C_I \times 1.05}{R \times T}$$

where

P = photosynthetic production, mg C/m^3/h

R = absolute activity (dpm) of carbon-14 added to sample

R_L = uptake carbon-14 in dpm from light bottles

R_D = uptake carbon-14 in dpm from dark bottles

T = time of incubation in hours

1.05 = isotope correction factor

C_I = total carbonate content of seawater in the BOD bottle as mg C

4.6 Measurement of phytoplankton growth

The duration of the growth experiments was approximately 10 to 20

days, depending on temperature tested. Every 2 days or at the end of the experiment, 5 ml aliquots were taken from the cultures. They were placed into test tubes, and killed by heating in a water bath at 30°C. Cell counts, for most of the phytoplankton cultures, were made with an AO Spencer hemacytometer, 0.1 mm deep, having Improved Neubauer ruling. For *Thalassiosira* sp. a Fuchs-Rosenthal hemacytometer, 0.2 mm deep, was used.

4.7 Determination of stimulation and inhibition

In order to determine the stimulatory or inhibitory response to the oils and/or Corexit, the cell count or photosynthetic production of each oil- and/or Corexit-treated sample was divided by the cell count or photosynthetic production of its control, and then multiplied by 100. A percentage less than 100 indicates that oil and/or Corexit inhibits cell growth and radiocarbon uptake, while a percentage greater than 100 indicates stimulation.

5. RESULTS

5.1 Standing stock, community structure, species composition, distribution and abundance of natural populations of phytoplankton

5.1.1 Standing stock

The standing stock in the euphotic zone of the southern Beaufort Sea as measured by cell counts, decreased with increasing distance from the shore. The highest standing stock value, 4802.0 X 10^3 cells/l, was encountered at inshore station 575; all other stations ranged from 2.0 to 654.0 X 10^3 cells/l. The averaged standing stock ranged from 7.23 to 240.4 X 10^4 cells/l for the inshore stations and 7.0 to 205.8 X 10^3 cells/l for offshore stations. Values for the inshore stations were consistently 10 times higher than nearby offshore stations. The standing stock in the water column was predominantly in the upper 1 metre at ice stations, in the upper 5 metres at open water stations. It then decreased with increasing depth (Fig. 2).

5.1.2 Community structure

There were 5 distinct phytoplankton communities in the southern Beaufort Sea, including diatoms, flagellates, dinoflagellates, chrysophytes and blue-green algae. Diatoms were generally dominant in numbers and total species represented at each station. Diatoms and flagellates were the most abundant, followed by dinoflagellates and chrysophytes; the blue-green algae were the least abundant. Their distributions varied with locality, depth and environmental conditions. Diatoms accounted for 52.0% to 99.5% of the phytoplankton at inshore stations and

5.1% to 20.0% at offshore stations, with the exception of station 14. The flagellate community was the most abundant at offshore stations where it formed up to 89% of the population, then decreased to about 0.7% of the total phytoplankton population at inshore stations. Dinoflagellates occurred more frequently at offshore stations than at inshore stations, with the exception of station 530. The chrysophytes were abundant particularly at offshore station 9 where they constituted from 39% to 40% of the population; at other stations they formed less than 1%. At inshore stations they accounted for about 0.5% to 3.8% of the phytoplankton. The blue-green algal community was occasionally found at inshore stations ranging from 0.6% to 1.3%, but it was very rare at offshore stations, except at station 14 where it made up 1.0% of the total phytoplankton population.

5.1.3 Species composition, distribution and abundance

There were 51 genera and 87 species of phytoplankton identified from the Beaufort Sea and Eskimo Lakes (Table 1). The species composition, distribution and abundance are given in detail in a technical report by Foy and Hsiao (1976).

There was a very conspicuous difference between the low salinity surface layer (1-5 m) and the more saline layer below, with the exception of station 575. Above 5 metres, all species of phytoplankton were relatively more abundant than at greater depths. Below there was a distinct reduction both qualitatively and quantitatively in the phytoplankton population.

Highest counts of Bacillariophyta were found at station 575 at 7 metres depth during early August, with the maximum total number of *Chaetoceros* spp. being 4,692,000 cells/l, when *C. socialis, C. septentrionalis, C. decipiens, C. wighamii* and *C. ceratosporum* were the most common species. The greatest number of Chlorophyta found was *Chlamydomonas* sp. with 21,000 cells/l in the surface water of station 29 in early August; of Euglenophyta the greatest number was *Euglena* sp. with 88,000 cells/l encountered at station 22 at 1 metre depth. *Dinobryon balticum*, obtained from the surface water of station 575 in early August, comprised the highest count of Chrysophyta found, while *Goniaulax catenata* in quantities of 166,000 cells/l at station 22 at 1 metre during mid-August gave the greatest number of Pyrrophyta. The species of Cyanophyta were never abundant, ranging from 1,000-3,000 cells/l, and were occasionally found in the waters of the upper 5 metres at inshore station 530, 540 and 527 during late July; they were found at only one offshore station (#14) at 1 metre depth during mid-July in numbers of 1,000 cells/l.

The distribution of dominant species of phytoplankton is listed in Tables 2 and 3. Three phytoplankton blooms occurred at inshore stations: A *Melosira islandica* bloom was found in the surface water at station 562 and 527, in early May and late July, respectively. A *Chaetoceros* spp. bloom was observed at station 575 at 7 metres depth during early August. A *Goniaulax catenata* bloom was noted at station 22 at 1 metre depth during mid-August.

Only flagellates formed blooms at offshore stations occurring at 2 different times and depths: the first was found during August at stations 29 and 544 from the waters of 1 metre and surface, respectively; the second was noted during late August and early September from the stations 552 and 559 at 3 metres depth.

5.2 In situ primary productivity of southern Beaufort Sea

The vertical distribution of in situ gross primary productivity of phytoplankton in the southern Beaufort Sea varied from the lowest value of 0.17 mg $C/m^3/h$ at 1 metre depth at station 566 during early July, to the highest value of 8.8 mg $C/m^3/h$ at 7 metres depth at station 575 during early August (Fig. 3). The average rate of primary production for inshore stations was generally 2 to 8 times higher than that at offshore stations with respect to the corresponding depths (Table 4). The maximum averaged production of inshore stations was 7.41 mg $C/m^3/h$ at 1 metre and at offshore stations was 1.67 mg $C/m^3/h$ at 7 metres. Then, primary production decreased with increasing depths for both stations.

Integrated productivity values for inshore stations were 45.4 to 49.5 mg $C/m^2/h$ and at offshore stations ranged from 4.1 to 18.2 mg $C/m^2/h$ (Table 5). The water column productivity averaged 47.45 mg $C/m^2/h$ at inshore stations, and 8.82 mg $C/m^2/h$ at offshore stations. The respective means were 1138.8 mg $C/m^2/day$ and 211.65 mg $C/m^2/day$. The most productive regions in the southern Beaufort Sea were found at inshore stations 22 and 575. The rate of primary production at inshore stations was 5 times greater than that at offshore stations.

5.3 In situ primary productivity of Eskimo Lakes

The vertical distribution of in situ gross primary productivity of the Eskimo Lakes showed a maximum at 3 metres depth of 1.7 mg $C/m^3/h$ and a minimum at 30 metres depth of 0.14 mg $C/m^3/h$ (Table 6, Fig. 4).

Integrated water column rates varied from 6.6 to 15.2 mg $C/m^2/h$ or 158.4 to 364.8 mg $C/m^2/day$ (Table 7). The average rate was 11.5 mg $C/m^2/h$ or 275.1 mg $C/m^2/day$. Station 515 apparently was the most productive in the Eskimo Lakes.

5.4 Effects of oils, Corexit and oil-Corexit mixtures on phytoplankton primary productivity

5.4.1 In situ oil toxicity tests

5.4.1.1 Oil-seawater emulsion

The results of studies on the effects of light and heavy emulsions of crude oils on phytoplankton primary production are presented in Fig. 5. This indicates that heavy emulsion concentrations are 1.5 to 3 times more toxic than are light concentrations. Venezuela crude oil was the most toxic to the phytoplankton. It caused 58% and 82% inhibition with light and heavy emulsions respectively.

Heavy emulsion concentrations of the three crude oils were tested again at station 507. Primary production was inhibited by 78.4%, 77.7% and 75.2% by the Atkinson Point, Norman Wells and Venezuela crude oils, respectively (Fig. 5).

5.4.1.2 Oil slick addition

The effects of 4 types of oil at a concentration of 1 µl/100 ml on the primary productivity of natural population of phytoplankton in the southern Beaufort Sea and Eskimo Lakes were determined. The results of these tests are presented in Tables 8 and 9.

Values for the Beaufort Sea samples ranged from 65.9% to 100.8% with the addition of Atkinson Point crude, from 53.7% to 156% in the presence of Norman Wells crude, from 75.9% to 184.1% in the samples treated with Pembina crude, and from 76.7% to 184.6% in the samples exposed to Venezuela crude (Fig. 6). Their respective average rates were 88.7%, 101.0%, 116.6% and 105.1% of the controls. These indicated that Atkinson Point crude caused 11.3% inhibition, while Norman Wells crude did not affect production significantly and Pembina and Venezuela crudes exhibited 16.6% and 5.1% stimulation respectively.

The primary productivity of natural populations of phytoplankton in the Eskimo Lakes was inhibited 27.8%,

14.8%, 12.6% and 30.1% respectively by exposure to Atkinson Point, Norman Wells, Pembina and Venezuela crude oils (Fig. 7). Venezuela crude was the most toxic to phytoplankton.

Production rates varied with oil types and species composition contained in each of the station samples tested (Tables 10 and 11).

5.4.2 In situ, oils, Corexit and oil-Corexit mixtures toxicity tests

The results of the effects of oils, Corexit and oil-Corexit mixtures at a concentration of 1 µl/100 ml on the primary productivity of natural populations of phytoplankton samples at station 507 in the Eskimo Lakes are shown in Fig. 8. Average primary production was inhibited 14.9% by Norman Wells crude, 10.7% by Pembina crude, 8.3% by Atkinson Point Crude-Corexit mixture, 19.6% by Norman Wells crude-Corexit mixture and 2.5% by Venezuela crude-Corexit mixture. It was unaffected by Venezuela crude, and stimulated 8.6% by Atkinson Point crude, 14.6% by Corexit alone and 7.1% by Pembina crude-Corexit mixture.

The species composition of test samples is listed in Table 12.

5.4.3 Oil toxicity in the laboratory cultures

Primary production of 4 indigenous species of phytoplankton was determined under standard culture conditions with the additions of 4 different types of oil at a concentration of 1 µl/100 ml, at temperatures of 0°, 5° and 10°C, and for exposure times of 4 to 96 hours. The results from the experiments are given in Figures 9 to 12.

5.4.3.1 *Chlamydomonas* sp.

Chlamydomonas sp. was considerably stimulated by all types of crude oil tested at both 0°and 5°C, and even for the longest exposure time of 96 hours (Fig. 9). The averaged magnitude of stimulation at 5°C was 3 to 5 times greater than that at 0°C. Although the stimulation was slightly decreased with increasing duration of exposure time, all types of oil still stimulated photosynthesis at least 3 and 15 times greater than the controls at 0°and 5°C, respectively.

After 96 hours exposure to Atkinson Point, Norman Wells, Pembina and Venezuela crude oils at 5°C, the primary production of this green flagellate was 21.1, 19.9, 16.6 and 14.9 times respectively greater than the controls; even at 0°C, they were still 4.7, 7.3, 4.9 and 3.4 times higher than the controls.

5.4.3.2 *Chaetoceros* sp.

Primary production of *Chaetoceros* sp. was very slightly inhibited after the first 4 hours of exposure to Atkinson Point and Norman Wells crude oils at all temperatures (0°, 5° and 10°C) tested; it was significantly inhibited by Venezuela crude oil at 10°C, and less inhibited at 0° and 5°C. In contrast Pembina crude oil stimulated primary production 24.8% at 0°C, did not affect it at 5°C and inhibited it 8.5% at 10°C (Figs. 10, 11 and 12). Generally, primary production of this centric diatom progressively decreased with increasing temperatures and longer exposure times. The inhibitory effect was greatly pronounced after 96 hours of exposure to the crude oils. The greatest inhibition occurred at 10°C and the smallest at 0°C for all types of crude oil tested. For this diatom, oil toxicity decreased in the following sequence: Venezuela crude > Atkinson Point crude > Norman Wells crude > Pembina crude.

5.4.3.3 *Navicula* sp.

Primary production of *Navicula* sp. at 0°C was inhibited 2.5% compared with the control during the first 4 hours of exposure to Atkinson Point crude, while the other 3 types of oil inhibited photosynthesis ranging from 12.5% to 17.7% of that in the controls (Figs. 13, 14, 15 and 16). After 8 hours, the production in Atkinson Point crude gradually increased with increasing exposure time; even up to 96 hours, the productivity was still 21.3% greater than that of the control. Similar responses were obtained from the cells treated with Norman Wells crude, Pembina crude and Venezuela crude, but the stimulatory effect was not noted until after 48 hours of exposure to the above mentioned crude oils. At 5°C, production was most inhibited and progressively decreased with increasing length of exposure time. A

decrease of primary production to 50% of the control occurred after 48 hours in the cells treated with Norman Wells crude, while in the other three types of crude oil a 50% decrease was not noted until after 72 hours of exposure. At 10°C, the degree of inhibition was less than at 5°C with respect to the corresponding types of oil and exposure time.

5.4.3.4 *Nitzschia* sp.

After the first 4 hours of exposure to Atkinson Point, Norman Wells, Pembina and Venezuela crude oils at 0°C, the primary production of *Nitzschia* sp. was respectively 3.4%, 19.6%, 7.2% and 12.8% lower than that in the control cells (Figs. 17, 18, 19 and 20). After 8 hours, the production of the diatom cells treated with Atkinson Point, Norman Wells, and Pembina crude oils was 8.9%, 10.3% and 18.7% respectively greater than that in the controls, while the cells exposed to Venezuela crude were still slightly inhibited. After 12 hours, the productivity was stimulated to a maximum by 30% to 39% of the control in the diatoms treated with Atkinson Point crude, Norman Wells crude and Pembina crude, while in the cells treated with Venezuela crude the maximum production reached after 12 hours was only 93.2% of that in the control. After 24 hours, all productions started to decline, but the cells in Atkinson Point crude and Pembina crude were still stimulated in the uptake of carbon-14. After 48 hours, the inhibitory effect was progressively pronounced in Atkinson Point crude, Norman Wells crude and Venezuela crude, while in Pembina crude, the inhibition occurred slightly.

The lowest primary production occurred at 10°C with respect to corresponding types of oil and lengths of exposure times. For *Nitzschia* sp. toxicity decreased in the following sequence: Venezuela crude > Norman Wells crude > Atkinson Point crude > Pembina crude.

5.4.4 Corexit and oil-Corexit mixture toxicity in the laboratory cultures

5.4.4.1 *Chlamydomonas* sp.

Corexit alone had a markedly stimulatory effect on the primary production of *Chlamydomonas* sp. cells after 4 to 96 hours of exposure (Fig. 21). It enhanced

photosynthesis, ranging from 7 to 8 times at 0°C and 21 to 37.5 times at 5°C greater than that of the control cells at corresponding temperatures and exposure times. The extent of stimulation decreased with the additions of 4 types of crude oil (Fig. 21). Although the production in oil-Corexit mixtures was lower than the Corexit alone, it was still greater than that of the cells treated with all types of crude oil alone, and was greater than the controls by at least 12.5 times.

Generally, the productivity was slightly changed by the increasing length of exposure time at 0°C for both Corexit alone and all crude oil-Corexit mixtures. At 5°C, Corexit alone, enhancing the greatest primary production, continuously stimulated photosynthesis during the course of the 96 hour experiment. Norman Wells crude-Corexit mixtures also continuously stimulated photosynthesis but at a lower rate and a lower primary production. The productivity of this green flagellate in the Corexit mixed with the 3 other individual types of crude oil was increased in the first 12 hours. After 12 hours, the productivity in the Venezuela-Corexit mixtures started to decrease, followed at 24 hours by that of Atkinson Point-Corexit mixtures, while the rate of productivity remained virtually the same in the Pembina-Corexit mixtures.

5.4.4.2 *Chaetoceros* sp.

After the first 12 hours of exposure to Corexit, primary productivity of *Chaetoceros* sp. at 0°C increased ranging from 2% to 28% greater than that of the controls (Fig. 22). Thereafter, it gradually decreased with increasing exposure time. At 5°C, the production initially increased 15% over the control after the first 4 hours of exposure to Corexit. From 8 to 96 hours, it progressively decreased. In contrast, at 10°C, after 24 hours, the productivity initially was inhibited by 2.3% to 13.8% of the control. After 48 hours, Corexit was reduced in toxicity, and stimulated photosynthesis.

The primary productivity of *Chaetoceros* sp. was stimulated 23.6%, 18.3% and 9.1% when the Corexit was added to Atkinson Point crude, Pembina crude and Venezuela

crude, while the addition of Corexit to Norman Wells crude did not alter the productivity (Figs. 23, 24, 25 and 26). Generally the greater inhibition occurred at longer periods of exposure and higher temperatures, except in the case of Pembina crude at 10°C after 96 hours when the production was 99.5% of the control.

5.4.4.3 *Navicula* sp.

Navicula sp. had various responses to Corexit (Fig. 27) and mixtures of Corexit with each individual crude oil depending on temperature and exposure time (Figs 13, 14, 15 and 16). At 0°C, primary production was first inhibited after 4 hours of exposure to Corexit alone and Corexit combined with each individual type of crude oil. Thereafter, it increased with increasing exposure time. After 96 hours, Corexit alone and the Atkinson Point crude-Corexit mixture stimulated photosynthesis, and thus production was 46% and 29% greater than that of the controls, while the Venezuela crude-Corexit, Norman Wells crude-Corexit and Pembina crude-Corexit mixtures slightly inhibited photosynthetic capacity. The production decreased more at 10°C than at 5°C, and with increasing length of exposure time except for the Corexit alone after 24 hours of exposure at 10°C when production continued to increase, while at 5°C it decreased slightly.

5.4.4.4 *Nitzschia* sp.

At 0°C primary production of *Nitzschia* sp. was stimulated by Corexit alone (Fig. 28). Its maximum production occurred at 12 hours after the addition of Corexit. Thereafter, it gradually decreased, but it was still 3.4% greater than that of the control. At 5°C the stimulatory effect appeared only during the first 12 hours of exposure to the Corexit. After that an inhibitory effect was noted. At 10°C, during the first 72 hours of exposure, the production was inhibited from 5.6% to 7.3%. After 72 hours it increased and by 96 hours was being stimulated.

The production was initially slightly inhibited after the cells were exposed to the mixtures of Corexit with the individual crude oils for 4 hours at 0°C (Figs. 17, 18, 19 and 20). After 8 to 12 hours, photosynthetic

capacity was enhanced about 21% in the Atkinson Point crude-Corexit mixture, 19% in Norman Wells crude-Corexit mixture and 22.5% in Pembina crude-Corexit mixture, while the cells treated with the Venezuela crude-Corexit mixture remained inhibited. The production decreased with increasing exposure time in all mixtures. Production at higher temperatures (5°and 10°C) consistently decreased more than at 0°C. For this diatom, the toxicity decreased in the following sequence: Venezuela crude-Corexit mixture > Norman Wells crude-Corexit mixture > Atkinson Point crude-Corexit mixture > Pembina crude-Corexit mixture > Corexit alone.

5.5 Effects of oils, Corexit and oil-Corexit mixtures on phytoplankton growth

5.5.1 Temperature and oil toxicity

Growth responses of phytoplankton in the presence of 4 types of oil and 4 different concentrations at temperatures of 0°, 5°and 10°C and for exposure times of 10 to 20 days are shown in Tables 13 to 17 inclusive.

At 0°C, at a concentration of 1 µl/100 ml, Atkinson Point and Venezuela crude oils inhibited growth of *Chlamydomonas* sp. by about 1.1%and 5.3%, respectively, while Norman Wells crude and Pembina crude stimulated growth by about 20.1% and 11.3% respectively (Table 13). At higher concentrations, all types of crude oil more greatly inhibited growth, varying from 18.8% (Atkinson Point crude at concentration 10 µl/100 ml) to 84.6% (Norman Wells crude at concentration 1000 µl/100 ml).

At 5°C, generally, the growth was the most inhibited with respect to the corresponding oil types and concentrations (Table 13). The maximum inhibition was 94.5% at 1000 µl/100 ml of Norman Wells crude. At 10° C, growth was little better than at 5°C, but worse than at 0° C in the corresponding oil types and concentrations.

Growth of 3 species of diatoms (*Chaetoceros* sp., *Navicula* sp. and *Nitzschia* sp.) was greatly inhibited by all types of crude oil tested at a concentration of 1 µl/100 ml (Tables 14 to 17). It sharply decreased with increasing oil concentrations and varied with temperatures. At 0°C, Norman Wells crude at a

concentration of 1000 µl/100 ml was lethal to *Chaetoceros* sp. while the same concentration of Atkinson Point crude, Pembina crude and Venezuela crude caused 98%, 99.5% and 99.4% inhibition of cell growth respectively.

At 5°C, the lethal concentration of Norman Wells crude was only one-tenth of the concentration at 0°C, i.e. 100 µl/100 ml. This concentration almost completely inhibited the growth of *Navicula* sp. and *Nitzschia* sp. The same concentration of Venezuela crude was lethal to *Chaetoceros* sp. The lethal concentration of Norman Wells, Pembina and Venezuela crude oils to *Nitzschia* sp. was 1000 µl/100 ml, while this concentration of Atkinson Point caused 99.6% inhibition of growth.

At 10°C, Venezuela crude became lethal at a concentation of 1000 µl/100 ml to *Chaetoceros* sp. (Table 17). Some growth (0.9% to 2.3% of control) occurred using the other 3 types of crude oil at this concentration (Tables 14 to 16). No concentration of any type of crude oil was found to be lethal to *Navicula* sp. and *Nitzschia* sp. Their growth ranged from 0.1% to 4.2% of the controls.

Toxicity of Norman Wells, Pembina and Venezuela crude oils for these 3 species of diatoms was the greatest at 5°C, then at 10°C and the least at 0°C (Tables 15 to 17), while the toxicity of Atkinson Point crude oil slightly increased with rising temperature (Table 14).

5.5.2 Exposure time and oil toxicity

Growth of *Chlamydomonas* at 0°C gradually increased with increasing exposure time up to 20 days in Atkinson Point crude oil at concentrations lower than 100 µl/100 ml. It progressively decreased in the other 3 types of oil at all concentrations (Tables 14 to 17). At 5°C, the growth decreased with increasing exposure time at all concentrations of Atkinson Point crude tested. It was slightly increased by extending the exposure time in all concentrations tested of Norman Wells, Pembina and Venezuela crude oils.

After 14 days of exposure to all types of crude oil at all concentrations at 0°C, the growth of *Chaetoceros* sp. was markedly inhibited (Tables 14 to 17). The range of inhibition was 94.4% to 99.7%, while all cells were killed by Norman Wells crude at concentrations higher than 10 µl/100 ml and by Pembina and Venezuela crude oils at concentrations higher than 100 µl/100 ml. After 20 days, the cells displayed growth of only 0.1% to 1.3% of the controls. The lethal

concentration of Atkinson Point was 1000 µl/100 ml. All cells were killed by Norman Wells, Pembina and Venezuela crude oils at concentration as low as 1 µl/100 ml.

At 5°C, growth of *Chaetoceros* sp. was limited by all types of crude oil (Tables 14 to 17). After 14 days of exposure, lethal concentrations of 100, 10 and 100 µl/100 ml of Atkinson Point, Norman Wells and Pembina crude oils respectively were observed. Concentrations 10 times greater were necessary for the oils to be lethal to the same cells after only 10 days of exposure. The lethal concentration of Venezuela crude remained the same.

Navicula sp. was also greatly affected by the length of exposure time to various concentrations of 4 different types of crude oil (Tables 14 to 17). Generally the growth of this diatom was highly limited by the prolonged exposure time, and was significantly inhibited by increasing the concentrations. At 0°C, cell production after 20 days of exposure to Atkinson Point, Norman Wells, Pembina and Venezuela crude oils was repsectively 2 to 3 times, 3 to 4 times, 2 to 7 times and 4 to 8 times lower than that at 10 days with respect to corresponding oil concentrations.

Nitzschia sp. was also considerably inhibited by prolonged exposure time to all types and concentrations of crude oil tested (Tables 14 to 17). The extent of inhibition at 0°C was less than that of *Navicula* sp. at corresponding oil concentrations and exposure times. At 5°C, *Nitzschia* sp. exhibited greater inhibition than *Navicula* sp. after 14 days of exposure to all types and concentrations of crude oil tested. The lethal concentration to *Nitzschia* sp. by Norman Wells crude was 100 µl/100 ml, and by Venezuela crude was 1000 µl/100 ml.

5.5.3 Temperature and Corexit toxicity

After 10 days of exposure to a Corexit concentration of 1 µl/100 ml, cell production of *Chlamydomonas* sp. increased by 3.8% to 34% when temperature was raised from 0°to 10°C (Table 18). It was slightly inhibited by Corexit at a concentration of 10 µl/100 ml at a temperature of 0° to 5°C. When incubated at 10°C, the growth of the cells was stimulated by about 2.2%. At higher temperatures and concentrations, a greater inhibition of *Chlamydomonas* growth was obtained.

At 0°and 5°C, the growth of *Chaetoceros* sp. was slightly stimulated by Corexit at 1 µl/100 ml, while it was inhibited

by 52.5% at 10°C (Table 18). At concentrations higher than 10 µl/100 ml, cell production of *Chaetoceros* sp. decreased greatly with higher temperatures. At 10° C, lethal concentration was 1000 µl/100 ml.

Cell growth of *Navicula* sp. was inhibited 76% more at 0°C than that at 5°C, while it was stimulated by 45.8% at 10°C (Table 18). At concentrations higher than 100 µl/100 ml, greater inhibition was shown at higher temperatures.

Growth of *Nitzschia* sp. was limited by about 22% at 0°C and 1.8% at 10°C, while it was stimulated by 17.2% at 5°C (Table 18). There was an appreciable inhibition with higher concentrations of Corexit when the temperatures were increased. At a concentration of 1000 µl of Corexit/100 ml, there was 78.8%, 95.8% and 98.7% inhibition on the cells incubated at 0°, 5° and 10°C respectively.

5.5.4 Exposure time and Corexit toxicity

Cell production of *Chlamydomonas* sp. at 0°C increased slightly with the length of exposure time (Table 18). It was 2.4% greater after 20 days of exposure to 1 µl/100 ml of Corexit than that of cells left for 10 days. At 10 µl/100 ml, the growth was initially inhibited by about 16.4% after 10 days of exposure. Cell numbers progressively increased with increasing incubation time up to 20 days. Cell production was 3.4% greater than that of the control at this time. At concentrations higher than 100 µl/100 ml, inhibition of growth significantly declined with longer exposure time. At 5°C the growth was more inhibited at 14 days of exposure than at 10 days of exposure.

Growth of *Chaetoceros* sp. was initially stimulated at 0°C after the first 10 days of exposure to Corexit at a concentration of 1 µl/100 ml, and then decreased with an increasing exposure time (Table 18). This phenomenon also occurred at 5°C. The greatest inhibition was observed at 20 days after exposure to Corexit at the concentration of 1000 µl/100 ml.

Cell production of *Navicula* sp. at 0°C was greatly inhibited by increasing the exposure time up to 20 days (Table 18). The extent of inhibition was greater at higher concentrations than at lower concentrations. At 5°C, toxicity of Corexit decreased with longer exposure.

Growth of *Nitzschia* sp. at 0°and 5°C gradually decreased with increasing exposure time with all concentrations of Corexit tested (Table 18). The inhibition of growth was greater at higher concentrations than at lower ones.

5.5.5 Oils, Corexit and oil-Corexit mixtures toxicity tests

Five species of phytoplankton were grown in ASP 2 medium containing 1 µl/100 ml of crude oil, Corexit or oil-Corexit mixture (1:1 ratio) for 14 days at 5°C and for 10 days at 10°C. The results are presented in Figures 29 to 32 inclusive.

At 5°C, cell growth of *Chlamydomonas* sp. was inhibited by about 11.6%, 24.0%, 8.4% and 28.3% after 10 days of exposure to Atkinson Point, Norman Wells, Pembina and Venezuela crude oils, respectively (Fig. 29). Their respective growth in the oil-Corexit mixtures was slightly decreased (Fig. 30). Only when the cells were grown with Corexit alone, did a small stimulation occur. This stimulation disappeared after a further 4 days' incubation. The cells treated with oil-Corexit mixtures increased in number slightly after 14 days of exposure. At 10°C, the pattern of growth in all types of crude oil was similar to that at 5°C after 10 days of exposure, but there was less inhibition (Fig. 31). Cell production in all types of oil-Corexit mixtures was stimulated from 1.5% to 12%, except with Venezuela Corexit mixtures which was inhibited by about 14% (Fig. 32).

Growth of *Chaetoceros* sp. at 5°C was enhanced by only Pembina crude oil after 10 days of exposure (Fig. 29). Corexit alone highly inhibited growth, and thus both Atkinson Point crude-Corexit and Pembina crude-Corexit mixtures decreased growth 29% and 80% respectively more than those treated with Atkinson Point crude and Pembina crude alone (Fig. 30). Growth was respectively 38% and 44% greater with Norman Wells crude-Corexit and Venezuela crude-Corexit mixtures than growth with the crude oils alone. Inhibition of growth was consistently increased with increasing the exposure time. Inhibition was greater at 10°C with Atkinson Point crude, Pembina crude, Corexit, Norman Wells crude-Corexit mixture, and Venezuela crude-Corexit mixture than at 5°C (Figs. 31 and 32), while the growth was a little greater at 10°C than at 5°C in the presence of Norman Wells crude, Venezuela crude, Atkinson Point crude-Corexit mixture, and Pembina crude-Corexit mixture.

Navicula sp. was greatly inhibited by all types of crude oil and oil- Corexit mixtures after 10 days of exposure at 5°C (Figs. 29 and 30). The inhibition of growth was about 99% in all cases. It did not change after 14 days of incubation.

Production was less inhibited by Corexit alone. After 10 days of exposure, the inhibition was about 26.5%, and decreased to 0.9% after 14 days of exposure. At a temperature of 10°C, cell production was 35.6% greater than that at 5°C (Figs. 31 and 32). There was 9.1% stimulation as compared to the control. Although growth at 10 C was increased slightly cell production with all types of oil and oil-Corexit mixtures was still low, ranging from 1.8%to 28.4% of the control (Figs. 31 and 32).

After 10 days of exposure to Atkinson Point, Norman Wells, Pembina and Venezuela crude oil, cell production of *Nitzschia* sp. was less than 13% of the control at 5°C (Fig. 29). The growth was only stimulated by Corexit alone, and increased with longer exposure time. It did not change significantly after Corexit was added to all types of crude oil, and was decreased slightly after a further 4 days of exposure (Fig. 30). At 10°C, cell production increased slightly with Atkinson Point and Pembina crude oils, while it decreased sharply with other types of crude oil, Corexit and all types of oil-Corexit mixtures (Figs. 31 and 32).

Growth of *Thalassiosira* sp. at 5°C was 1.5 to 5.5 times greater than that at 10°C after 10 days of exposure to all types of crude oil and oil-Corexit mixtures (Figs. 29 to 32). Although there was better growth with Corexit, cell production decreased with increasing the exposure time. The number of cells grown with the oil-Corexit mixture were slightly lower than those with all the types of crude oil alone and Corexit alone.

5.6 In situ primary productivity of seaweed

During the summers of 1974 and 1975, the maximum rate of net primary production for *Laminaria* sp. and *Phyllophora* sp. measured in situ in the Eskimo Lakes was 994.7 and 891.2 µg C/g dry weight/h respectively (Fig. 33). Their production rates varied with changes in light intensity and environmental temperature. The overall average of primary productivity for *Laminaria* sp. and *Phyllophora* sp. was 945 and 780 µg C/g dry weight/h respectively.

5.7 Effects of oils on primary productivity of seaweed

During August, 1974, oil toxicity experiments were performed in the Eskimo Lakes on *Phyllophora* sp. and *Laminaria* sp. All types and concentrations of oil tested inhibited from 0.8% to 47.3% phytosynthesis of both *Phyllophora* sp. and *Laminaria* sp. (Fig. 34). The primary production of *Phyllophora* sp. was inhibited 28% by Norman Wells crude oil in a heavy emulsion concentration, while it appeared to be unaffected by a light emulsion concentration. A heavy emulsion concentration of Atkinson Point crude oil inhibited photosynthesis 10% more than did a light emulsion concentration. Light and heavy emulsion concentrations of Venezuela crude inhibited primary production at about the same rate. *Laminaria* sp. had a 26.2% to 47.3% photosynthetic reduction when tested with a heavy emulsion of all types of oil. Venezuela crude oil was the most toxic.

During late July 1975, similar experiments were carried out, but 1 ml of oil applied as a slick was directly added to 300 ml of millipore filtered seawater in a BOD bottle. All oil types inhibited primary production of both species (Fig. 35). *Laminaria* sp. was inhibited by 10% to 27% more than *Phyllophora* sp. with respect to corresponding oil types. Both species were most sensitive to Venezuela crude oil.

6. DISCUSSION

It is difficult to designate a single factor as being a limiting one in controlling the primary productivity taking place in the waters of the southern Beaufort Sea. Such a process is controlled by a combination of factors acting at different rates throughout the successive months of the year.

Light penetration is a prime factor operating in this area. During the summer months it may become limiting because of ice cover or from the heavy sediment content of the water added to the system by the Mackenzie River (Grainger, 1975). Nutrient availability is not likely a limiting factor in the inshore regions. Nutrients generally exist in high concentrations in this area, continually being replenished by the Mackenzie River outflow (Grainger, 1975). Mineralization in the shallow inshore waters might add to the available organic and inorganic nutrients. However, in the far offshore regions, the nutrient content of the euphotic zone, which is separated from the deeper nutrient rich waters by a thermocline during the summer, may very quickly become depleted and thus, limiting. The higher water temperatures of the inshore regions during the summer may determine to some extent the selection of phytoplankton species. Bursa (1963) stated that individual groups of the phytoplankton community might show seasonal succession in accordance with changes in temperature.

Diatoms dominated the floristic composition of the phytoplankton at inshore stations while flagellates were more important at offshore stations. Diatom growth and photosynthesis are generally favoured by high nutrient levels, low light intensities and warmer temperatures (Sverdrup *et al.*, 1942; Ryther, 1956; Raymont, 1963; Hulburt, 1970), all conditions that prevailed at inshore stations (Grainger, 1975). In general, diatoms show a tendency for auxotrophy, requiring for their growth three B vitamins - B_{12}, thiamine and biotin (Lewin, 1959; Droop, 1962; Provasoli, 1963). Vitamins occur in greater concentrations in coastal waters than in oceanic waters (Vishniac and Riley, 1961; Provasoli, 1963; Ohwada and Taga, 1972). The greater importance of flagellates at offshore stations is probably a reflection of poor conditions for the growth of other groups and a tolerance of flagellates for high light intensities and low nutrient levels (Raymont, 1963; Fogg, 1965). The majority of photosynthetic pigmented flagellates are photoautotrophs, not requiring presynthesized vitamins (Lewin, 1959; Provasoli, 1963).

The standing stock and primary productivity of the southern Beaufort Sea was about 10 and 5 times greater respectively at inshore stations than at offshore stations. This can be attributed primarily to the higher nutrient content and warmer temperatures of the inshore waters. The average productivity rate for surface waters of the southern Beaufort Sea was 6.74 mg $C/m^3/h$ for inshore stations and 1.39 mg $C/m^3/h$ for offshore stations. These rates compare well with the averages 1.8 mg $C/m^3/h$ for the Simpson Lagoon and Thetis Island transects, 0.6 mg $C/m^3/h$ for the Harrison Bay stations and 0.4 mg $C/m^3/h$ for the Beaufort Sea outside the Barrier Islands in the western Beaufort Sea (Alexander, 1974). Taniguchi (1969) found comparable values of 1.46 mg $C/m^3/h$ for Bristol Bay and the northern part of the eastern Bering Sea and 5.04 mg $C/m^3/h$ for east of Bowers Bank in the Bering Sea. McRoy *et al.* (1972) found a similar value of 2.0 mg $C/m^3/h$ for the Aleutian Islands but a far greater average production of 18.24 mg $C/m^3/h$ in the Bering Strait.

In this study the integrated productivity values averaged 47.45 mg $C/m^2/h$ for inshore stations and 8.82 mg $C/m^2/h$ for offshore stations with an average of 28.14 mg $C/m^2/h$. Comparable values for the western Beaufort Sea were 6.9 mg $C/m^2/h$ (Alexander, 1974) and 16.2 mg $C/m^2/h$ for the Aleutian Islands (McRoy *et al.*, 1972); but it is far lower than 182.5 mg $C/m^2/h$ for the Bering Strait (McRoy *et al.*, 1972).

The phytoplankton community in the southern Beaufort Sea was relatively uncomplicated and low in numbers of species and individuals. It was composed largely of diatoms and small flagellates. The 5 most common genera (*Chaetoceros, Dinobryon, Navicula, Nitzschia* and *Thalassiosira* and 1 species (*Nitzschia closterium*) identified in the southern Beaufort Sea were also found by Alexander (1974) to be common in the western Beaufort Sea.

Crude oil is a complex mixture containing 4 types of hydrocarbon molecules - paraffins, naphthenes, olefins, and aromatics (Van Overbeek & Blondeau, 1954). In addition it contains small amounts of nitrogen-, oxygen-, and sulfur-containing compounds as well as trace amounts of heavy metals (Rossini, 1960). Some compounds in crude oil may be growth regulating (Gordon and Prouse, 1973). The highly volatile and relatively water soluble aromatic compounds of crude oil seem to be primarily responsible for its toxicity (Soto *et al.*, 1975), and the varying toxicity of different crude oils is dependant on their content of these aromatics (Baker, 1971).

During the "weathering" process, bacteria attack the least toxic paraffins leaving the toxic aromatic hydrocarbons (Blumer, 1971) which being for the most part highly volatile, dissipate very quickly into the atmosphere of an open system. During the decomposition of the paraffins, the bacteria may release nutrients which become available for plant use but at the same time produce intermediates (i.e. alcohols, organic acids, etc.) which may be toxic in themselves (Blumer, 1971).

In our studies the diatoms used (*Chaetoceros* sp., *Navicula* sp. and *Nitzschia* sp.) all exhibited marked inhibition of C^{14} uptake in the presence of all 4 crude oils tested, alone and in combination with Corexit at 5°C and 10°C. At 0°c the diatoms varied in their response to different oil and oil-Corexit combinations but generally they exhibited an initial period of inhibition followed by a period of stimulation which was in turn followed by a second period of inhibition. The initial inhibition may have been caused by the presence of toxic aromatic hydrocarbons which may act by increasing cell membrane permeability (Goldacre, 1968), by destroying chlorophyll (Soto *et al.*, 1975), by accumulating in the chloropasts to inhibit photosynthesis (Van Overbeek and Blondeau, 1954) or by a combination of all three. With the removal of these volatile aromatics from this open system (caps on Erlenmeyer flasks were only loosely attached) the cells may have been able to utilize any growth regulating compounds that may have been present in the oil and nutrients released from the oil by microbial degradation. However, the accumulation of intermediates from the bacterial degradation would eventually reach the point where their concentration would be great enough to inhibit photosynthesis once more. The total inhibition at 5°and 10°C may reflect an increase in reaction times of the first inhibition and stimulation periods, leaving only the final inhibition period to be observed in the 4 to 96 hour time period.

Generally Corexit alone stimulated diatom photosynthesis to some extent at 0°C over the 96 hour experimental runs while at 5°C an initial stimulation period was followed by a final period of inhibition. At 10°C this order was reversed with most of the diatoms showing an initial period of inhibition followed by one of stimulation. The reasons for this are not clear since the specific chemical nature of Corexit is not known but may involve sequences of nutrient, toxin, nutrient activity which is increased in rate by higher temperatures. Thus, while only stimulation occurs in the 0°C experiments, stimulation and inhibition occurs at 5°C and inhibition and a final period of stimulation occurs at 10°C.

Corexit in combination with crude oils generally increased inhibition and decreased stimulation of photosynthesis in the diatoms over that of the oils alone. In the process of emulsification, more of the low molecular weight aromatics may be released from the oils over a longer period of time thus producing a synergistic effect, increasing the toxicity of the oils.

The reaction of *Chlamydomonas* sp. C^{14} uptake was markedly different than that of the diatoms. At all temperatures and with all combinations of Corexit and/or crude oil, photosynthesis was stimulated. It may be that this species is able to assimilate and utilize certain non-toxic hydrocarbons heterotrophically or utilize the breakdown products of bacterial degradation while blocking the effects of the aromatics. This "blocking" effect may result from the nature of the cell wall which has a complex layered and lattice structure of proteinaceous material (Horne *et al.*, 1971) with an outer capsule containing polysaccharids (Round, 1965). In contrast, the cell walls of the three diatom species used are composed of pectin impregnated throughout with silica and covered with mucilage (Fritsch, 1945). However, Soto *et al.*, (1975) found that *Chlamydomonas angulosa* reacted to the addition of naphthalene by an immediate and almost complete loss of photosynthetic capacity and speculated that its rapid absorption from the medium was due to the high affinity of lipid-containing membranes for such compounds. Clearly, much more work must be done on the nature and mechanisms of crude oil toxicity.

Because the C^{14} uptake of individual phytoplankton species reacts in different ways to various oil and oil-Corexit combinations, effects on a given phytoplankton population would depend on the species composition of that population. In experiments performed in the Beaufort Sea with 1 µl/100 ml (10 ppm) of oil directly added to the samples it was found that Atkinson Point crude caused 11.3% inhibition, Norman Wells crude did not affect productivity while

Pembina and Venezuela crude oils exhibited 16.6% and 5.1% stimulation, respectively, of photosynthesis. Primary production of the Eskimo Lakes phytoplankton was consistently inhibited by the same oils used at the same concentration. Shiels et al. (1973) reported that 2.0 ppm of Prudhoe Bay crude oil caused 50% inhibition of photosynthesis on the natural populations of phytoplankton from Port Valdez near Jackson Point, Alaska, while 0.003 ppm stimulated photosynthesis by twice that of the control. Gordon and Prouse (1973) demonstrated that three oils (Venezuela crude, No. 2 and No. 6 fuel oils) all were capable of inhibiting photosynthesis; but at low concentrations Venezuela crude stimulated photosynthesis.

The photosynthetic capacities of two macrophytes (*Laminaria* sp. and *Phyllophora* sp.) were consistently inhibited by the presence of all four oils tested, *Laminaria* sp. the most with respect to corresponding oil types. Both species were most sensitive to Venezuela crude. Clendenning (1958) found that the photosynthetic capacity of *Macrocystis pyrifera* was reduced by 25% after 24 hours of exposure to 1% of diesel oil. Shiels *et al.* (1973) showed that photosynthetic inhibition occurred in *Laminaria saccharina, Cladophora stimpsonii* and *Ulva fenestrata* at 7 ppm of Prudhoe Bay crude oil, whereas other species were not significantly affected at this concentration.

The growth of the flagellate, *Chlamydomonas* and diatoms was inhibited by all the crude oils at a concentration of 1 µl/100 ml at all temperatures, except for *Chlamydomonas* which was slightly stimulated by Norman Wells crude and Pembina crude at 0°C. These cultures were incubated under the same conditions as for primary productivity experiments, but for a 6-day longer exposure time. This indicates that with longer exposure time more toxic intermediates may be produced by bacterial degradation. However, the growth of flagellate was stimulated by these two arctic crude oils probably reflecting a capacity to utilize growth-regulating compounds in the oils or an increase of nitrogen fixation (Baker, 1971). With oil concentrations higher than 10 µl/100 ml, growth of both flagellates and diatoms was inhibited; diatoms more severely than flagellates. This implies that different phytoplankton species have different tolerance limits for oil toxicity and undergo different rates of cell division. Thus a large oil spill would result in a change in species composition of a phytoplankton community. It would probably become dominated by flagellates and diatoms would be reduced greatly as a result of differential sensitivity of phytoplankton and selective toxicity of pollutants. Consequently, zooplankton communities would be altered because of selective herbivory, and possibly each subsequent trophic level and eventually the total ecosystem.

7. CONCLUSIONS

7.1 Standing stock and primary productivity in the southern

Beaufort Sea are higher than in the western Beaufort Sea, but lower than in other arctic waters. Both decrease with increasing depth and distance from the shore.

7.2 The phytoplankton community was composed largely of diatoms and flagellates, with diatoms dominating the inshore stations and flagellates being more abundant at offshore stations. Dinoflagellates and chrysophytes occurred in relatively low numbers except in a few cases when blooms were observed. Blue-green algae were found occasionally in very low numbers.

7.3 Results from in situ and laboratory studies on the effect of crude oils on primary productivity indicated that the production rates varied with type and concentration of oil used, methods of preparation of oil-seawater mixtures, duration of exposure, and species composition of each sample tested.

7.4 Crude oils, Corexit and crude oil-Corexit mixtures stimulated *Chlamydomonas* photosynthesis, but slightly inhibited or did not affect its growth. Photosynthesis and growth of the diatoms were mostly inhibited by these pollutants, but inhibited considerably more in crude oil-Corexit mixtures than in crude oil or Corexit alone.

7.5 In situ primary productivity of seaweeds was significantly inhibited by all types and concentrations of oil tested.

8. IMPLICATIONS AND RECOMMENDATIONS

Because of the multiplicity of physical, chemical and biological factors acting on the ecology of the southern Beaufort Sea and because of the very large gaps existing in our knowledge of the nature and interactions of these factors, it is difficult to make predictions, with any degree of accuracy, on the effects of a large oil spill.

In the shallow coastal waters, the euphotic zone is probably limited to a very few centimetres beneath the surface as a result of poor light penetration because of the heavy silt content introduced by the Mackenzie River. This area would be primarily affected by the presence of oil contamination on the surface. As well as the detrimental effects of a further reduction in light, growth and photosynthesis of phytoplankton (predominantly diatoms in this area) would probably be further inhibited by the highly toxic and relatively water soluble aromatics. With the evaporation of these components, the phytoplankton might be expected to recover. The rate of recovery would be highly dependent on many variables (i.e. oil composition and quantity, time of year, river outflow, etc.). For instance, during the long period of ice cover, the evaporation of the aromatics might be severely restricted, exposing the phytoplankton to their toxic effects for a longer period of time.

The use of Corexit in oil clean up activities, while perhaps advantageous in some respects, would probably increase the toxicity of the oils on phytoplankton photosynthesis and growth. Thus the period of recovery might be extended.

It has been suggested by Fisher (1976) that organic pollution, including the presence of petroleum hydrocarbons, may be one of the factors contributing to the changes in composition (Reid, 1975) of the North Sea phytoplankton (i.e. a decline in diatom populations and a possible increase in microflagellate populations). An increase in the hydrocarbon content of the southern Beaufort Sea waters, resulting from oil exploitation, would seem a distinct possibility over the long term. Thus one of the more serious implications of oil contamination might be a change in community structure at the primary level which could result in changes at higher levels of the food chain.

9. NEEDS FOR FURTHER STUDY

Apart from the desirability of increasing our insight into the nature of the marine environment of the north and the interrelationships of algal standing stock and primary productivity with other marine life and trophic levels, it is extremely important that we understand the possible consequences of large scale alterations to this environment which will inevitably be brought about directly and indirectly by exploitation of oil reserves and other resources. It is vitally important for us to know the capacity of this environment to absorb, without permanent change, these alterations and to know the recovery rates involved in smaller scale man-induced disturbances.

Primary production is, as the term implies, the basis for all life. Knowledge of standing stock and productivity rates of the arctic marine environment and their relationships and interdependence with and on physical factors and other marine life is sadly lacking. When these aspects are more fully understood, the effects of disturbances such as oil pollution, to the environment, can be more easily determined.

With these considerations in mind, need for further long-term studies at the primary level in the following areas is required:

1) location and identification of algal communities and algal-animal associations

2) location and quantification of primary productivity rates

3) response of algal communities to changes in physical parameters including large-scale additions to the environment of foreign chemicals (i.e. oil, oil dispersants, heavy metals, etc.)

4) algae-bacteria relationships and associations particularly in relation to oil utilizing and/or oil degrading bacteria

5) producer/decomposer relationships (i.e. algae-animals/ bacteria-fungi)

6) identification of possible oil utilizing or oil degrading capacities within the algae in respect to biological clean-up methods

With more knowledge in these areas we will be better prepared to predict consequences of alterations to the arctic marine environment and to evaluate economic versus environmental considerations.

10. LITERATURE CITED

Alexander, V., R. Clasby and C. Coulon. 1972. Primary productivity and phytoplankton studies in the Barrow tundra ponds. Proceedings, 1972 Tundra Biome Symposium, Lake Wilderness Center, Univ. of Washington, U.S. Int. Biol. Program, pp. 169-173.

Alexander, V. 1974. Primary productivity regimes of the nearshore Beaufort Sea, with reference to potential roles of ice biota. *In:* J. C. Reed and J. E. Sater (eds.). The coast and shelf of the Beaufort Sea pp. 609-635.

Baker, J. B. 1971. Growth stimulation following oil pollution. *In*: E. G. Cowell (ed.). The ecological effects of oil pollution on littoral communities. Inst. of Petroleum, London, pp. 72-77

Bellamy, D. J. and A. Whittick. 1968. Problems in the assessment of the effects of pollution on inshore marine ecosystems dominated by attached macrophytes. Fld. Stud. 2 (Suppl.) 49-54.

Blumer, M. 1971. Scientific aspects of the oil spill problem. Environmental Affairs, vol. 1, pp. 54-73.

Bursa, A. S. 1963. Phytoplankton successions in the Canadian Arctic. *In*: C. H. Oppenheimer (ed.). Symposium on marine microbiology. Thomas, Springfield. pp. 625-628.

Clendenning, K. A. 1958. The effects of waste discharges on kelp: fuel oil. Inst. Mar. Resources Ref. 59-4, Univ. Calif., San Diego, pp. 4-12.

Craigie, J. S. and J. McLachlan. 1971. Observations on the littoral algae of Chedabucto Bay following the "Arrow" oil spill. Unpubl. Rept. Atlantic Regional Laboratory, Nat. Res. Council, Halifax, N.S. (ARL-8; NRC #11489).

Doty, M. S. and M. Oguri. 1956. The island mass effect. J. Cons. Perm. Int. Explor. Mer. 22: 33-37.

Droop, M. R. 1962. Organic micronutrients. *In*: R. A. Lewin (ed.). Physiology and biochemistry of algae. Academic Press, New York, pp. 141-159.

Fisher, N. S. 1976. North Sea phytoplankton. Nature, vol. 259, p. 160.

Fogg, G. E. 1965. Algal culture and phytoplankton ecology. Univ. Wisconsin Press, Madison, Wis. 126 pp.

Foy, M. G. and S. I. C. Hsiao. 1976. Phytoplankton data from the Beaufort Sea, 1973 to 1975. Env. Can., Fish. and Mar. Serv. Tech. Rept. No. . Arctic Biol. Sta., Ste. Anne de Bellevue Que. (is being prepared for publication).

Fritsch, F. E. 1945. Structure and reproduction of algae. Cambridge Univ. Press, London Vol 1: 791 pp; Vol. II, 939 pp.

Goldacre, R. J. 1968. Effect of detergents and oils on the cell membrane. *In:* J. D. Carthy and D. R. Arthur (eds.), The biological effects of oil pollution on littoral communities. Field Studies (Suppl.), Vol. 2: pp. 131-137.

Gordon, D. C. and N. J. Prouse. 1973. The effects of three oils on marine phytoplankton photosynthesis. Mar. Biol. 22: 329-333.

Grainger, E. H. 1975. Biological productivity of the southern Beaufort Sea: the physical-chemical environment and the plankton Beaufort Sea Project, Tech. Rept. No. 12a, Dept. of the Environment Victoria, B. C., Canada. 82 pp.

Hellebust, J. A., B. Hanna, R. G. Sheath, M. Gergis, and T. C. Hutchinson. 1975. Experimental crude oil spills on a small subarctic lake in the Mackenzie Valley, N.W.T.: effects on phytoplankton, periphyton and attached aquatic vegetation. *In*: Proceedings of Conference on Prevention and Control of oil pollution, March 25-27, 1975. San Francisco, Calif. pp. 509-515.

Holmes, R. W. 1969. The Santa Barbara oil spill. *In*: D. P. Hoult (ed.). Oil on the sea. Plenum Press, New York, pp. 15-27.

Horne, R. W., D. R. Davies, K. Norton and M. Gurney-Smith. 1971. Electron microscope and optical diffraction studies on isolated cell walls from *Chlamydomonas*. Nature, Vol. 232, pp. 493-495.

Hulburt, E. M. 1970. Competition for nutrients by marine phytoplankton in oceanic, coastal and estuarine regions. Ecology 51: 475-484.

Kauss, P., T. C. Hutchinson, C. Soto, J. Hellebust and M. Griffiths. 1973. The toxicity of crude oil and its components to freshwater algae. *In*: Proceedings of Joint Conference on Prevention and Control of oil spills, Washington, D. C., pp. 703-714. American Petroleum Institute.

Lewin, R. A. 1959. Phytoflagellates and algae. *In*: W. Ruhland (ed.), Handbuch pflanzenphysiologie, Springer, Berlin Bd 14: 401-417.

Lobban, C. S. 1974. A simple, rapid method of solubilizing algal tissue for scintillation counting. Limnol. Oceanog. 19: 356-359.

McRoy, C. P., J. J. Goering and W. E. Shiels. 1972. Studies of primary production in the eastern Bering Sea. *In*: A. Y. Takenouti *et al*. (ed.). Biological Oceanography of the northern north Pacific Ocean. Idemitsu Shoten, Tokyo, Japan. pp. 199-216.

Mommaerts-Billiet, F. 1973. Growth and toxicity tests on the marine nannoplanktonic alga *Platymonas tetrathele* G. S. West in the presence of crude oil and emulsifiers. Environ. Pollut. 4: 261-282.

Nuzzi, R. 1973. Effects of water soluble extracts of oil on phytoplankton. *In*: Proceedings of Joint Conference on Prevention and Control of oil spills, Washington, D. C. pp. 809-813. Amer. Petroleum Inst.

Ohwada, K. and Taga, N. 1972. Distribution and seasonal variation of vitamin B_{12}, thiamine and biotin in the sea. Mar. Chem. 1: 61-73.

Percy, J. A. and T. C. Mullin. 1975. Effects of crude oils on arctic marine invertebrates. Beaufort Sea Project Technical Report No. 11, Dept. of the Environment, Victoria B. C., Canada 167 pp.

Provasoli, L. 1963. Organic regulation of phytoplankton fertility *In*: M.N. Hill (ed.), The Sea. Interscience, New York, N. Y. 2: 165-219.

Provasoli, L., J. J. A. McLaughlin, and M. R. Droop. 1957. The development of artificial media for marine algae. Arch. Mikrobiol. 25: 392-428.

Pulich, W. M., Jr., K. Winters and C. van Baalen. 1974. The effects of a No. 2 fuel oil and two crude oils on the growth and photosynthesis of microalgae. Mar. Biol. 28: 87-94.

Raymont, J. E. G. 1963. Plankton and productivity in the Oceans. Pergamon Press, London, 660 pp.

Reid, P. C. 1975. Large scale changes in North Sea phytoplankton. Nature, vol. 257: pp. 217-219.

Rossini, F. D. 1960. Hydrocarbons in petroleum. J. Chem. Educ. 37: 554-561.

Round, F. E. 1965. The biology of the algae. Edward Arnold, London, 269 pp.

Ryther, J. R. 1956. Photosynthesis in the ocean as a function of light intensity. Limnol. Oceanog. 1: 61-70.

Schindler, D. W. 1966. A liquid scintillation method for measuring carbon-14 uptake in photosynthesis. Nature 211: 844-845.

Shiels, W. E., J. J. Goering and D. W. Hood. 1973. Crude oil phytotoxicity studies. *In*: D. W. Hood, W. E. Shiels and E. J. Kelley (eds.), Environmental studies of Port Valdez. Inst. Mar. Sci. Univ. Alaska, Fairbanks, Occasional Publ. No. 3, pp. 413-446.

Smith, J. E. (ed.). 1970. "Torrey Canyon pollution and marine life." A report by the Plymouth Laboratory of the Marine Biological Association of the United Kingdom. Cambridge University Press. 196 pp.

Soto, C., J. A. Hellebust and T. C. Hutchinson. 1975. Effect of naphthalene and aqueous crude oil extracts on the green flagellate *Chlamydomonas angulosa* II. Photosynthesis and the uptake and release of naphthalene. Can. J. Bot. 53: 118-126.

Strand, J. A., W. L. Templeton, J. A. Lichatowich and C. W. Apts. 1971. Development of toxicity test procedures for marine phytoplankton. *In*: Proceedings of Joint Conference on Prevention and Control of Oil Spills, June 15-17, 1971. Washington, D. C. pp. 279-286. American Petroleum Inst. Environmental Protection Agency and U.S. Coast Guard.

Strickland, J. D. H. and T. R. Parsons. 1968. A practical handbook of seawater analysis. Bull. Fish. Res. Board Can. 167: 1-311.

Sverdrup, H. U., M. W. Johnson and R. H. Fleming. 1942. The Oceans - their physics, chemistry and general biology. Prentice-Hall, Englewood, N.J. 1087 pp.

Taniguchi, A. 1969. Regional variations of surface primary production in the Bering Sea in summer and the vertical stability of water affecting the production. Bull. Fac. Fish., Hokkaido Univ. 20: 169-179.

Van Overbeek, J. and R. Blondeau. 1954. Mode of action of phytotoxic oils. Weeds, vol. 3: pp. 55-65.

Vishniac, H. S. and G. A. Riley. 1961. Cobalamin and thiamine in Long Island Sound: patterns of distribution and ecological significance. Limnol. Oceanogr 6: 36-41.

Walker, J. D., R. R. Colwell, Z. Vaituzie and S. A. Meyer. 1975. Petroleum-degrading achlorophyllous alga *Prototheca zopfii*. Nature 254: 423-424.

11. APPENDICES

Table 1. Phytoplankton genera and species from the Beaufort Sea and Eskimo Lakes

Bacillariophyta
  Centrales
    Cerataulina H. Peragallo *ex* Schuett
    Chaetoceros Ehrenberg
      C. ceratosporum Ostenfeld
      C. decipiens Cleve
      C. furcellatus J. W. Bailey
      C. neogracile S. van Landingham
      C. septentrionalis Oestrup
      C. simplex Ostenfeld
      C. socialis Lauder
      C. wighamii Brightwell
    Coscinodiscus Ehrenberg
    Cyclotella Kuetzing
      C. caspia Grunow
    Eucampia Ehrenberg
      E. zodiacus Ehrenberg
    Melosira Agardh
      M. arctica (Ehrenberg) Dickie *in* Pritchard
      M. granulata (Ehrenberg) Ralfs *in* Pritchard
      M. islandica O. Müeller
    Porosira Joergensen
      P. glacialis (Grunow) Joergensen
    Rhizosolenia Ehrenberg
    Sceletonema Greville
      S. costatum (Greville) Cleve
    Stephanodiscus Ehrenberg
      S. astraea (Ehrenberg) Grunow
      S. hantzschii Grunow
    Thalassiosira Cleve
      T. baltica (Grunow) Ostenfeld
      T. gravida Cleve
      T. nordenskioldii Cleve
  Pennales
    Achnanthes Bory
      A. lanceolata (Brébisson *in* Kuetzing) Grunow *in* Cleve and Grunow
      A. lemmermannii Hustedt
      A. taeniata Grunow *in* Cleve and Grunow
    Amphipleura Kuetzing
      A. pellucida (Kuetzing) Kuetzing
      A. rutilans (Trentepohl *ex* Roth) Cleve

Table I (cont'd.)

Amphiprora Ehrenberg
A. kjellmanii Cleve *in* Cleve and Grunow
Amphora Ehrenberg
Asterionella Hassall
A. formosa Hassall
Ceratoneis Ehrenberg
C. arcus (Ehrenberg) Kuetzing
Cocconeis Ehrenberg
Cylindrotheca Rabenhorst
Cymbella Agardh
Diatoma A. P. de Candolle
D. elongatum (Lyngbye) Agardh
Diploneis Ehrenberg
D. litoralis (Donkin) Cleve
D. litoralis v. clathrata (Oestrup) Cleve
D. ovalis (Hilse *in* Rabenhorst) Cleve v. *oblongella* (Naegeli *in* Kuetzing) Cleve
D. smithii (Brébisson *in* Wm. Smith) Cleve
D. smithii v. rhombica Mereschkowsky
Eunotia Ehrenberg
Fragilaria Lyngbye
F. construens (Ehrenberg) Grunow
Fragilariopsis Hustedt *in* Schmidt *et al.*
F. cylindrus (Grunow) Helmcke and Krieger
F. oceanica (Cleve) Hasle
Gomphonema Agardh
G. kamtschaticum Grunow
Gyrosigma
G. fasciola (Ehrenberg) Griffith and Henfrey
G. wansbeckii (Donkin) Cleve
Licmophora Agardh
Navicula Bory
N. bahusiensis (Grunow *in* Van Heurck) Grunow
N. crucigeroides Hustedt
N. delicatula Cleve
N. digitoradiata (Gregory) Ralfs *in* Pritchard
N. directa (Wm. Smith) Ralfs *in* Pritchard
N. directa v. cuneata Oestrup
N. forcipata Greville
N. hodgeana Patrick and Freese
N. humerosa Brébisson *in* Wm. Smith
N. kariana Grunow *in* Cleve and Grunow
N. kjellmanii (Cleve *in* Cleve and Grunow) Cleve
N. pseudocrassirostris Hustedt
N. rhynchocephala Kuetzing
N. salinarum Grunow *in* Cleve and Mueller

Table 1 (cont'd.)

N. scopulorum Brebisson *in* Kuetzing
N. scutelloides Wm. Smith
N. subinflata Grunow *in* Cleve and Mueller
N. vanhoeffenii Gran
Neidium Pfitzer
N. bisulcatum (Lagerst.)Cleve
Nitzschia Hassall
N. closterium (Ehrenberg) Wm. Smith
N. frigida Grunow *in* Cleve and Grunow
N. seriata Cleve
N. sigma (Kuetzing) Wm. Smith
Pinnularia Ehrenberg
Pleurosigma Wm. Smith
P. clevei Grunow *in* Cleve and Grunow
P. salinarum Grunow *in* Cleve and Grunow
P. strigosum Wm. Smith
P. stuxbergii Cleve and Grunow
Stauroneis Ehrenberg
Surirella Turpin
S. ovata Kuetzing
Synedra Ehrenberg
S. acus Kuetzing v. *radians* (Kuetzing) Hustedt
S. fasciculata (Agardh) Kuetzing
S. hyperborea Grunow
Tabellaria Ehrenberg
T. fenestrata (Lyngbye) Kuetzing
T. flocculosa (Roth) Kuetzing
Thalassionema Grunow
T. nitzschioides Grunow
Tropidoneis Cleve

Chlorophyta
Chlamydomonas Ehrenberg
Scenedesmus Meyen

Chrysophyta
Dinobryon Ehrenberg
D. balticum (Schuett) Lemmermann
Distephanus Haeckel
D. speculum (Ehrenberg) Haeckel
Ebria Borgert
E. tripartita (Schumann) Lemmermann

Table 1 (cont'd.).

Cyanophyta
Coelosphaerium Naegeli
Euglenophyta
Euglena Ehrenberg
Trachelomonas Ehrenberg
Pyrrophyta
Amphidinium Claparède and Lachmann
Dinophysis Ehrenberg
D. acuminata Claparède and Lachmann
Goniaulax Diesing
G. catenata (Levander) Kofoid
Peridinium Ehrenberg
P. cerasus Paulsen
P. minusculum Pavillard
P. pellucidum (Bergh) Schuett

Table 2. The distribution of dominant species of phytoplankton at inshore stations of the southern Beaufort Sea.

Station	Dominant species	Cell numbers X 10^4/l	Depth (m) at which species was dominant
22	*Amphidinium* sp.	4.6	1
	Chlamydomonas sp.	1.2	1
	Euglena sp.	8.8	1
	Fragilariopsis cylindrus	4.1	5
	Goniaulax catenata	16.6	1
	Nitzschia spp.	1.6	1
	Thalassiosira gravida	1.8	1
527	*Melosira islandica*	11.3	0
	Thalassiosira spp.	3.1	5
529	*Thalassiosira* spp.	4.8	5
	Euglena spp.	3.7	5
530	*Euglena* spp.	4.4	0
	Goniaulax catenata	1.9	0
	Thalassiosira spp.	1.8	3
538	*Melosira islandica*	7.3	3
540	*Melosira* spp.	8.9	3
	Unidentified flagellates	1.5	3
575	*Chaetoceros* spp.	469.2	7
	Choanoflagellates	2.0	5
	Dinobryon balticum	3.6	3
	Euglena spp.	2.6	0
	Melosira arctica	1.8	1
	Nitzschia closterium	1.8	7
	N. seriata	4.4	1
	Thalassiosira nordenskioldii	2.0	7
	Unidentified flagellates	1.0	1

Table 3. The distribution of dominant species of phytoplankton at offshore stations of the southern Beaufort Sea.

Stations	Dominant species	Cell numbers X 10^4/l	Depth (m) at which species was dominant
7	*Chaetoceros furcellatus*	1.6	0
	Nitzschia spp.	1.9	1
9	Unidentified flagellates	1.6	0
	Unidentified Chrysophyta	1.6	0
14	*Chaetoceros* spp.	3.5	3
	Fragilariopsis cylindrus	1.6	0
	Melosira islandica	4.5	0
	Navicula spp.	1.6	0
29	*Amphidinium* sp.	1.9	1
	Chaetoceros spp.	1.1	0
	Euglena spp.	6.8	1
	Goniaulax catenata	1.3	3
	Chlamydomonas sp.	2.1	0
	Thalassiosira gravida	3.7	5
	Unidentified flagellates	50.0	1
544	*Euglena* spp.	1.2	0
	Nitzschia closterium	1.5	0
	Thalassiosira gravida	3.4	0
	Unidentified flagellates	24.6	0
552	*Chaetoceros* spp.	1.9	3
	Euglena spp.	5.4	3
	Peridinium spp.	1.0	0
	Thalassiosira spp.	2.6	5
	Unidentified flagellates	39.0	3
559	*Thalassiosira* spp.	2.6	3
	Unidentified flagellates	20.4	3

Table 4. Vertical distribution of *in situ* gross primary productivity (mg C/m^3/h) in the southern Beaufort Sea.

Station	Date	Depth (m) 0	1	3	5	7	10	20	30
Inshore									
22	12 Aug 75	6.74	7.11	1.06	1.56	1.73	2.34	2.57	2.02
575	9 Aug 75	-	7.70	7.80	8.60	8.80	-	-	-
Mean		6.74	7.41	4.43	5.08	5.27	2.34	2.57	2.02
Offshore									
7	19 Jul 74	0.82	0.94	0.39	0.38	0.27	0.17	0.10	-
29	2 Aug 74	1.95	2.24	2.39	1.93	3.06	2.09	2.73	0.81
566	5 Jul 75	-	0.17	-	-	-	0.73	0.89	-
567	12 Jul 75	-	1.47	-	-	-	0.59	0.29	-
568	18 Jul 75	-	0.55	-	-	-	1.06	1.02	-
572	7 Aug 75	-	0.53	0.41	0.98	-	0.89	0.48	-
574	8 Aug 75	-	0.51	0.92	1.28	-	2.18	0.96	-
Mean		1.39	0.92	1.03	1.14	1.67	1.10	0.92	0.81

Table 5. Primary productivity of the water column in the southern Beaufort Sea

Station	Date	Productivity	
		mg C/m^2/h	mg C/m^2/day
Inshore			
22	12 Aug 74	45.4	1089.6
575	9 Aug 75	49.5	1188.0
Mean		47.45	1138.8
Offshore			
7	19 Jul 74	4.29	102.96
29	2 Aug 74	18.20	436.80
566	5 Jul 75	4.10	98.40
567	12 Jul 75	9.30	223.20
568	18 Jul 75	7.20	172.80
572	7 Aug 75	6.54	156.96
574	8 Aug 75	12.10	290.40
Mean		8.82	211.65

Table 6. Vertical distribution of *in situ* gross primary production (mg C/m^3/h) of Eskimo Lakes.

Station	Date	Depth (m) 0	1	3	5	7	10	20	30
508	13 Jul 74	0.44	0.45	1.27	0.88	0.57	0.15	0.09	-
510	16 Jul 74	1.02	1.58	2.02	0.91	0.52	0.21	-	-
515	27 Jul 74	2.71	2.87	2.84	1.18	0.82	0.47	0.58	0.30
	3 Aug 74	1.03	1.64	3.20	1.59	1.12	0.83	0.73	0.68
	10 Aug 74	2.34	2.67	2.02	1.34	0.58	0.19	0.02	0.01
	16 Aug 74	0.80	1.81	3.25	1.30	0.60	0.27	0.08	0.03
520	7 Aug 74	0.38	0.77	0.79	0.61	0.43	0.20	0.04	0.02
560	31 Jul 74	1.65	1.72	1.58	0.86	0.11	-	-	-
Mean		1.04	1.35	1.70	0.92	0.48	0.25	0.16	0.14

Table 7. Primary productivity of the water column in the Eskimo Lakes.

Station	Date	Productivity	
		mg $C/m^2/h$	mg $C/m^2/day$
508	13 Jul 74	6.6	158.4
510	16 Jul 74	10.4	249.6
515	27 Jul 74	16.5	396.0
	3 Aug 74	16.6	398.4
	10 Aug 74	13.6	326.4
	16 Aug 74	14.1	338.4
520	7 Aug 74	5.5	132.0
560	31 Jul 74	8.4	201.6
Mean		11.46	275.10

Table 8. Effect of crude oils on primary production of phytoplankton at 1 metre at various Beaufort Sea stations. Results expressed as percentage of control.

Types of oil	566	567	568	570	571	572	574	575	Mean
Atkinson Point crude	65.9	90.8	93.3	69.4	99.2	100.8	91.2	98.6	88.7
Norman Wells crude	53.7	93.1	103.8	81.0	63.9	156.1	140.1	116.4	101.0
Pembina crude	75.9	100.1	97.3	125.9	99.3	115.2	184.1	135.1	116.6
Venezuela crude	75.3	89.7	92.5	76.7	94.1	86.4	184.6	141.2	105.1

Table 9. Effect of crude oils on primary production of phytoplankton at 1 metre at station 515 in the Eskimo Lakes. Results expressed as percentage of control.

Types of oil	15/6/75	26/6/75	2/7/75	9/7/75	15/7/75	21/7/75	Mean
Atkinson Point crude	51.4	81.1	53.2	63.0	97.6	87.1	72.9
Norman Wells crude	148.5	89.3	54.3	59.2	80.9	79.1	85.2
Pembina crude	73.6	120.7	67.7	83.1	96.4	82.9	87.4
Venezuela crude	25.8	118.6	58.6	61.3	87.6	67.4	69.9

Table 10. Species composition and abundance of phytoplankton from 1 metre water of various Beaufort Sea stations used in oil toxicity experiments during 1975

Station Date	566 5 July	567 12 July	568 18 July	572 7 Aug	574 8 Aug	575 9 Aug
Total Phytoplankton (cells/litre)	98,000	440,000	801,000	61,000	123,000	1,896,000
Bacillariophyta	60,000	312,000	631,000	26,000	72,000	1,828,000
Centrales	11,000	247,000	329,000	20,000	61,000	1,782,000
Chaetoceros	10,000	233,000	323,000	20,000	56,000	1,738,000
C. ceratosporum	4,000	+	+	2,000	13,000	-
C. decipiens	-	-	-	-	+	+
C. septentrionalis	+	+	+	-	-	+
C. simplex	-	-	-	-	40,000	-
C. socialis	+	-	-	-	-	+
C. wighamii	-	+	+	-	-	+
C. spp.	6,000	+	+	18,000	3,000	-
Eucampia	+	-	-	-	-	-
E. zodiacus	+	-	-	-	-	-
Melosira	-	4,000	1,000	-	2,000	18,000
M. arctica ?	-	4,000	1,000	-	2,000	18,000
Porosira	-	+	+	-	-	+
P. glacialis	-	+	+	-	-	+
Sceletonema	-	-	-	-	2,000	-
S. costatum	-	-	-	-	2,000	-
Thalassiosira	-	10,000	5,000	-	+	24,000
T. nordenskioldii	-	-	+	-	-	+
T. spp.	-	10,000	+	-	+	+
Unidentified	1,000	-	-	-	1,000	2,000
Pennales	49,000	65,000	302,000	6,000	11,000	46,000
Achnanthes	+	9,000	26,000	-	-	-
A. taeniata	-	9,000	26,000	-	-	-
A. spp.	+	-	+	-	-	-

Table 10 (cont'd.).

Station Date	566 5 July	567 12 July	568 18 July	572 7 Aug	574 8 Aug	575 9 Aug
Amphiprora	-	+	+	-	-	-
A. spp.	-	+	+	-	-	-
Amphora	-	+	+	-	-	-
A. spp.	-	+	+	-	-	-
Cocconeis	-	-	-	-	+	-
C. spp.	-	-	-	-	+	-
Cymbella ?	-	-	-	-	-	+
C. sp.	-	-	-	-	-	+
Diploneis	-	+	+	+	-	-
D. litoralis	-	+	-	-	-	-
D. spp.	-	+	+	+	-	-
Fragilariopsis	5,000	3,000	10,000	+	-	+
F. cylindrus	5,000	3,000	10,000	+	-	+
F. oceanica	-	+	-	-	-	-
Gomphonema	-	+	+	-	-	-
G. kamtschaticum ?	-	-	+	-	-	-
G. spp.	-	+	-	-	-	-
Navicula	+	+	1,000	+	-	+
N. crucigeroides	-	-	+	-	-	-
N. delicatula ?	-	-	+	-	-	-
N. directa	-	+	+	-	-	-
N. kariana ?	-	-	+	-	-	-
N. pseudocrassirostris	-	-	+	-	-	-
N. spp.	+	+	+	+	-	+
Nitzschia	15,000	45,000	61,000	1,000	10,000	44,000
N. closterium	13,000	2,000	33,000	+	7,000	-
N. frigida	-	-	+	-	-	-
N. seriata	+	42,000	21,000	1,000	3,000	44,000
N. spp.	2,000	1,000	7,000	+	+	+

Table 10 (cont'd.).

Station Date	566 5 July	567 12 July	568 18 July	572 7 Aug	574 8 Aug	575 9 Aug
Pleurosigma	-	-	+	-	-	-
P. salinarum	-	-	+	-	-	-
Stauroneis	+	+	+	+	-	-
S. spp.	+	+	+	+	-	-
Synedra	+	+	+	+	-	-
S. hyperborea	+	+	+	-	-	-
S. spp.	-	-	-	+	-	-
Thalassionema	+	-	-	+	+	-
T. nitzschioides	+	-	-	+	+	-
Unidentified	29,000	8,000	204,000	5,000	1,000	2,000
Chlorophyta	+	-	-	-	-	-
Chlamydomonas	+	-	-	-	-	-
C. spp.	+	-	-	-	-	-
Chrysophyta	17,000	8,000	29,000	28,000	16,000	18,000
Dinobryon	+	-	6,000	16,000	9,000	18,000
D. balticum	+	-	6,000	16,000	9,000	18,000
Distephanus	-	-	-	-	+	-
D. speculum	-	-	-	-	+	-
Ebria	-	-	+	+	1,000	+
E. tripartita	-	-	+	+	1,000	+
Choanoflagellates	-	-	-	10,000	6,000	-
Unidentified	17,000	8,000	23,000	2,000	-	-
Euglenophyta	-	3,000	38,000	-	-	16,000
Euglena ?	-	3,000	38,000	-	-	16,000
E. spp.	-	3,000	38,000	-	-	16,000

Table 10 (cont'd.).

Station Date	566 5 July	567 12 July	568 18 July	572 7 Aug	574 8 Aug	575 9 Aug
Pyrrophyta	4,000	83,000	4,000	2,000	9,000	24,000
Amphidinium ?	-	12,000	-	-	-	-
A. spp.	-	12,000	-	-	-	-
Dinophysis	-	-	-	-	-	+
D. acuminata	-	-	-	-	-	+
Goniaulax	+	63,000	-	-	-	-
G. catenata	+	63,000	-	-	-	-
Peridinium	-	2,000	+	-	+	-
P. minusculum	-	-	+	-	-	-
P. pellucidum ?	-	-	-	-	+	-
P. spp.	-	2,000	-	-	+	-
Unidentified	4,000	6,000	4,000	2,000	9,000	24,000
Others	17,000	34,000	99,000	5,000	26,000	10,000
Pigmented flagellates	17,000	34,000	99,000	5,000	26,000	10,000

Table 11. Species composition and abundance of phytoplankton from 1 metre water of Station 515, Eskimo Lakes, used in oil toxicity experiments during 1975.

Date	15 June	2 July	9 July	15 July	21 July	16 Aug
Total phytoplankton (cells/litre)	784,000	392,000	73,000	172,000	194,000	64,000
Bacillariophyta	600,000	371,000	4,000	16,000	24,000	5,000
Centrales	574,000	353,000	+	10,000	7,000	4,000
Chaetoceros	574,000	351,000	+	10,000	7,000	4,000
C. ceratosporum	566,000	344,000	-	3,000	+	-
C. neogracile	-	-	-	7,000	5,000	-
C. spp.	8,000	7,000	+	+	2,000	4,000
Cyclotella	-	-	-	-	+	+
C. spp.	-	-	-	-	+	+
Melosira	-	-	+	-	-	-
M. spp.	-	-	+	-	-	-
Thalassiosira	+	2,000	+	-	+	+
T. spp.	+	2,000	+	-	+	+
Unidentified	-	-	-	-	+	-
Pennales	26,000	18,000	4,000	6,000	17,000	1,000
Achnanthes	+	+	+	+	+	+
A. lanceolata	-	-	-	-	+	-
A. lemmermannii	-	-	-	-	+	-
A. spp.	+	+	+	+	+	+
Amphipleura	-	+	-	+	+	+
A. rutilans	-	+	-	+	+	+
Amphiprora	+	+	-	+	-	-
A. spp.	+	+	-	+	-	-
Amphora	+	+	+	+	+	-
A. spp.	+	+	+	+	+	-
Cocconeis	-	-	-	+	-	+
C. spp.	-	-	-	+	-	+
Diatoma	-	+	-	+	+	-
D. elongatum	-	+	-	+	+	-

Table 11 (cont'd.).

Date	15 June	2 July	9 July	15 July	21 July	16 Aug
Diploneis	+	+	+	+	+	+
D. litoralis	+	+	+	+	+	-
D. smithii	-	-	-	-	+	+
D. spp.	-	+	-	-	-	-
Fragilariopsis	+	3,000	-	+	+	-
F. cylindrus	+	3,000	-	+	+	-
Gomphonema	+	+	-	-	+	-
G. kamtschaticum	+	+	-	-	+	-
Gyrosigma	+	+	-	-	+	-
G. spp.	+	+	-	-	+	-
Licmophora	-	-	-	-	+	-
L. spp.	-	-	-	-	+	-
Navicula	+	+	+	+	+	+
N. crucigeroides	-	+	-	+	+	-
N. directa	+	+	-	-	+	-
N. hodgeana	-	-	-	-	+	-
N. pseudocrassirostris	+	+	-	-	+	-
N. rhynchocephala	-	+	-	-	-	-
N. salinarum	+	-	-	-	-	-
N. spp.	+	+	+	+	+	+
Nitzschia	4,000	4,000	+	+	2,000	+
N. closterium	4,000	2,000	-	+	1,000	+
N. seriata	-	2,000	-	-	-	-
N. spp.	+	+	+	+	1,000	+
Pinnularia ?	-	-	+	-	+	-
P. spp.	-	-	+	-	+	-
Pleurosigma	-	-	-	-	+	+
P. clevei	-	-	-	-	+	-
P. spp.	-	-	-	-	-	+
Stauroneis	+	+	-	-	+	-
S. spp.	+	+	-	-	+	-

Table 11 (cont'd.).

Date	15 June	2 July	9 July	15 July	21 July	16 Aug
Synedra	+	+	-	+	+	+
S. fasciculata	-	+	-	-	-	-
S. spp.	+	+	-	+	+	+
Unidentified	22,000	11,000	4,000	6,000	15,000	1,000
Chrysophyta	-	+	+	5,000	13,000	4,000
Ebria	-	+	+	2,000	+	-
E. tripartita	-	+	+	2,000	+	-
Unidentified	-	-	-	3,000	13,000	4,000
Euglenophyta	+	-	-	-	-	-
Euglena	+	-	-	-	-	-
E. spp.	+	-	-	-	-	-
Pyrrophyta	165,000	13,000	3,000	4,000	4,000	+
Amphidinium ?	2,000	1,000	1,000	-	-	-
A. spp.	2,000	1,000	1,000	-	-	-
Dinophysis	-	2,000	+	+	+	-
D. acuminata	-	2,000	+	-	-	-
D. spp.	-	-	-	+	+	-
Goniaulax	147,000	+	-	-	-	-
G. catenata	147,000	+	-	-	-	-
Peridinium	-	1,000	-	+	-	-
P. minusculum	-	-	-	+	-	-
P. spp.	-	1,000	-	-	-	-
Unidentified	16,000	9,000	2,000	4,000	4,000	+
Others	19,000	8,000	66,000	147,000	153,000	55,000
Pigmented flagellates	19,000	8,000	66,000	147,000	153,000	55,000

Table 12 Species composition and abundance of phytoplankton from 1 metre water of Station 507, Eskimo Lakes, used in oil, Corexit and oil-Corexit mixture experiments during 1975.

Date	13 Aug	14 Aug	15 Aug
Total phytoplankton (cells/litre)	48,000	55,000	54,000
Bacillariophyta	12,000	22,000	16,000
Centrales	1,000	+	+
Chaetoceros	1,000	+	+
C. spp.	1,000	+	+
Coscinodiscus ?	-	+	-
C. spp.	-	+	-
Cyclotella	+	+	-
C. caspia	+	+	-
Thalassiosira	+	+	-
T. spp.	+	+	-
Pennales	11,000	22,000	16,000
Achnanthes	+	+	+
A. lemmermannii	+	+	+
A. spp.	+	+	+
Amphipleura	+	+	+
A rutilans	+	+	-
A. spp.	-	-	+
Amphiprora	+	-	-
A. spp.	+	-	-
Amphora	1,000	+	+
A. spp.	1,000	+	+
Cocconeis	+	-	+
C. spp.	+	-	+
Diatoma	-	+	-
D. elongatum	-	+	-

Table 12 (cont'd.).

Date	13 Aug	14 Aug	15 Aug
Diploneis	+	+	+
D. litoralis	+	+	-
D. smithii	+	+	+
Gomphonema	+	+	+
G. spp.	+	+	+
Gyrosigma	+	+	+
G. fasciola	+	+	-
G. wansbeckii	+	+	+
G. spp.	-	-	+
Licmophora	-	+	-
L. spp.	-	+	-
Navicula	+	+	+
N. crucigeroides	+	-	+
N. digitoradiata	+	-	-
N. directa	+	-	+
N. forcipata ?	+	-	-
N. hodgeana	+	+	+
N. humerosa	+	-	-
N. rhynchocephala	+	-	-
N. salinarum	+	+	+
N. scopulorum	+	+	+
N. spp.	+	+	+
Nitzschia	4,000	7,000	3,000
N. closterium	4,000	7,000	3,000
N. spp.	+	+	+
Pinnularia ?	+	-	-
P. spp.			

Table 12 (cont'd.).

Date	13 Aug	14 Aug	15 Aug
Stauroneis	+	+	-
S. spp.	+	+	-
Surirella	+	-	-
S. spp.	+	-	-
Synedra	+	+	+
S. fasciculata	+	+	+
S. spp.	+	+	+
Unidentified	6,000	15,000	13,000
Chrysophyta	1,000	+	-
Ebria	-	+	-
E. tripartita	-	+	-
Unidentified	1,000	-	-
Pyrrophyta	+	-	-
Unidentified	+	-	-
Others	35,000	33,000	38,000
Pigmented flagellates	35,000	33,000	38,000

Table 13. Effect of different types and concentrations of oil on the growth of phytoplankton in relation to temperatures (10 day exposure). Results expressed as percentage of control.

Organism	Oil concentration µl/100 ml	Atkinson Point crude			Norman Wells crude			Pembina crude			Venezuela crude		
		0°C	5°C	10°C	0°C	5°C	10°C	0°C	5°C	10°C	0°C	5°C	10°C
Chlamydomonas sp.	1	98.9	96.5	78.8	120.1	55.6	63.5	111.3	67.6	75.8	94.7	56.8	64.8
	10	81.2	67.0	73.2	28.1	16.1	19.4	74.6	34.5	62.7	44.2	35.0	35.1
	100	34.0	17.8	29.5	19.0	7.8	13.2	48.2	15.3	14.5	31.6	8.6	11.8
	1000	19.3	10.2	15.6	15.4	5.5	10.6	29.9	8.6	8.0	23.1	7.1	4.6
Chaetoceros sp.	1	20.5	20.8	19.3	2.6	10.8	17.2	1.9	27.3	64.1	3.5	16.5	16.2
	10	5.0	15.0	8.9	0.9	2.7	4.2	1.2	8.1	21.1	2.9	2.7	3.8
	100	3.5	4.2	4.1	0.5	0	2.4	0.6	4.2	5.4	1.4	0	2.7
	1000	2.0	0	1.7	0	0	0.9	0.5	2.7	2.3	0.6	0	0
Navicula sp.	1	4.9	2.0	1.9	5.9	1.2	2.8	5.0	2.0	2.9	7.0	1.9	2.4
	10	4.7	1.3	1.2	3.3	1.2	1.8	4.6	1.7	2.7	6.0	1.6	2.1
	100	4.7	1.2	0.9	1.4	0.3	0.9	3.7	1.6	2.0	4.3	1.3	0.8
	1000	1.4	0.6	0.5	0.9	0.1	0.6	2.8	0.2	0.9	3.1	0.3	0.6
Nitzschia sp.	1	29.7	3.3	4.2	28.5	4.2	2.1	31.9	2.4	2.0	40.6	1.4	2.0
	10	20.6	2.4	2.5	18.2	1.8	1.2	31.7	1.8	1.9	17.6	0.8	1.6
	100	16.2	1.2	2.4	16.4	0.6	1.1	23.2	1.2	1.6	16.4	0.4	1.4
	1000	8.5	0.4	0.1	10.7	0	1.0	20.8	0	1.3	15.0	0	0.1

Table 14. Effect of various concentrations of Atkinson Point crude oil on the growth of phytoplankton in relation to temperatures and exposure times. Results expressed as percentage of control.

Species of phytoplankton tested	Oil concentration µl/100 ml	Temperature (°C) 0 Exposure time (days) 10	14	20	5 Exposure time (days) 10	14	10 Exposure time (days) 10
Chlamydomonas sp.	1	98.9	99.2	115.6	96.5	89.3	78.8
	10	81.2	82.7	87.8	67.0	66.4	73.2
	100	34.0	34.3	37.8	17.8	14.0	29.5
	1000	19.3	19.1	18.0	10.2	10.5	15.6
Chaetoceros sp.	1	20.5	5.6	1.3	20.8	11.3	19.3
	10	5.0	1.2	0.1	15.0	3.1	8.9
	100	3.5	0.7	0.1	4.2	0	4.1
	1000	2.0	0.3	0	0	0	1.7
Navicula sp.	1	4.9	5.6	1.8	2.0	1.4	1.9
	10	4.7	4.6	1.7	1.3	1.1	1.2
	100	4.7	2.8	1.6	1.2	1.0	0.9
	1000	1.4	1.2	0.6	0.6	0.5	0.5
Nitzschia sp.	1	29.7	14.2	14.5	3.3	0.6	4.2
	10	20.6	10.5	6.9	2.4	0.4	2.5
	100	16.2	8.1	5.3	1.2	0.3	2.4
	1000	8.5	6.7	3.2	0.4	0.1	0.1

Table 15. Effect of various concentrations of Norman Wells crude oil on the growth of phytoplankton in relation to temperatures and exposure times. Results expresses as percentage of control.

Species of phytoplankton tested	Oil concentration µl/100 ml	Temperature (°C) 0 Exposure time (days) 10	0 14	0 20	5 10	5 14	10 10
Chlamydomonas sp.	1	120.1	89.7	82.6	55.6	59.2	63.5
	10	28.1	19.3	14.2	16.1	16.2	19.4
	100	19.1	12.4	12.4	7.8	8.3	13.2
	1000	15.4	8.9	7.4	5.5	7.6	10.6
Chaetoceros sp.	1	2.6	0.3	0	10.8	3.1	17.2
	10	0.9	0	0	2.7	0	4.2
	100	0.5	0	0	0	0	2.4
	1000	0	0	0	0	0	0.9
Navicula sp.	1	5.9	4.6	1.5	1.2	0.9	2.8
	10	3.3	2.6	0.9	1.2	0.7	1.8
	100	1.4	0.5	0.5	0.3	0.2	0.9
	1000	0.9	0.2	0.2	0.1	0	0.6
Nitzschia sp.	1	28.5	21.2	11.5	4.2	0.6	2.1
	10	18.2	11.8	8.4	1.8	0.1	1.2
	100	16.4	9.5	2.3	0.6	0	1.1
	1000	10.7	8.1	1.8	0	0	1.0

Table 16. Effect of various concentrations of Pembina crude oil on the growth of phytoplankton in relation to temperatures and exposure times. Results expressed as percentage of control.

Species of phytoplankton tested	Oil concentration µl/100 ml	Temperature (°C) 0 — Exposure time (days) 10	14	20	5 — Exposure time (days) 10	14	10 — Exposure time (days) 10
Chlamydomonas sp.	1	111.3	103.8	102.9	67.6	73.2	75.8
	10	74.6	73.2	66.4	34.5	41.7	62.7
	100	48.2	46.3	43.2	15.3	21.4	14.5
	1000	29.9	19.3	11.6	8.6	8.9	8.0
Chaetoceros sp.	1	1.9	0.5	0	27.3	11.8	64.1
	10	1.2	0.2	0	8.1	1.6	21.1
	100	0.6	0	0	4.2	0	5.4
	1000	0.5	0	0	2.7	0	2.3
Navicula sp.	1	5.0	3.9	1.9	2.0	1.2	2.9
	10	4.6	3.1	1.8	1.7	1.0	2.7
	100	3.7	1.8	1.6	1.6	0.7	2.0
	1000	2.8	1.3	0.4	0.2	0.1	0.9
Nitzschia sp.	1	31.9	16.6	14.5	2.4	0.6	2.0
	10	31.7	13.7	9.1	1.8	0.5	1.9
	100	23.2	13.3	8.1	1.2	0.3	1.6
	1000	20.8	13.0	6.9	0	0.1	1.3

Table 17. Effect of various concentrations of Venezuela crude oil on the growth of phytoplankton in relation to temperatures and exposure times. Results expressed as percentage of control.

Species of phytoplankton tested	Oil concentration µl/100 ml	Temperature (°C) 0 — Exposure time (days) 10	0 — 14	0 — 20	5 — 10	5 — 14	10 — 10
Chlamydomonas sp.	1	94.7	93.0	83.8	56.8	72.4	64.8
	10	44.2	40.9	40.8	35.0	58.4	35.1
	100	31.6	20.5	17.8	8.6	9.6	11.3
	1000	23.1	16.3	8.9	7.1	7.3	4.6
Chaetoceros sp.	1	3.5	0.6	0	16.5	6.8	16.2
	10	2.9	0.2	0	2.7	2.1	3.8
	100	1.4	0	0	0	0	2.7
	1000	0.6	0	0	0	0	0
Navicula sp.	1	7.0	3.8	1.6	1.9	1.3	2.4
	10	6.0	3.8	1.6	1.6	1.0	2.1
	100	4.3	2.3	0.8	1.3	0.4	0.8
	1000	3.1	0.6	0.4	0.3	0.1	0.6
Nitzschia sp.							
	1	40.6	13.3	6.3	1.4	0.8	2.0
	10	17.6	6.3	4.6	0.8	0.3	1.6
	100	16.4	5.1	3.2	0.4	0.2	1.4
	1000	15.0	4.9	2.9	0	0	0.1

Table 18. Effect of various concentrations of Corexit on the growth of phytoplankton in relation to temperatures and exposure times. Results expressed as percentage of control.

Species of phytoplankton tested	Corexit concentration µl/100 ml	Temperature (°C) 0 — Exposure time (days) 10	0 — 14	0 — 20	5 — 10	5 — 14	10 — 10
Chlamydomonas sp.	1	103.8	104.9	106.2	104.9	83.4	134.3
	10	83.6	96.7	103.4	87.8	80.4	102.2
	100	74.3	71.9	62.0	46.8	40.1	79.0
	1000	21.3	13.9	11.6	15.2	12.6	13.2
Chaetoceros sp.	1	102.2	98.5	76.4	107.7	77.4	46.5
	10	76.5	76.2	71.1	28.6	20.8	33.4
	100	22.8	4.8	1.3	4.4	0.6	4.3
	1000	15.2	1.9	0.4	2.7	0.4	0
Navicula sp.	1	22.8	34.3	29.6	98.8	103.3	145.8
	10	19.1	27.9	25.0	63.3	79.5	102.5
	100	8.0	5.9	1.9	10.8	31.1	5.8
	1000	3.9	2.7	0.6	0.3	0.3	2.2
Nitzschia sp.	1	78.0	76.5	49.9	117.2	93.4	98.2
	10	43.2	46.3	11.2	32.9	3.0	34.4
	100	32.6	13.8	6.5	7.7	0.7	1.4
	1000	21.2	11.5	5.1	4.2	0.7	1.3

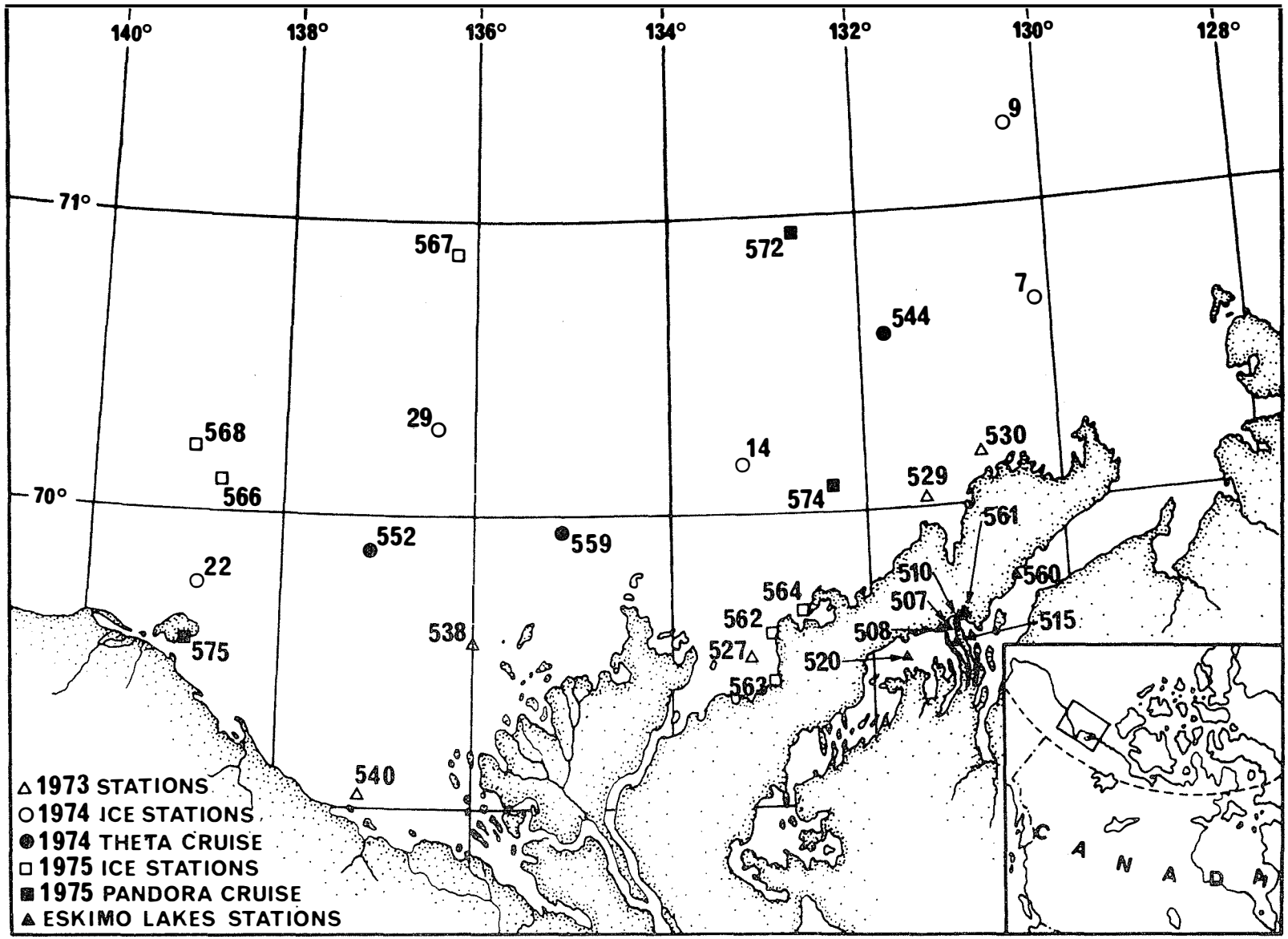

Fig. 1. Southern Beaufort Sea and Eskimo Lakes stations.

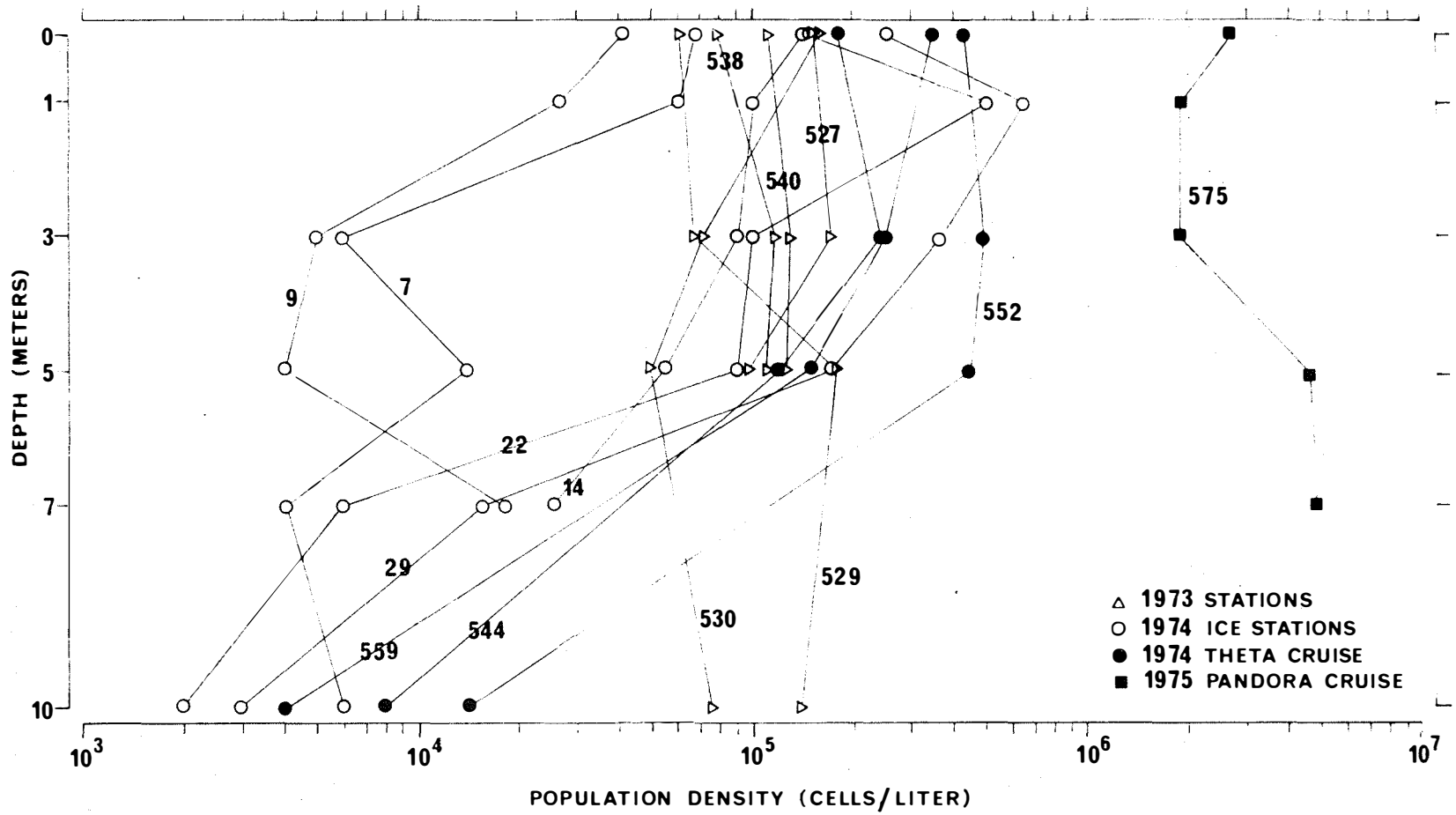

Fig. 2. Vertical distribution of phytoplankton in the southern Beaufort Sea.

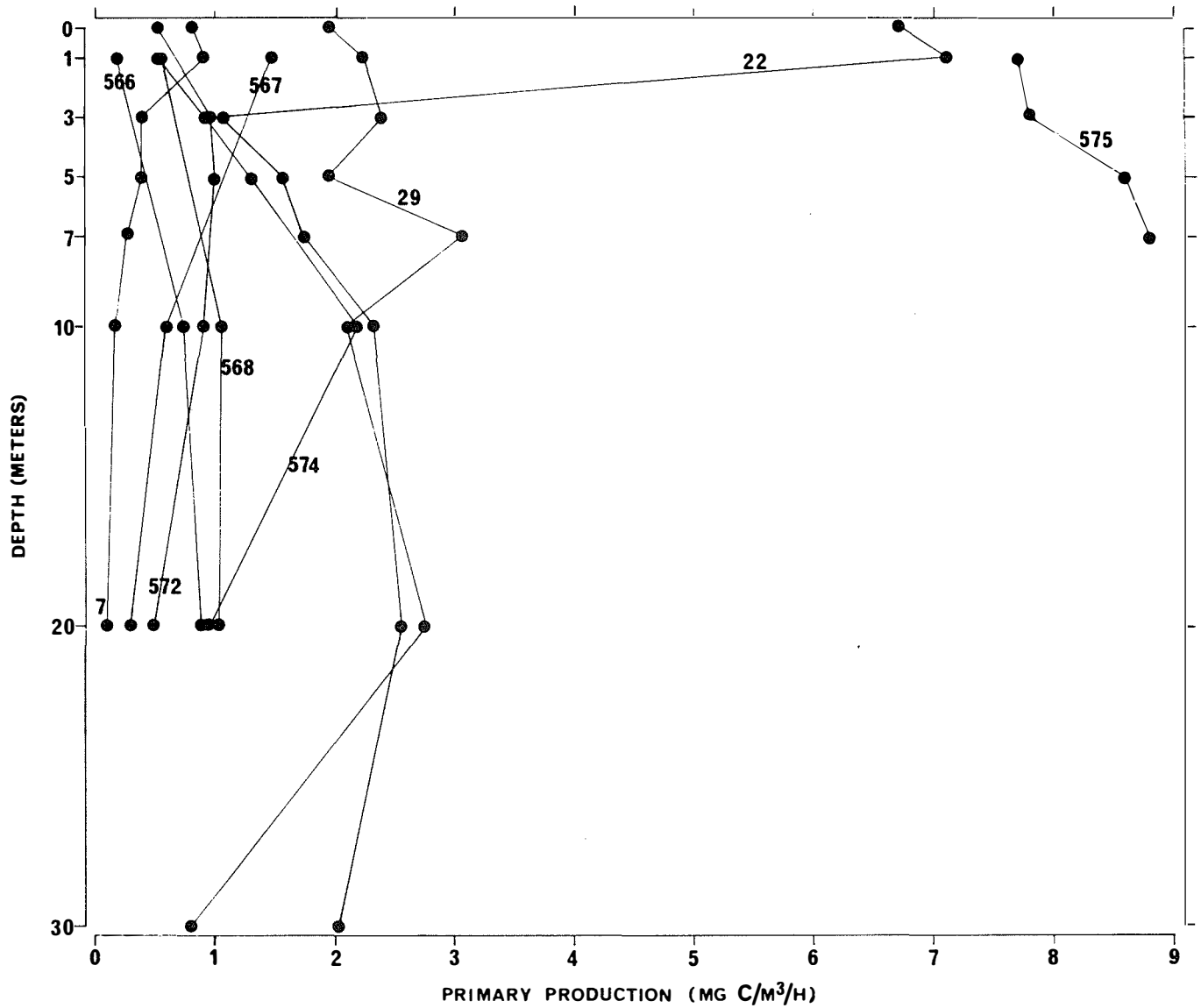

Fig. 3. Vertical distribution of *in situ* gross primary productivity in the southern Beaufort Sea.

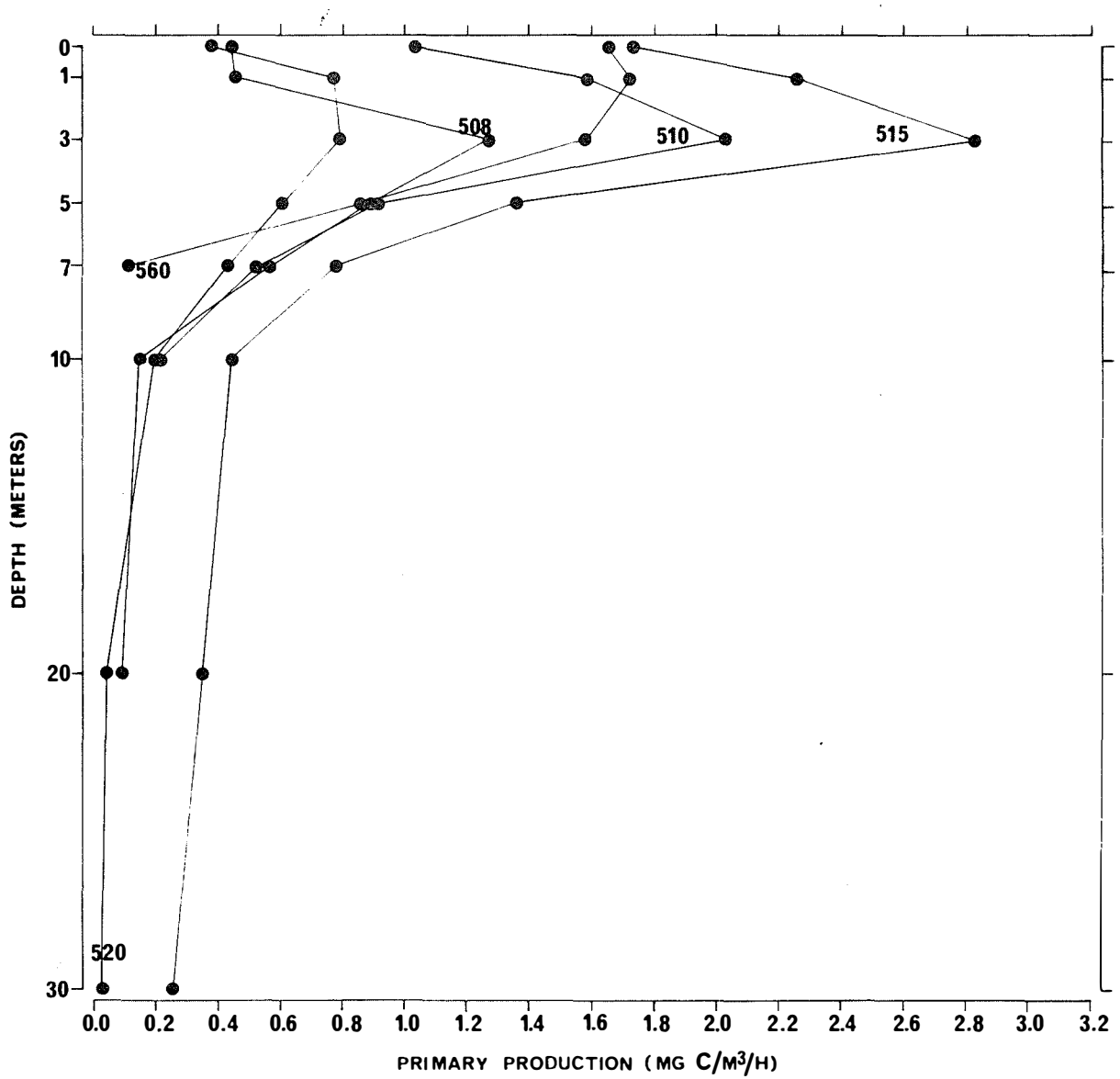

Fig. 4. Vertical distribution of <u>in</u> <u>situ</u> gross primary productivity in the Eskimo Lakes.

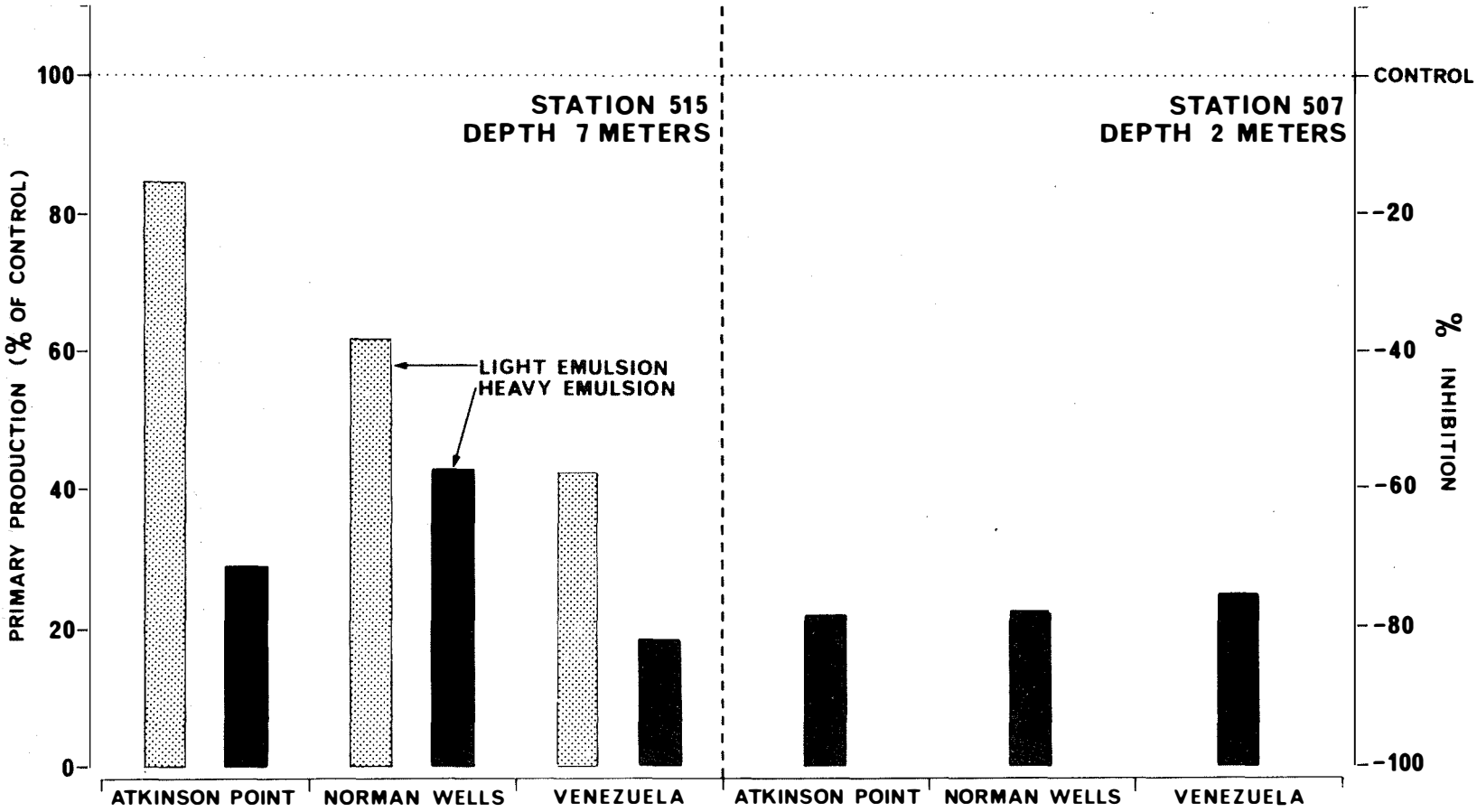

Fig. 5. Effects of light and heavy concentrations of crude oil-seawater emulsion on primary productivity of phytoplankton in the Eskimo Lakes during July, 1974.

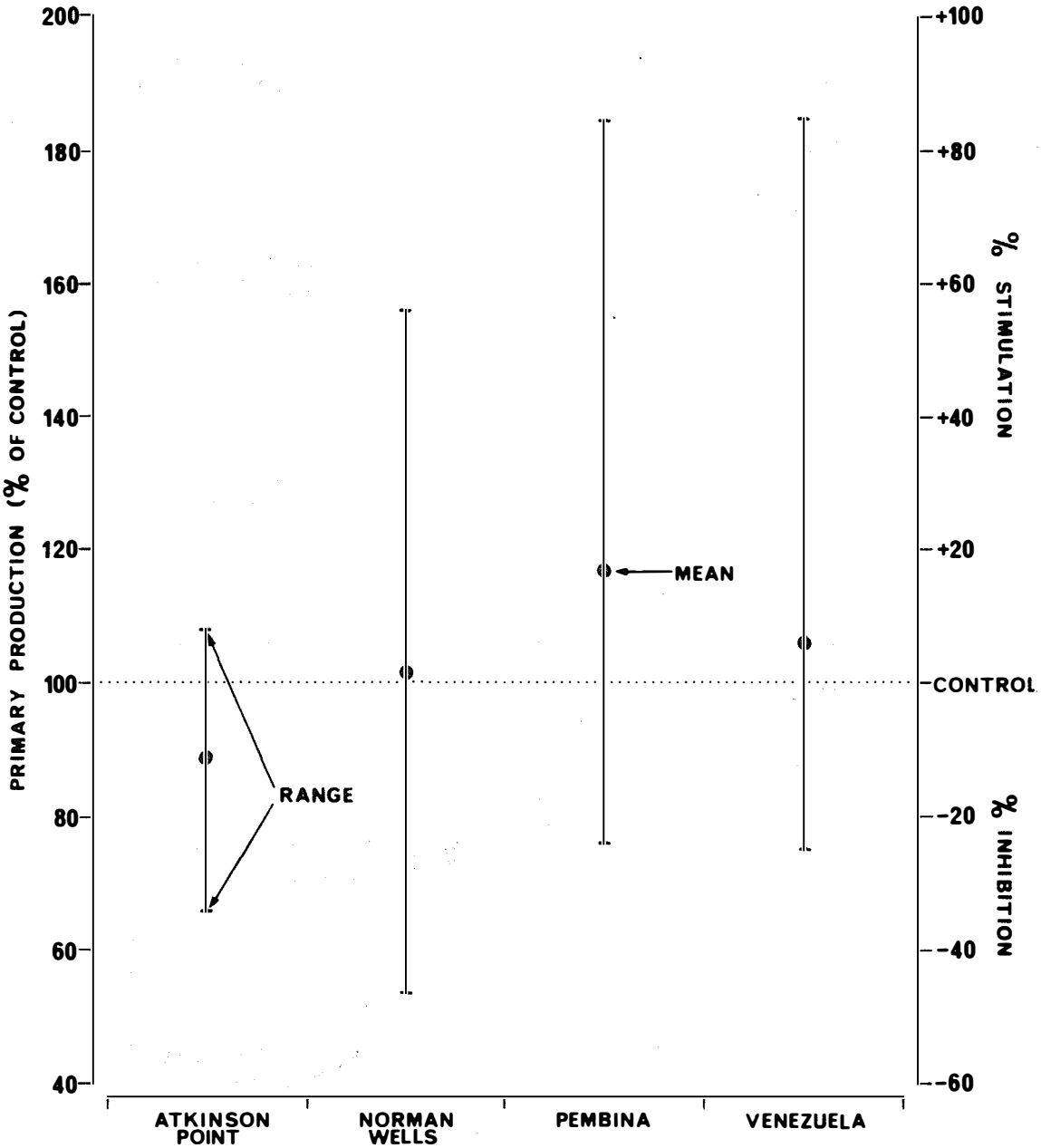

Fig. 6. Effect of crude oils on the in situ gross primary productivity of phytoplankton at 1 metre at various Beaufort Sea stations.

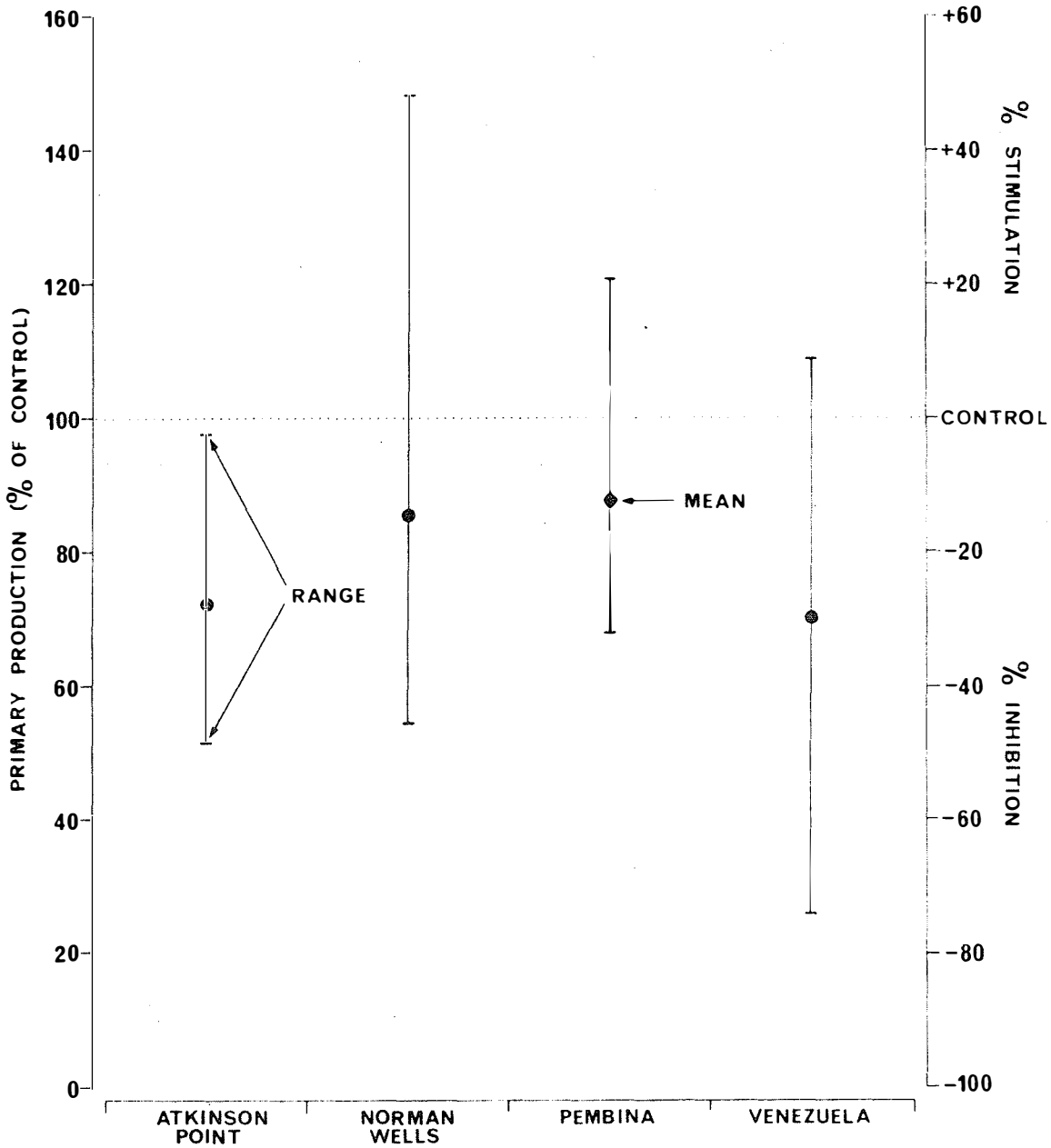

Fig. 7. Effect of crude oils on the in situ gross primary production of phytoplankton at 1 metre at station 515 in the Eskimo Lakes.

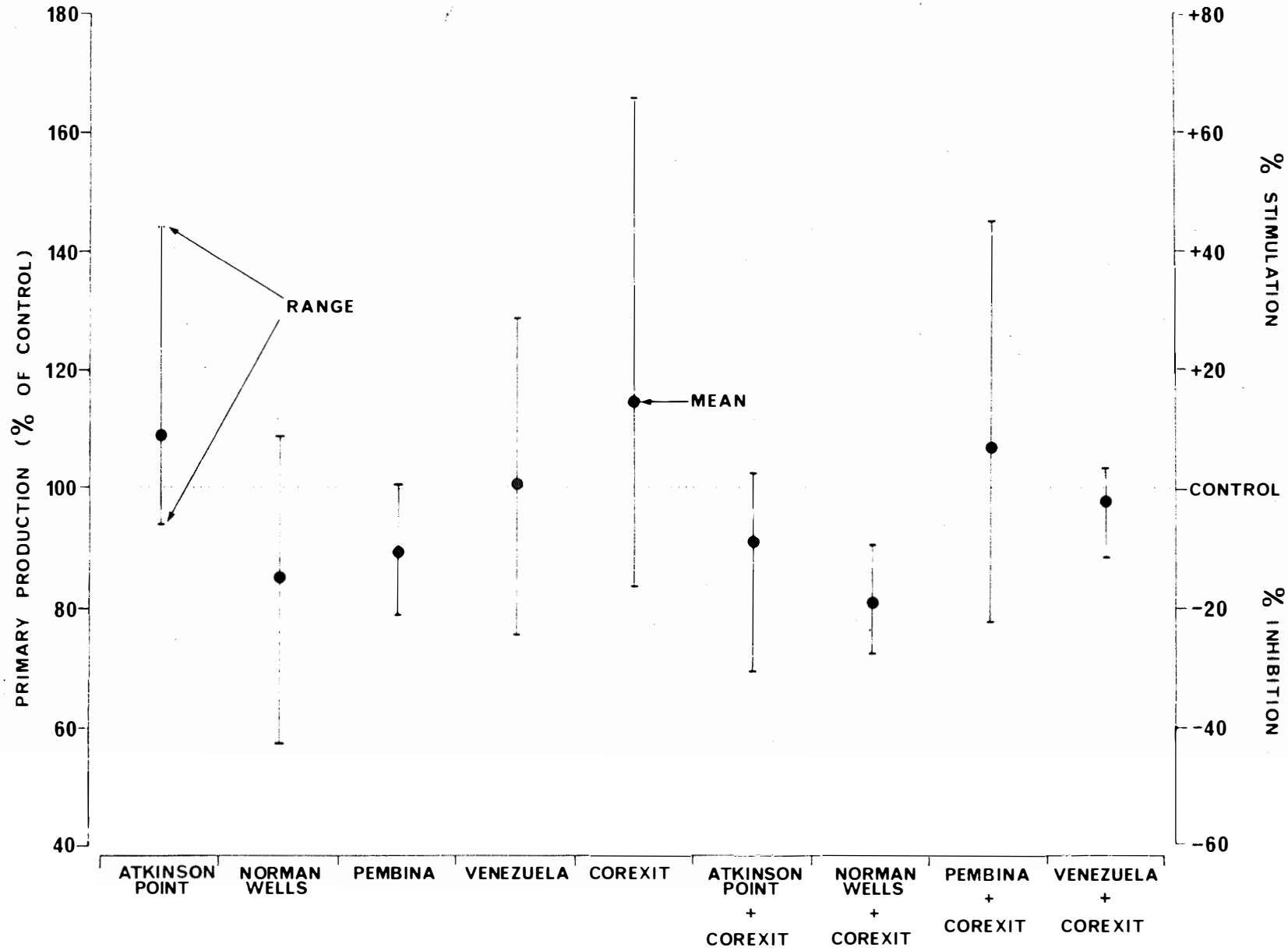

Fig. 8. Effects of crude oils, Corexit and crude oil-Corexit mixtures on the primary production of Eskimo Lakes phytoplankton at 1 metre at station 507.

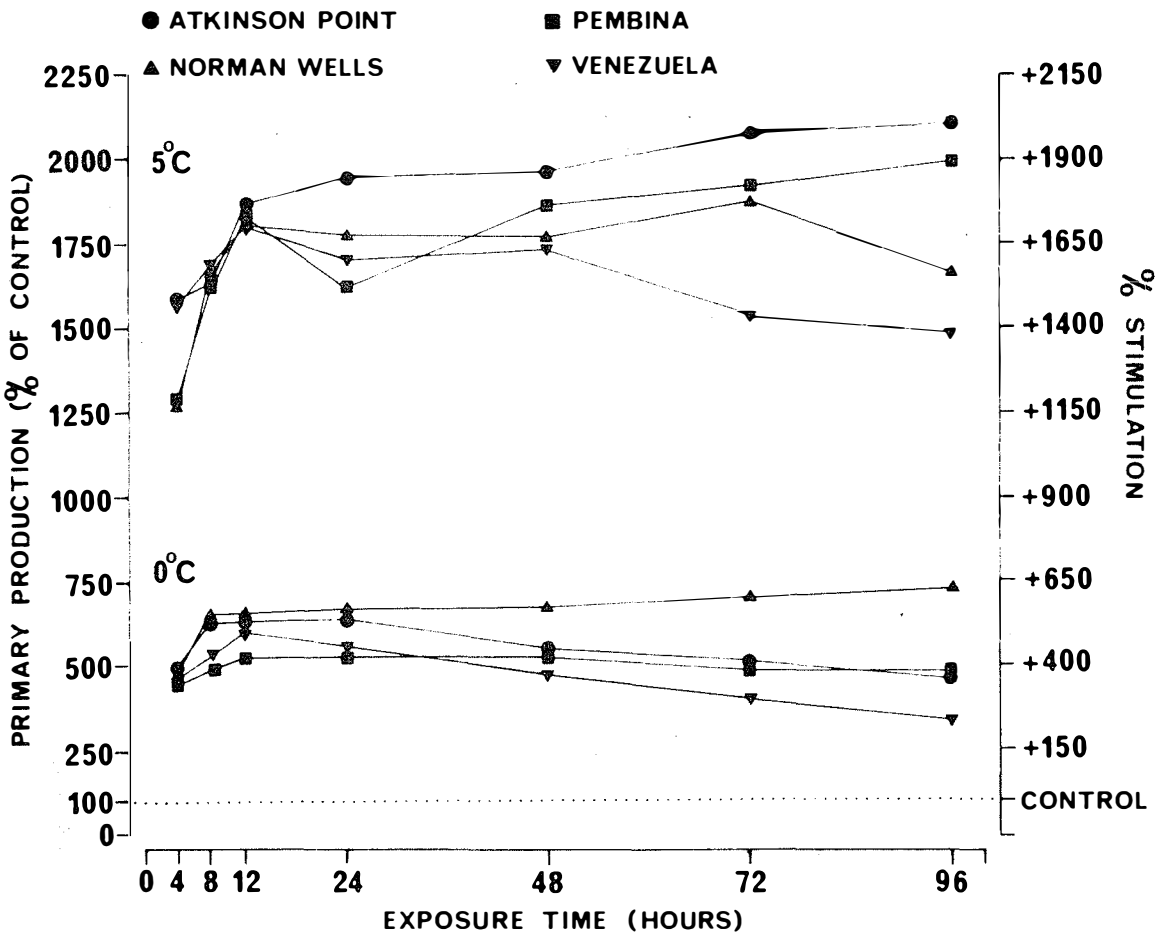

Fig. 9. Effect of crude oils on primary production of *Chlamydomonas* sp. in relation to temperatures and exposure times.

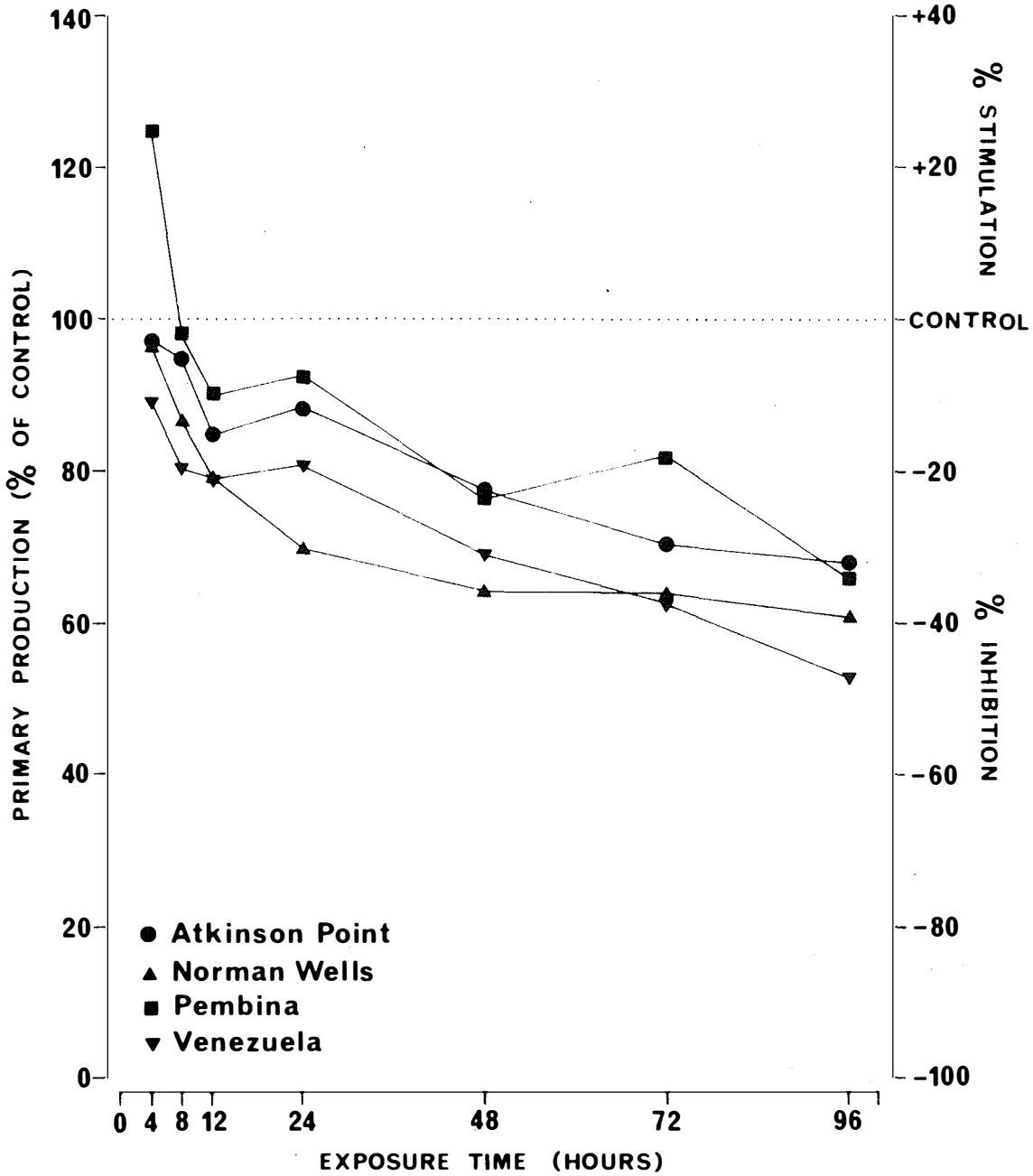

Fig. 10. Effect of crude oils on primary production of *Chaetoceros* sp. in relation to exposure times at 0°C.

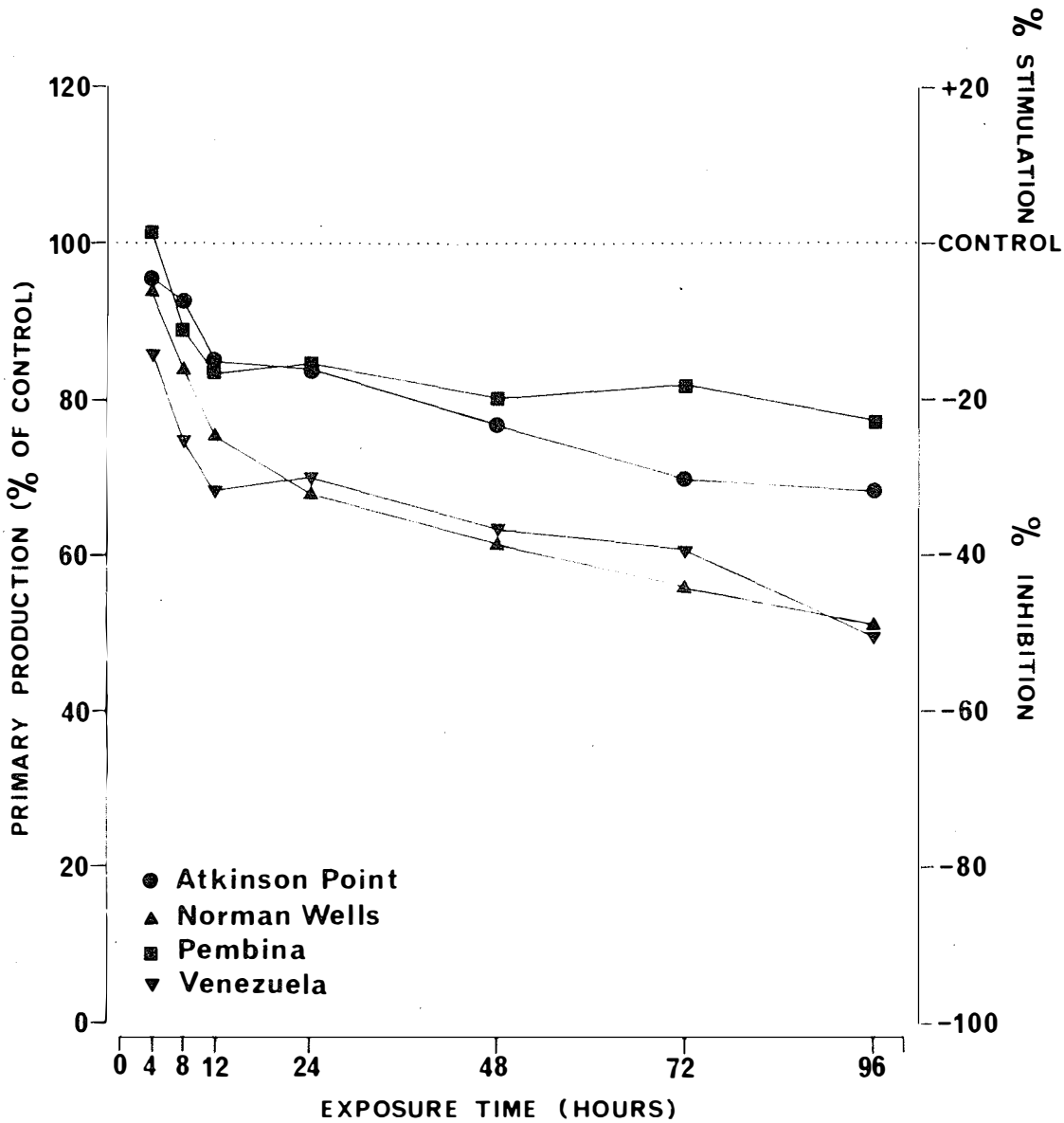

Fig. 11. Effect of crude oils on primary production of *Chaetoceros* sp. in relation to exposure times at 5°C.

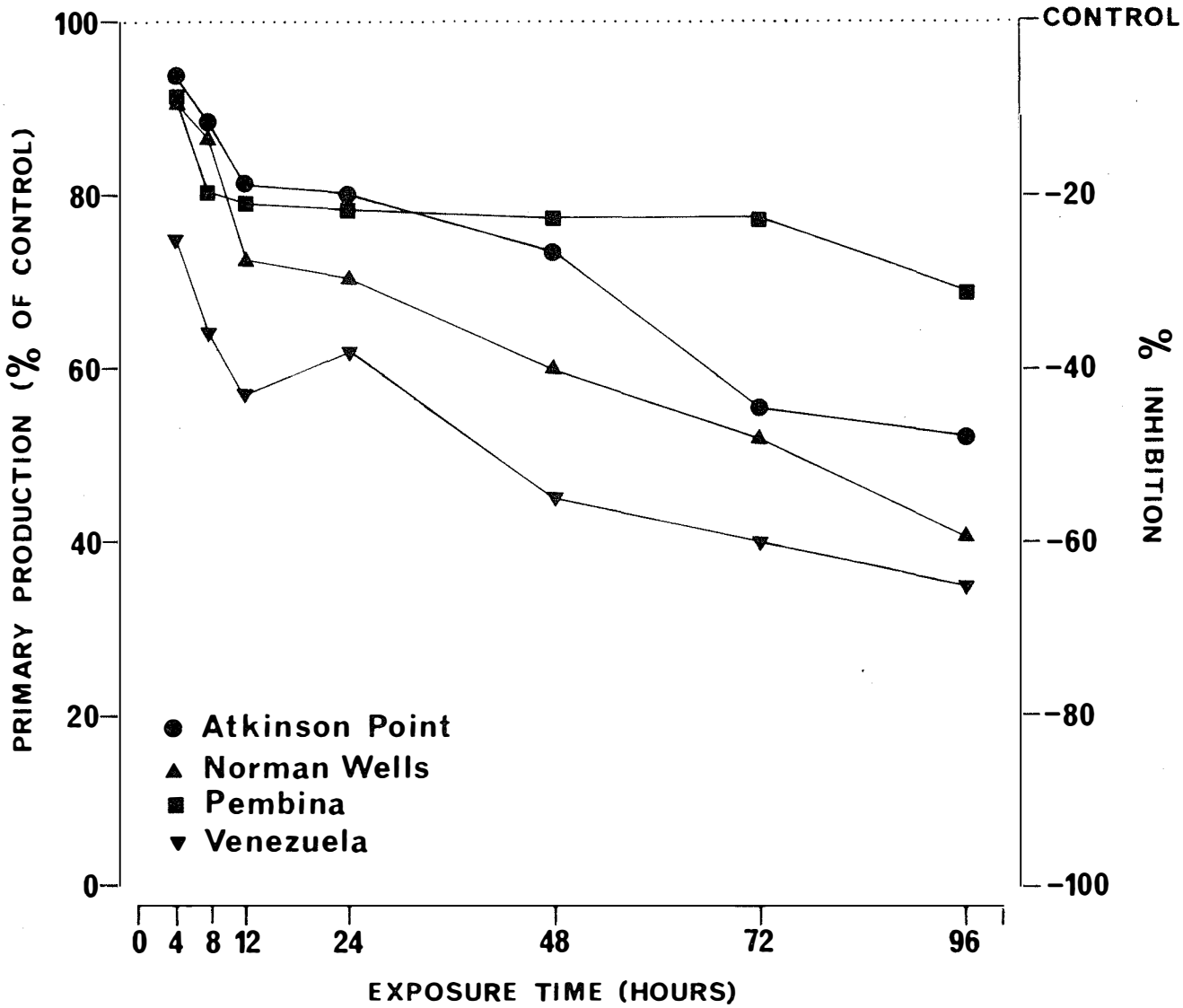

Fig. 12. Effect of crude oils on primary production of *Chaetoceros* sp. in relation to exposure times at 10°C.

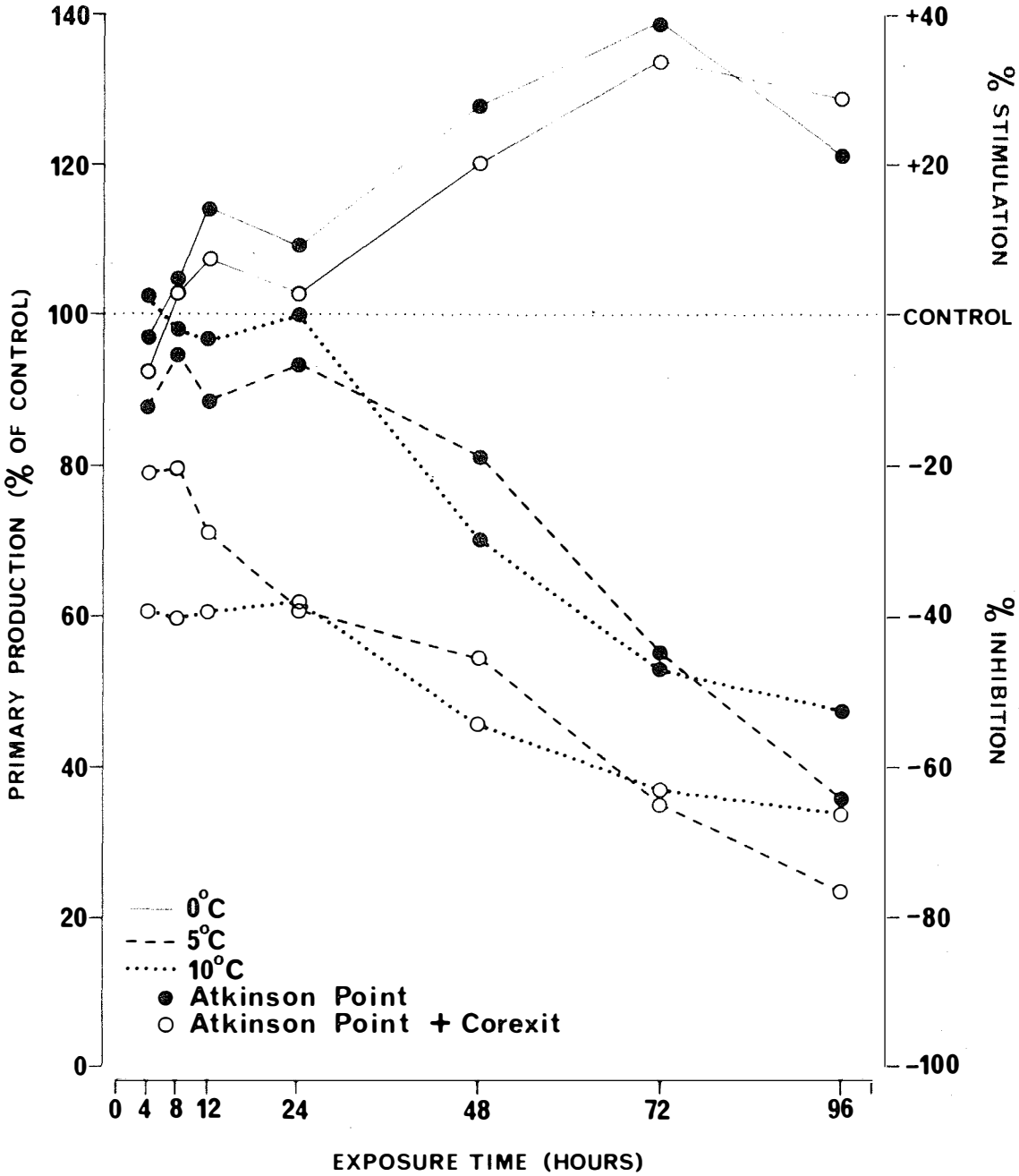

Fig. 13. Effects of Atkinson Point crude and Atkinson Point crude-Corexit mixture on primary production of *Navicula* sp. in relation to temperature and exposure time.

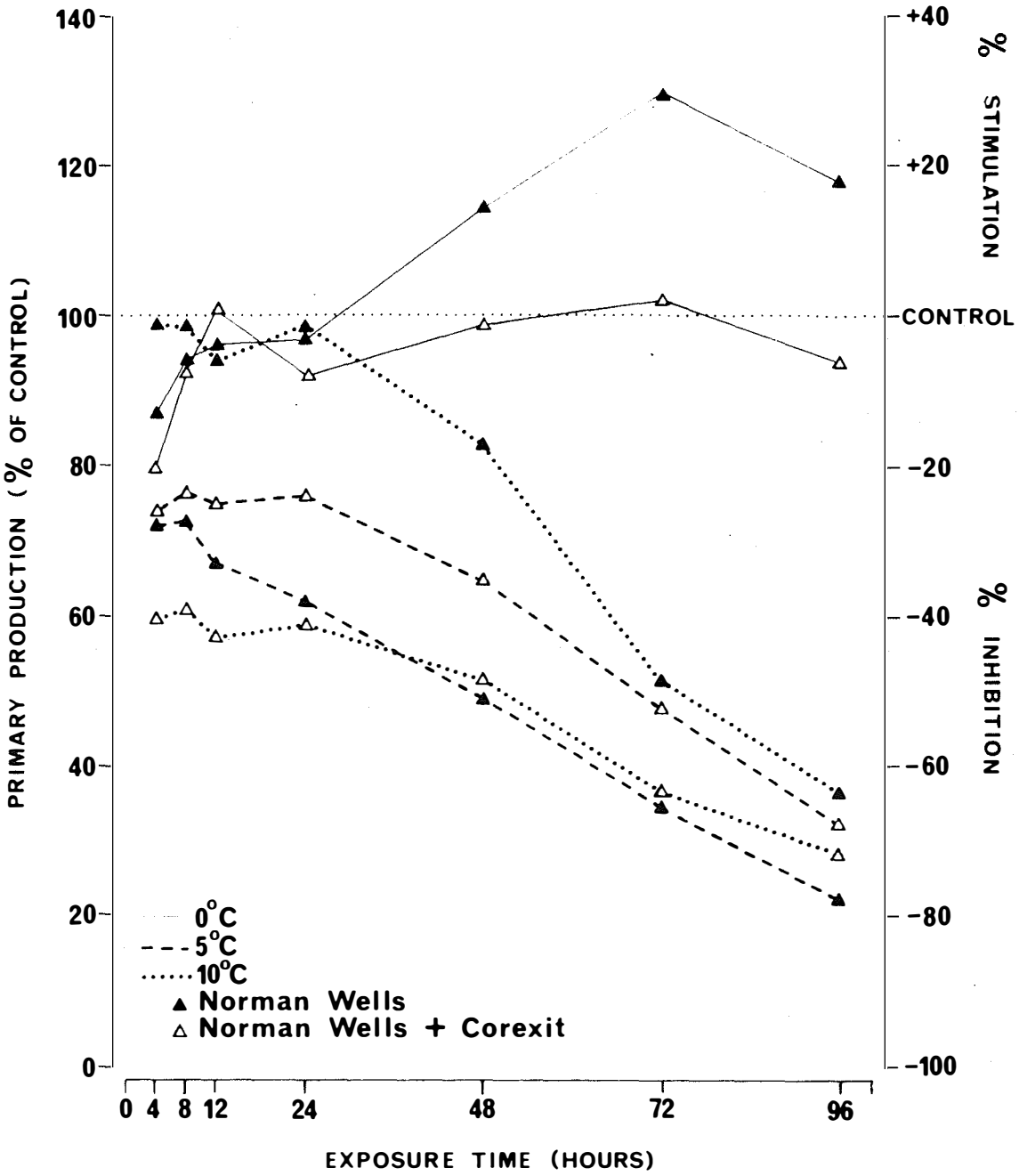

Fig. 14. Effects of Norman Wells crude and Norman Wells crude-Corexit mixture on primary production of *Navicula* sp. in relation to temperature and exposure time.

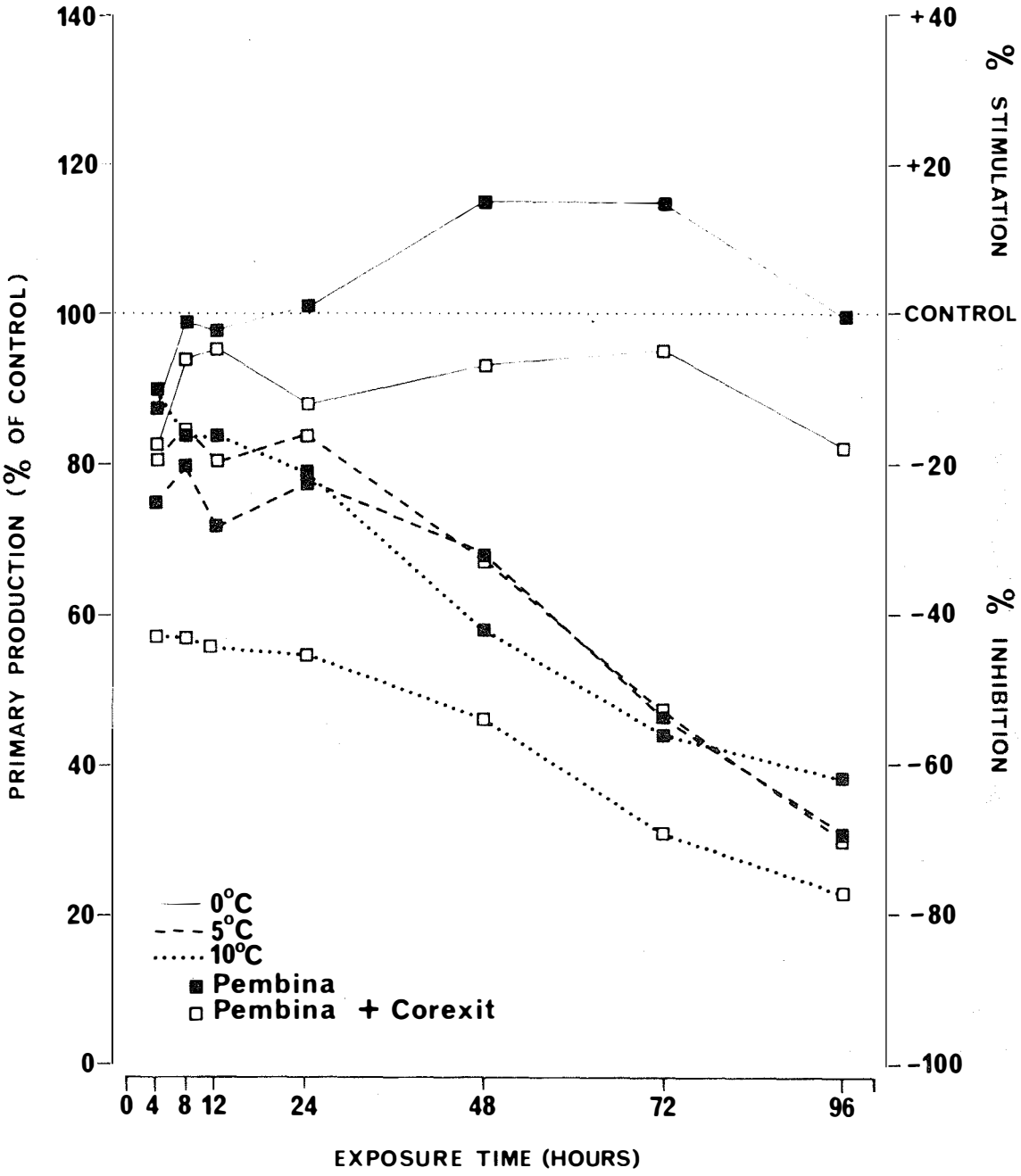

Fig. 15. Effects of Pembina crude and Pembina crude-Corexit mixture on primary production of *Navicula* sp. in relation to temperature and exposure time.

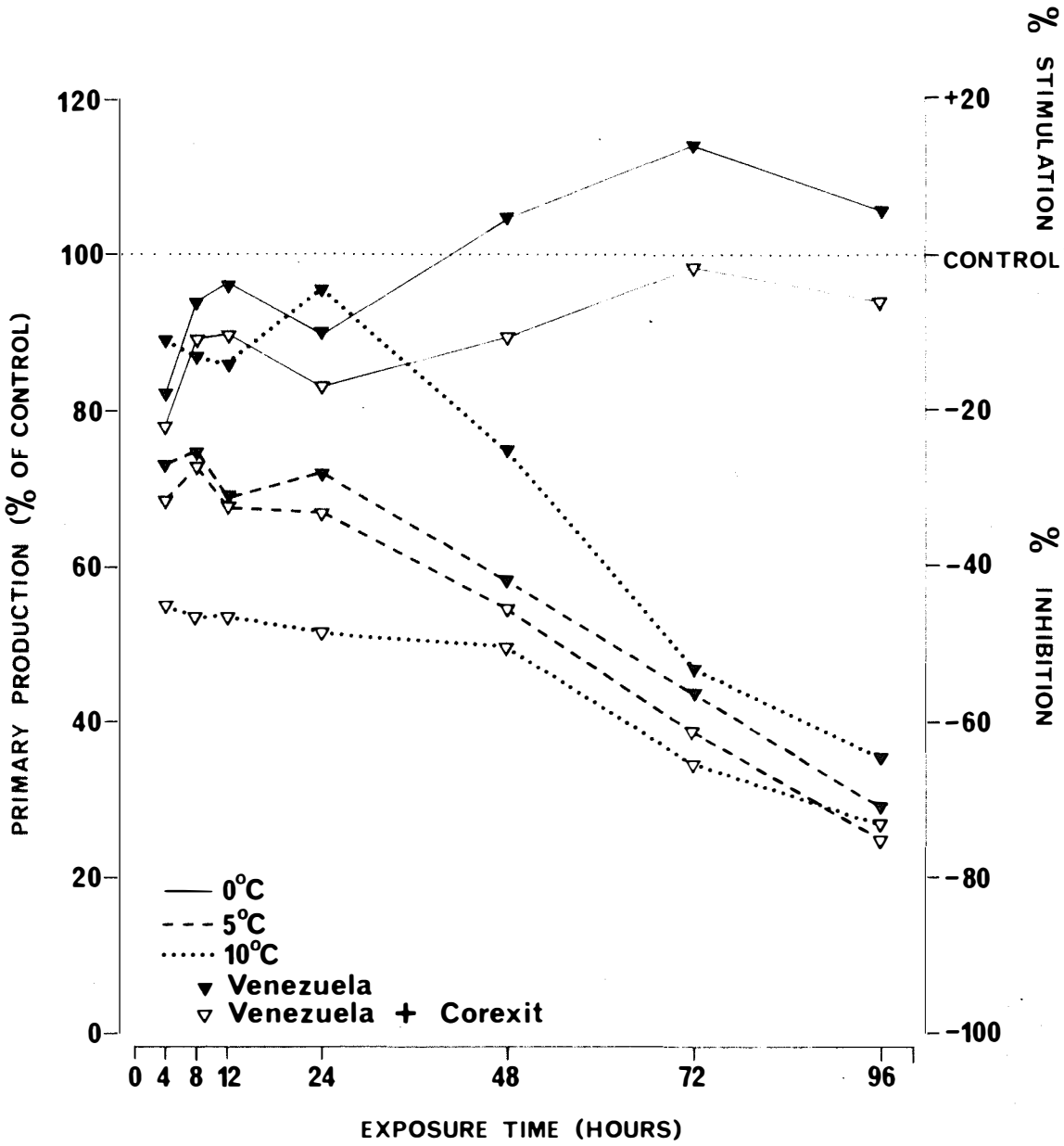

Fig. 16. Effects of Venezuela crude and Venezuela crude-Corexit mixture on primary production of *Naviçula* sp. in relation to temperature and exposure time.

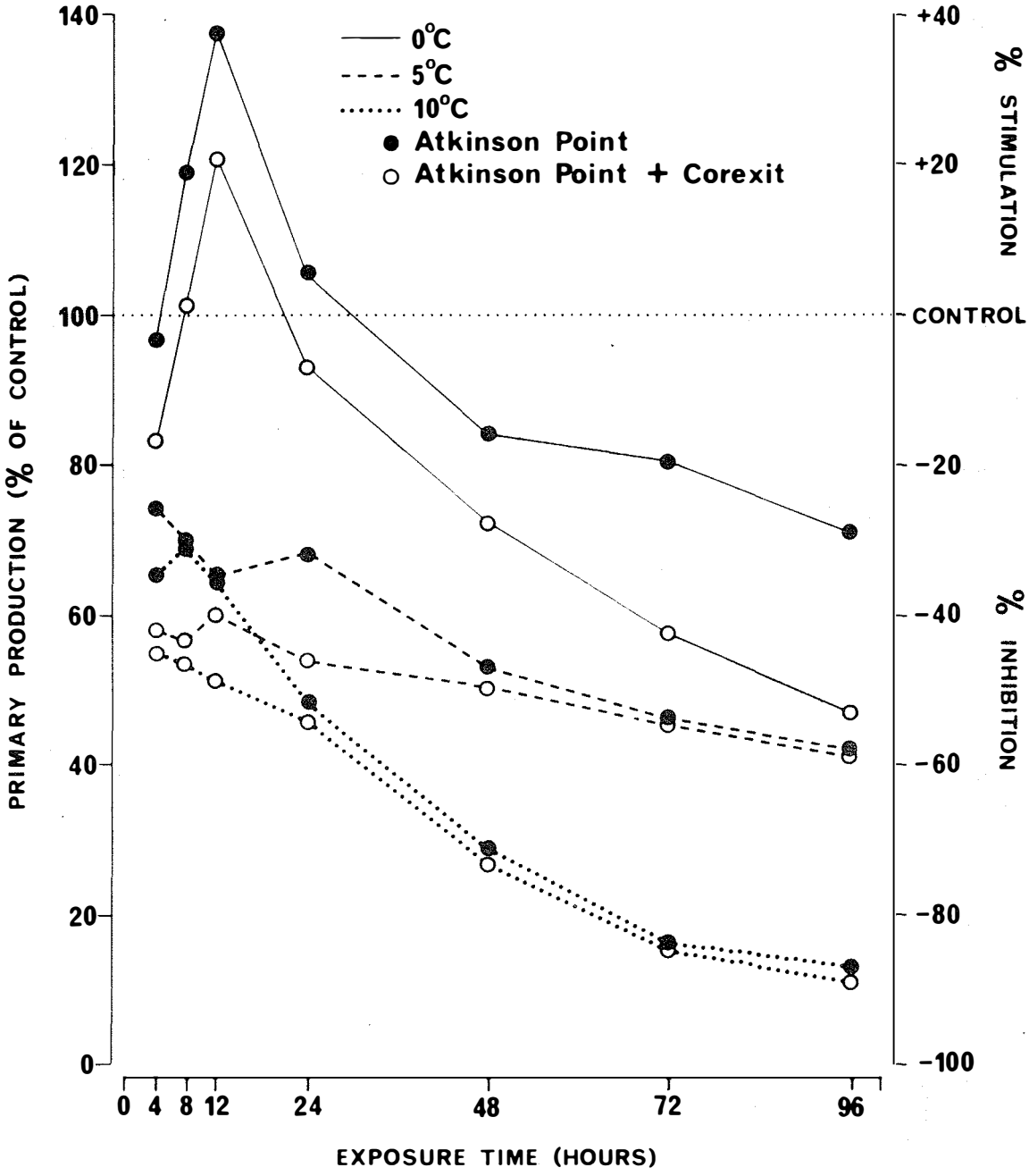

Fig. 17. Effects of Atkinson Point crude and Atkinson Point crude-Corexit mixture on primary production of *Nitzschia* sp. in relation to temperature and exposure time.

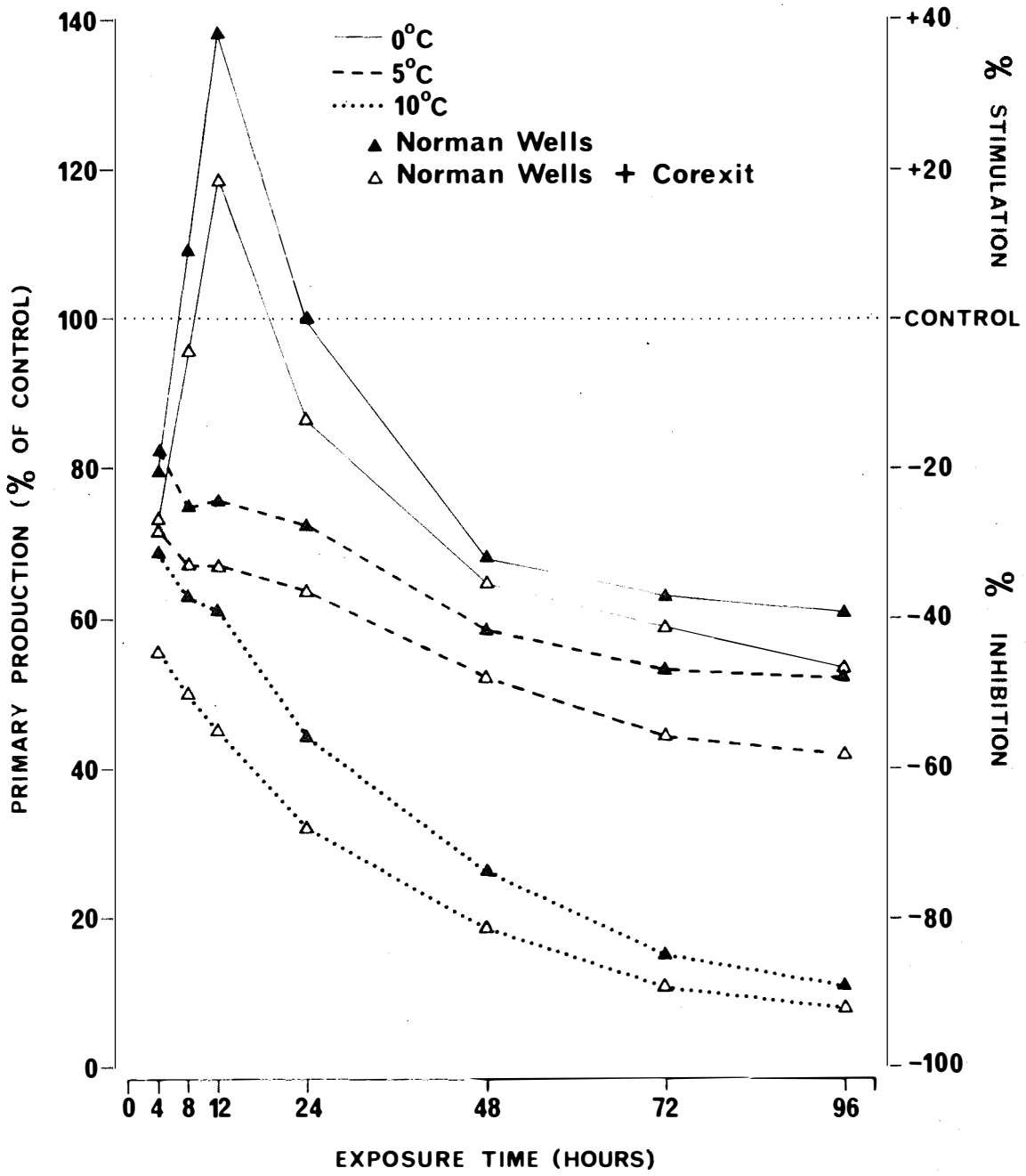

Fig. 18. Effects of Norman Wells crude and Norman Wells crude-Corexit mixture on primary production of *Nitzschia* sp. in relation to temperature and exposure time.

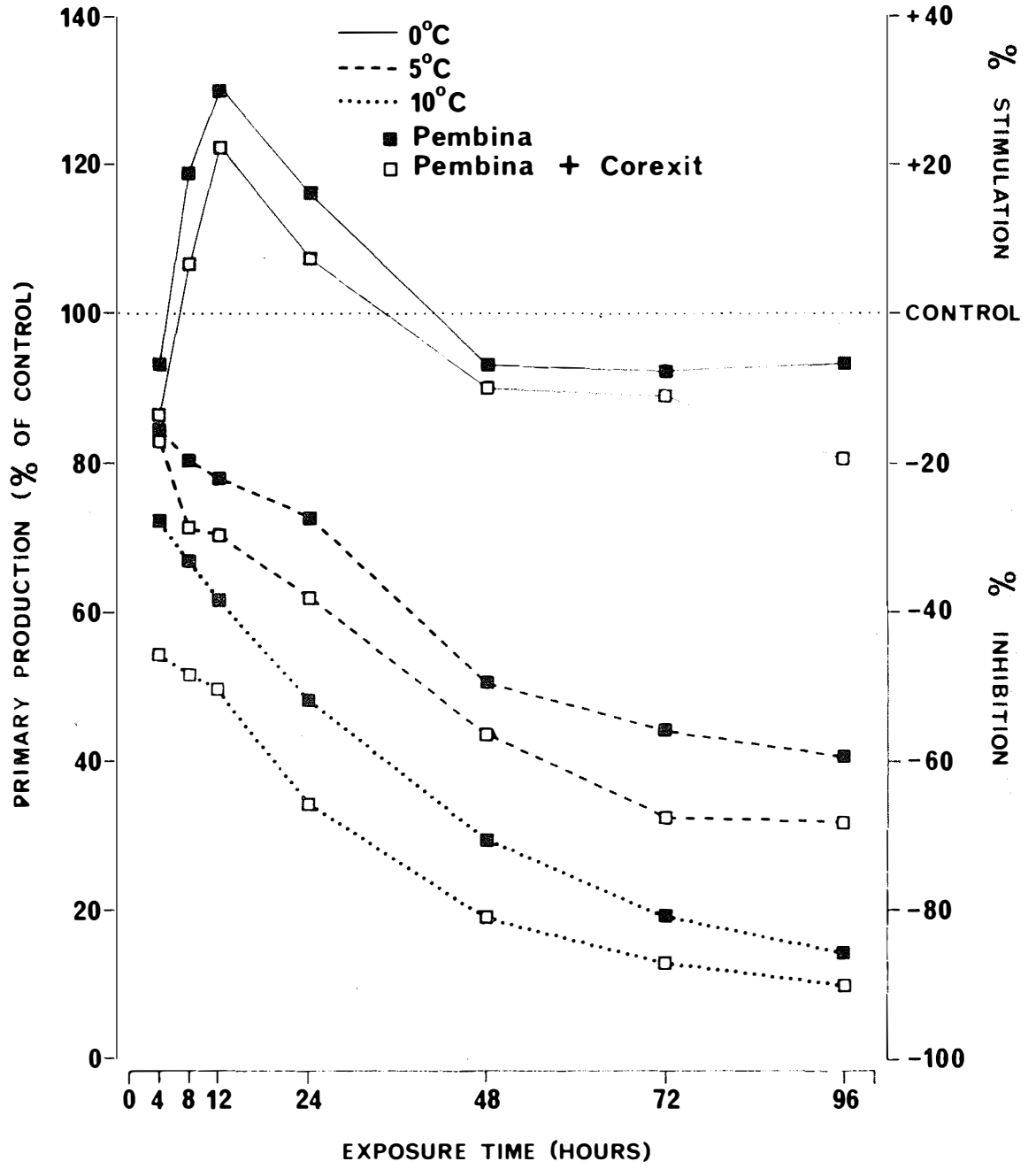

Fig. 19. Effects of Pembina crude and Pembina crude-Corexit mixture on primary production of *Nitzschia* sp. in relation to temperature and exposure time.

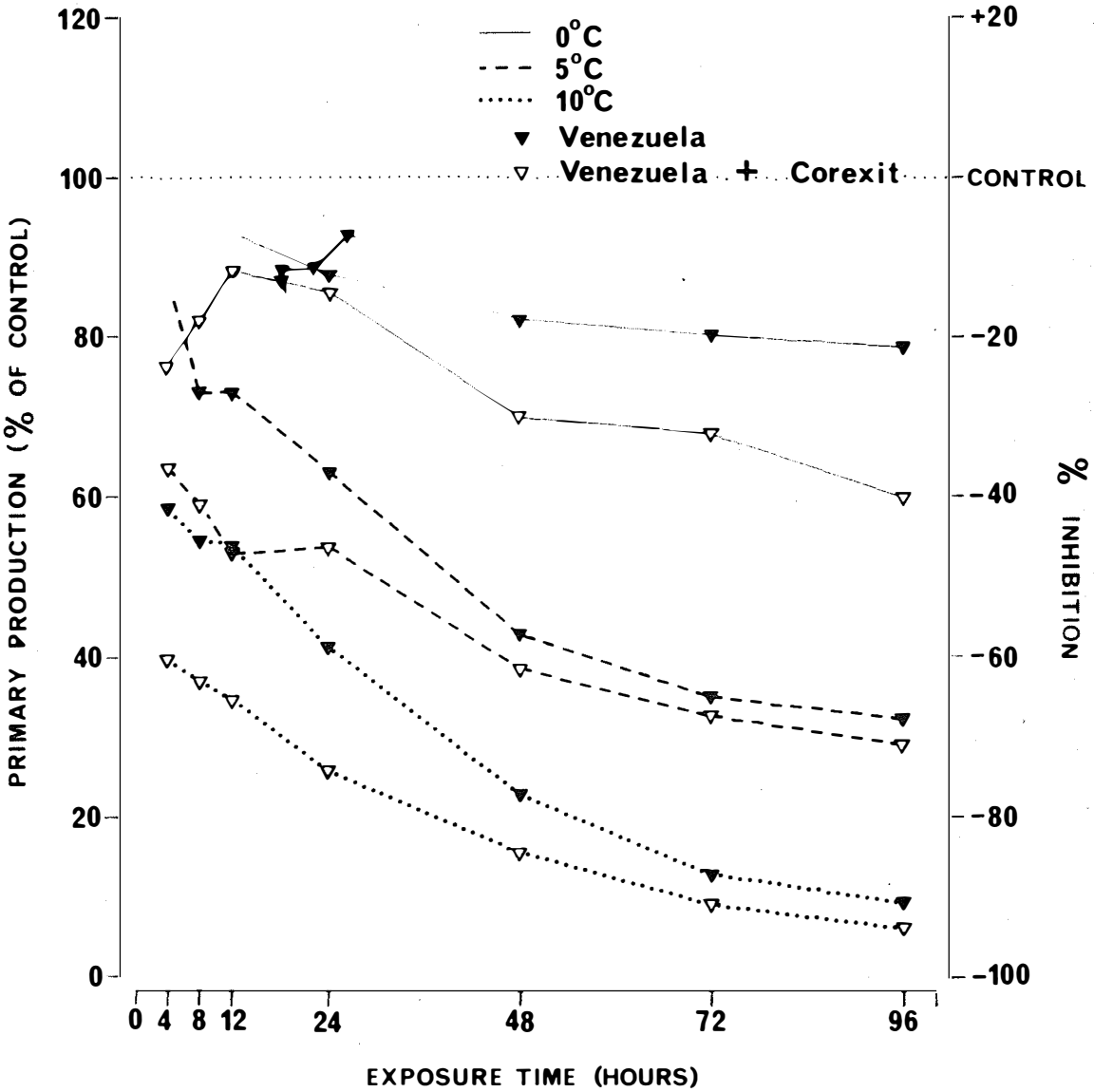

Fig. 20. Effects of Venezuela crude and Venezuela crude-Corexit mixture on primary production of *Nitzschia* sp. in relation to temperature and exposure time.

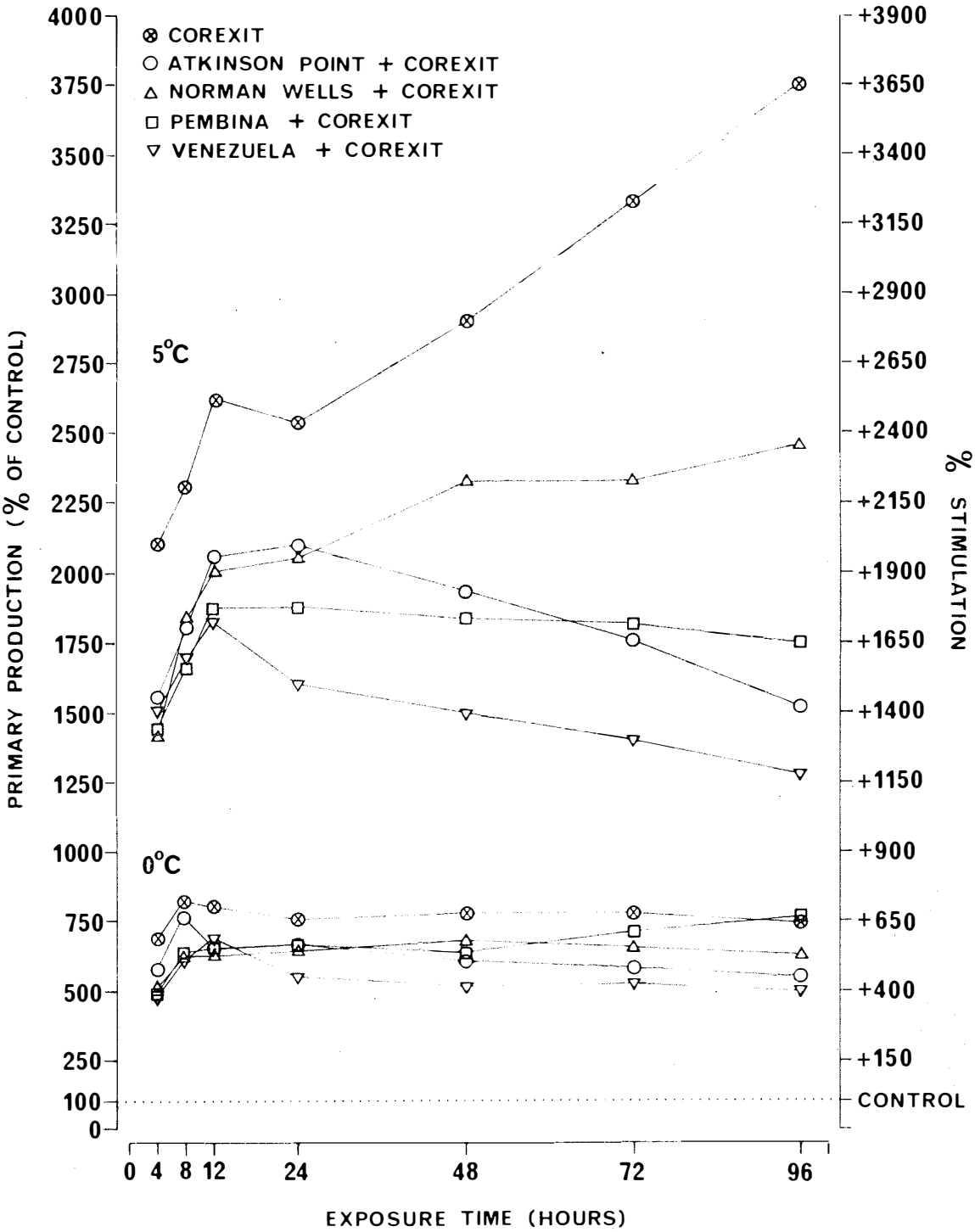

Fig. 21. Effects of Corexit and oil-Corexit mixtures on primary production of *Chlamydomonas* sp. in relation to temperature and exposure time.

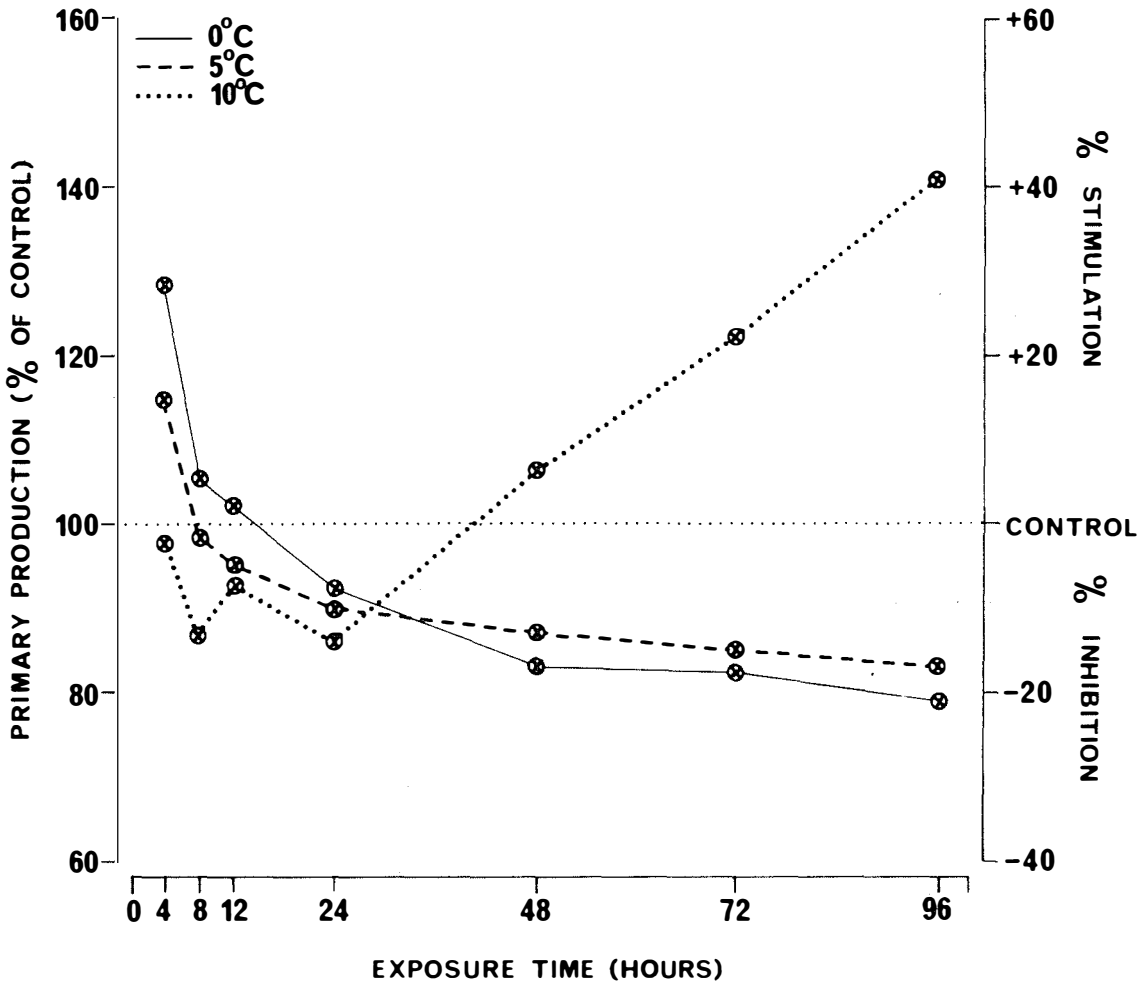

Fig. 22. Effect of Corexit on primary production of *Chaetoceros* sp. in relation to temperature and exposure time.

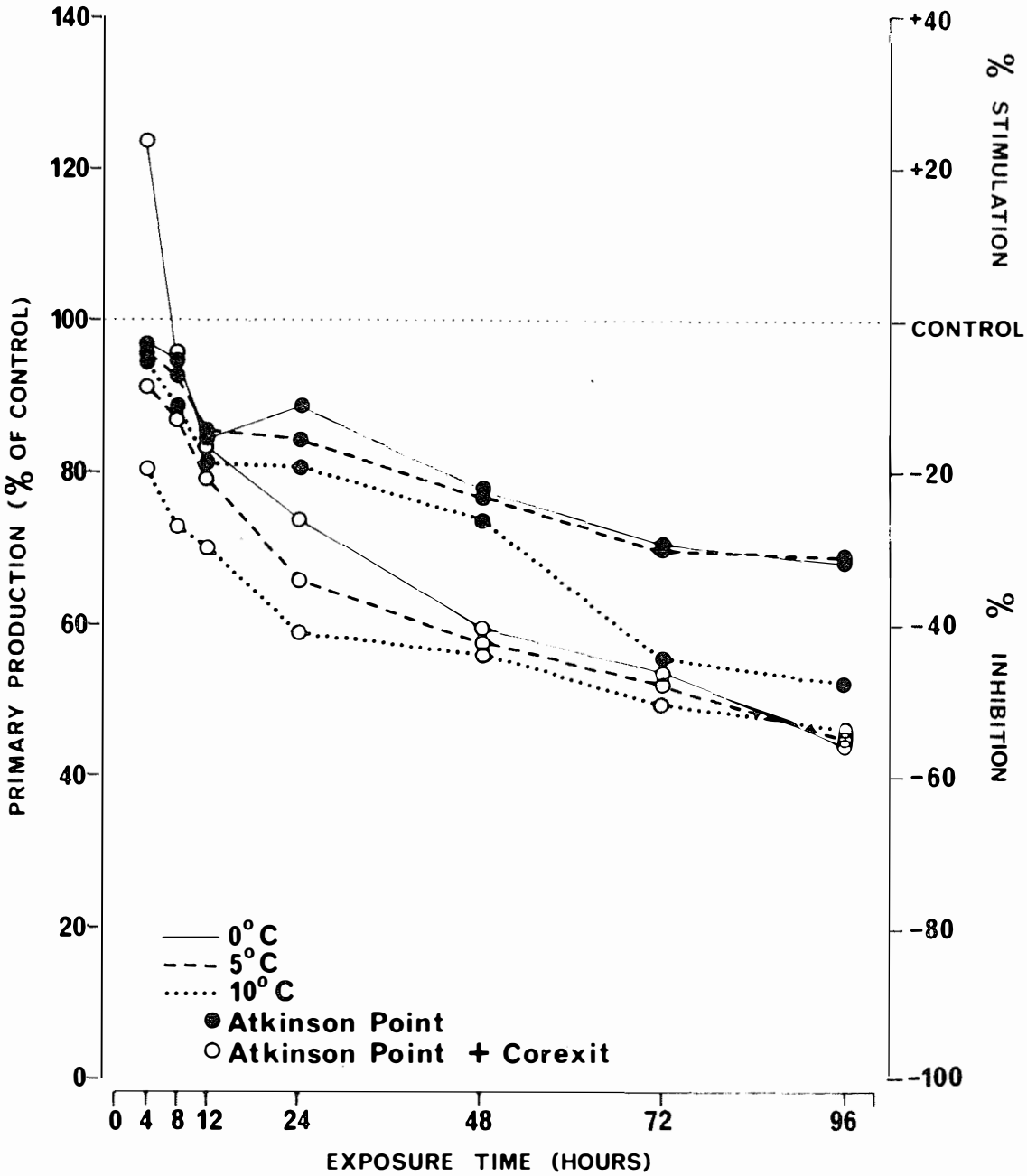

Fig. 23. Effects of Atkinson Point crude and Atkinson Point crude-Corexit mixture on primary production of *Chaetoceros* sp. in relation to temperature and exposure time.

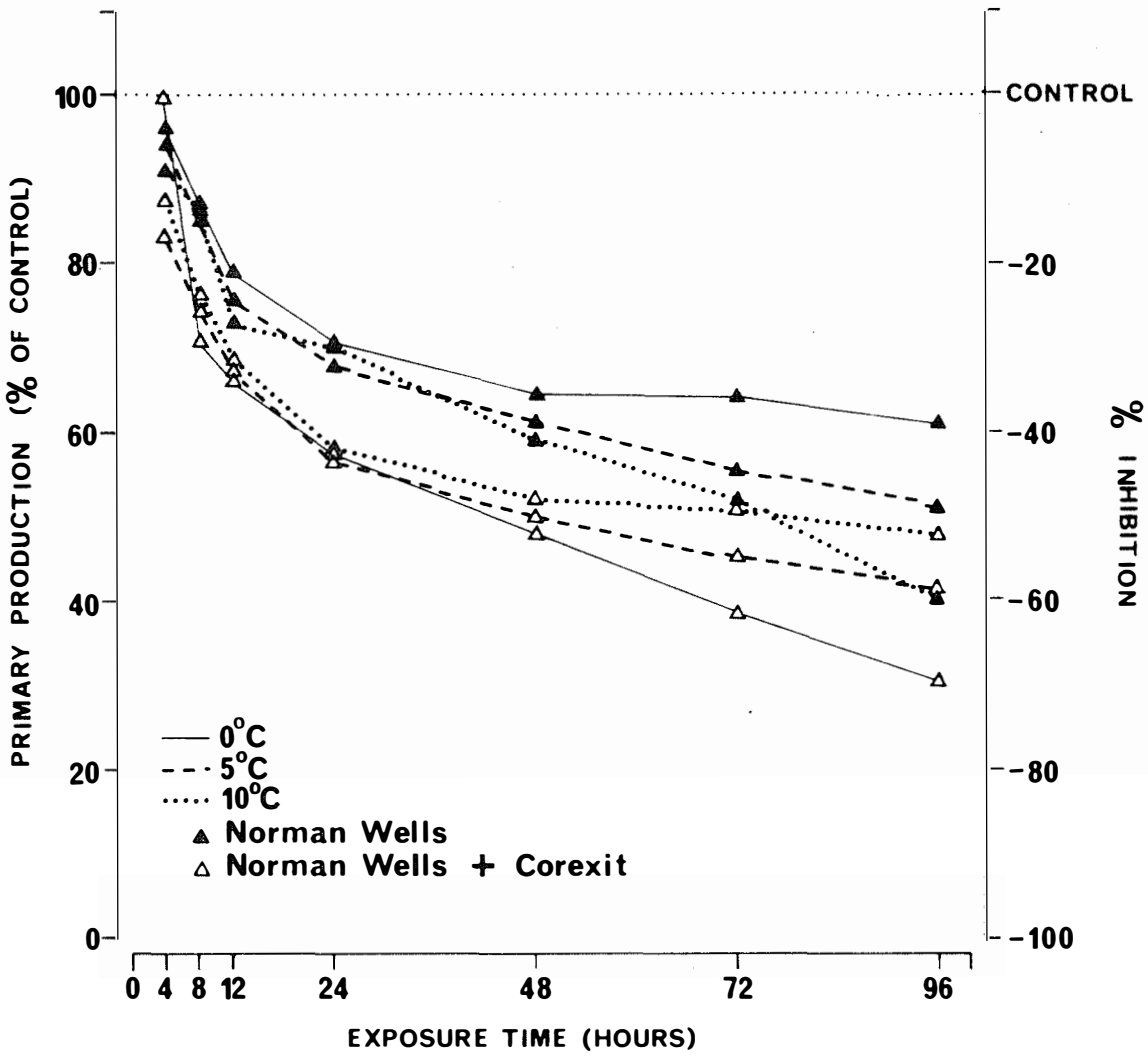

Fig. 24. Effects of Norman Wells crude and Norman Wells crude-Corexit mixture on primary production of *Chaetoceros* sp. in relation to temperature and exposure time.

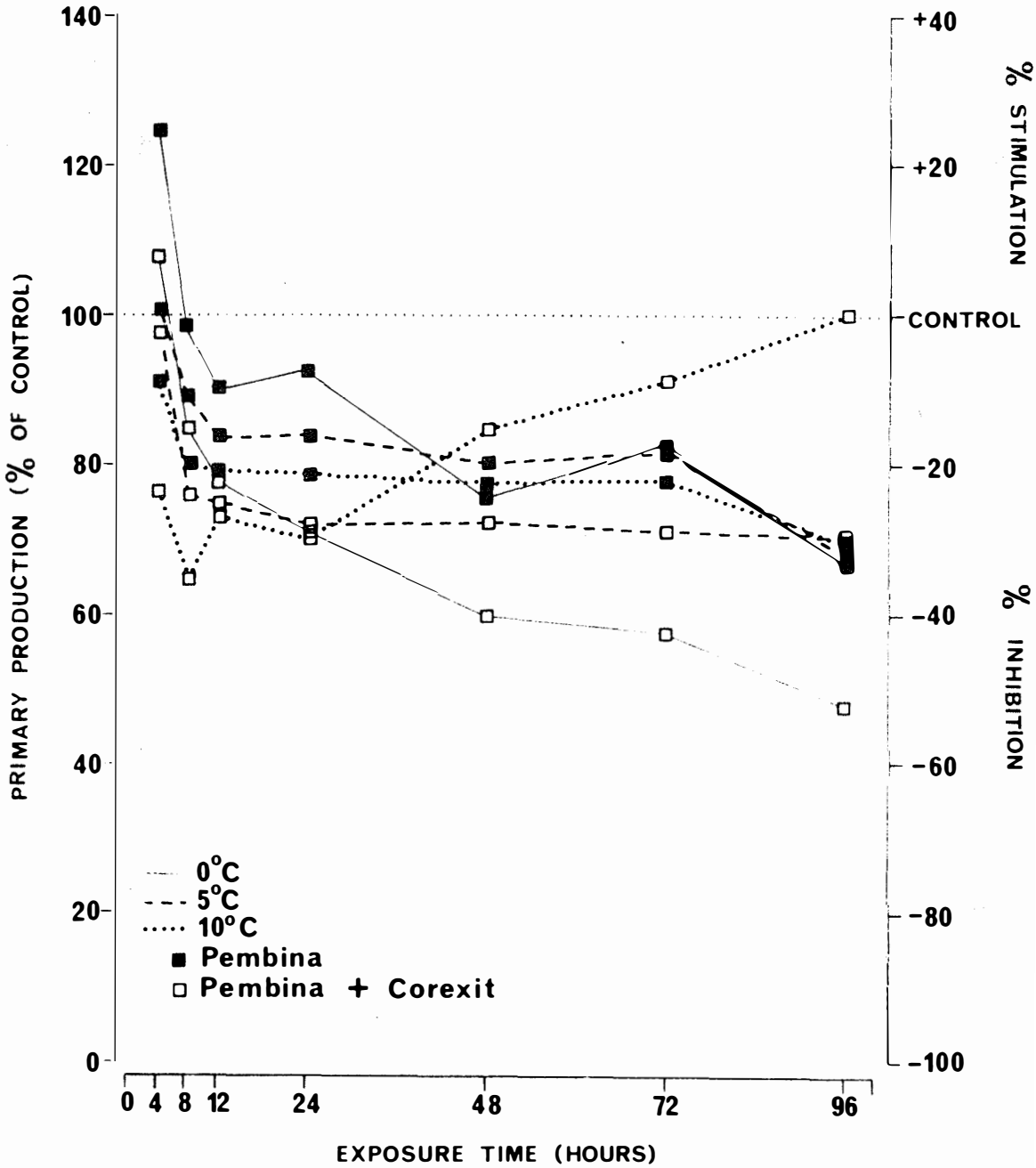

Fig. 25. Effects of Pembina crude and Pembina crude-Corexit mixture on primary production of *Chaetoceros* sp. in relation to temperature and exposure time.

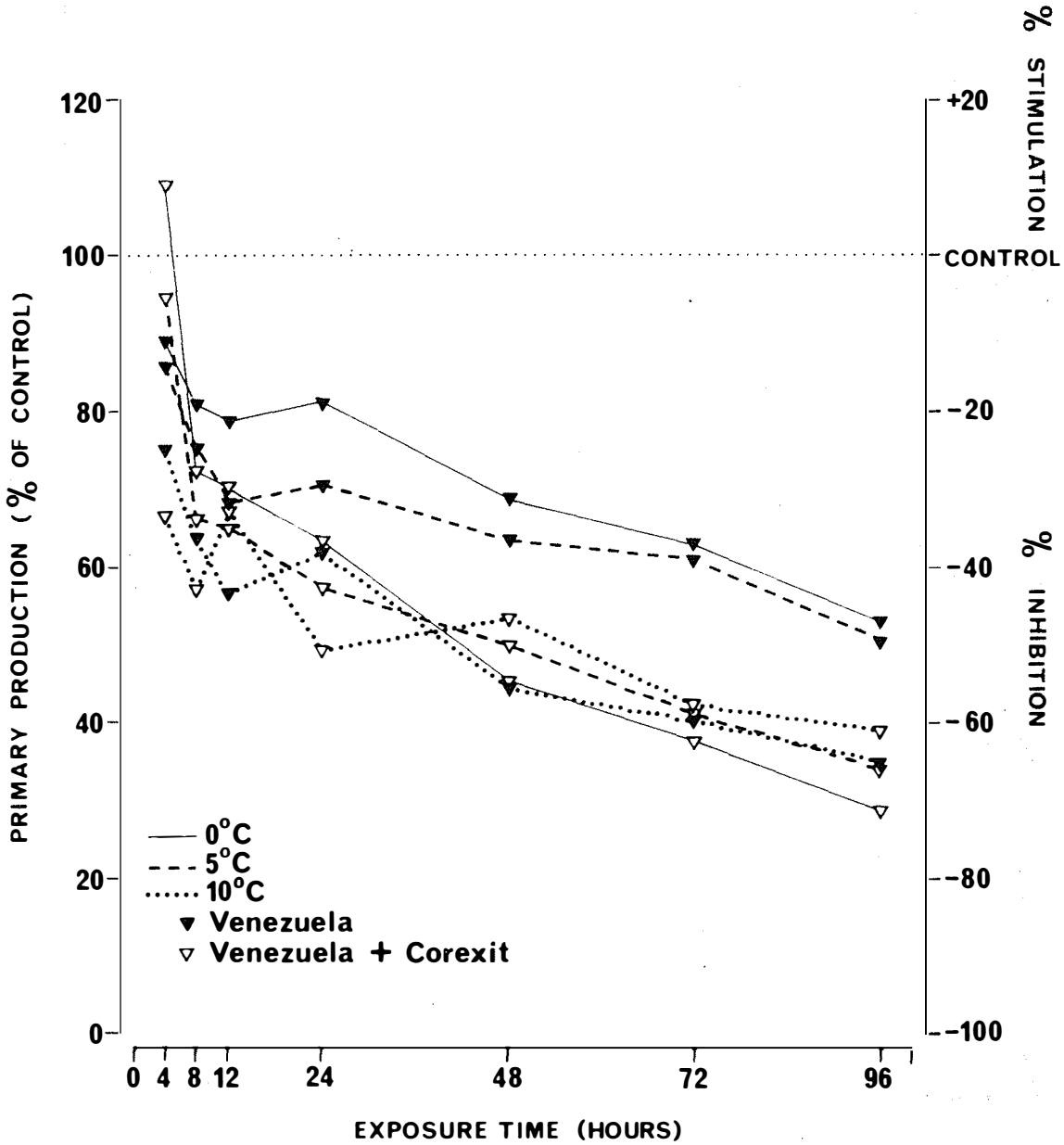

Fig. 26. Effects of Venezuela crude and Venezuela crude-Corexit mixture on primary production of *Chaetoceros* sp. in relation to temperature and exposure time.

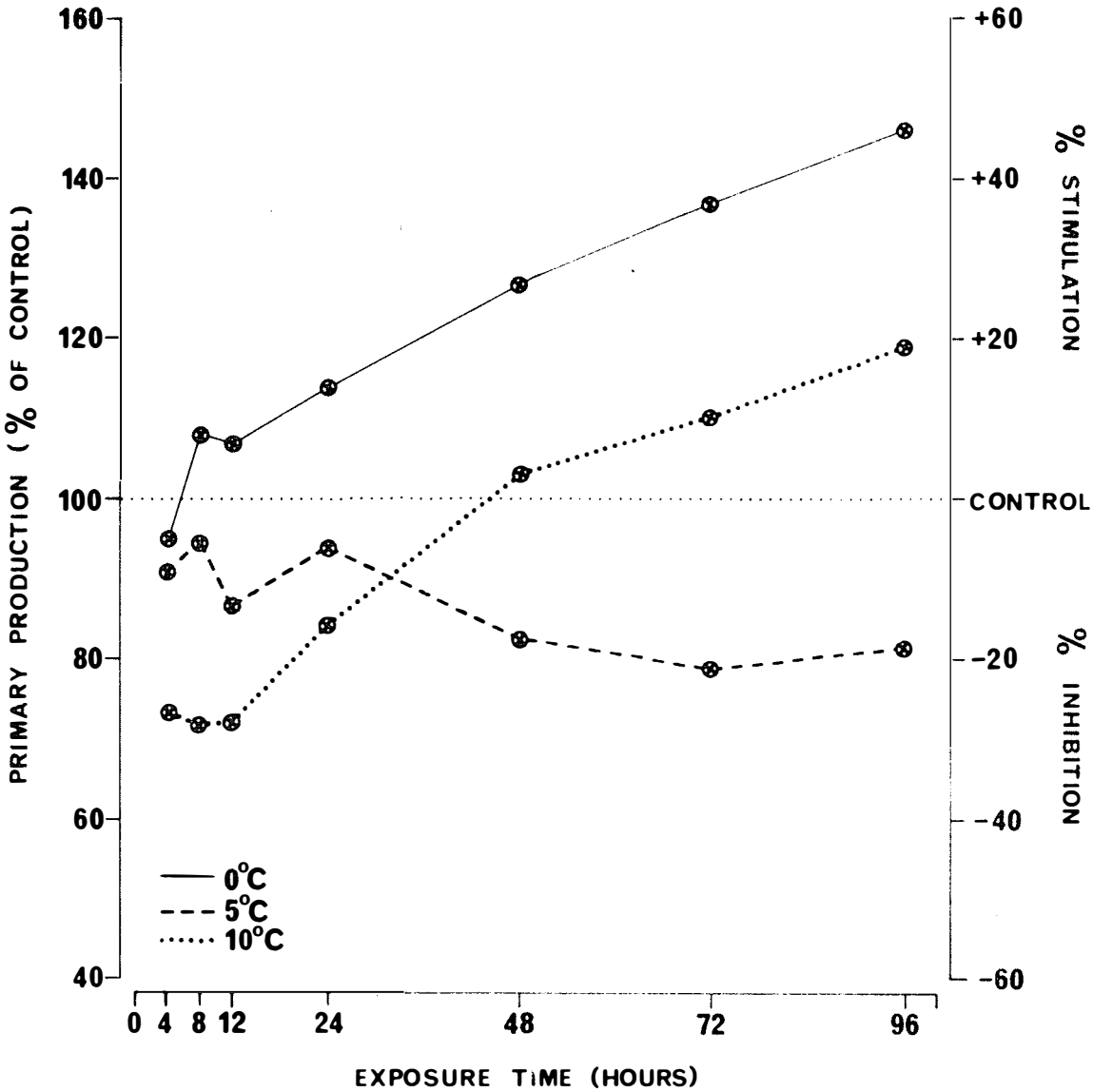

Fig. 27. Effect of Corexit on primary production of *Naviçula* sp. in relation to temperature and exposure time.

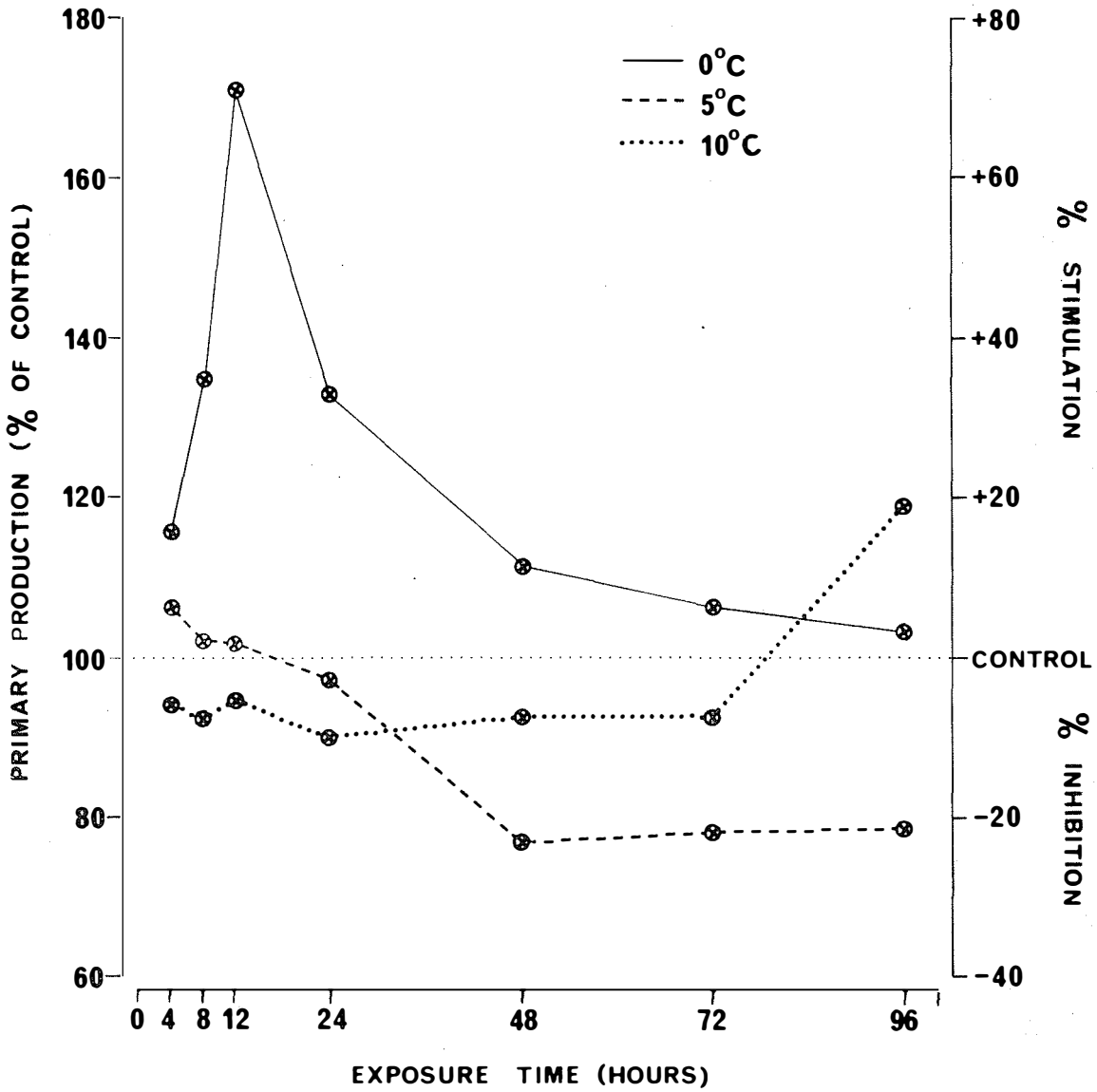

Fig. 28. Effect of Corexit on primary production of *Nitzschia* sp. in relation to temperature and exposure time.

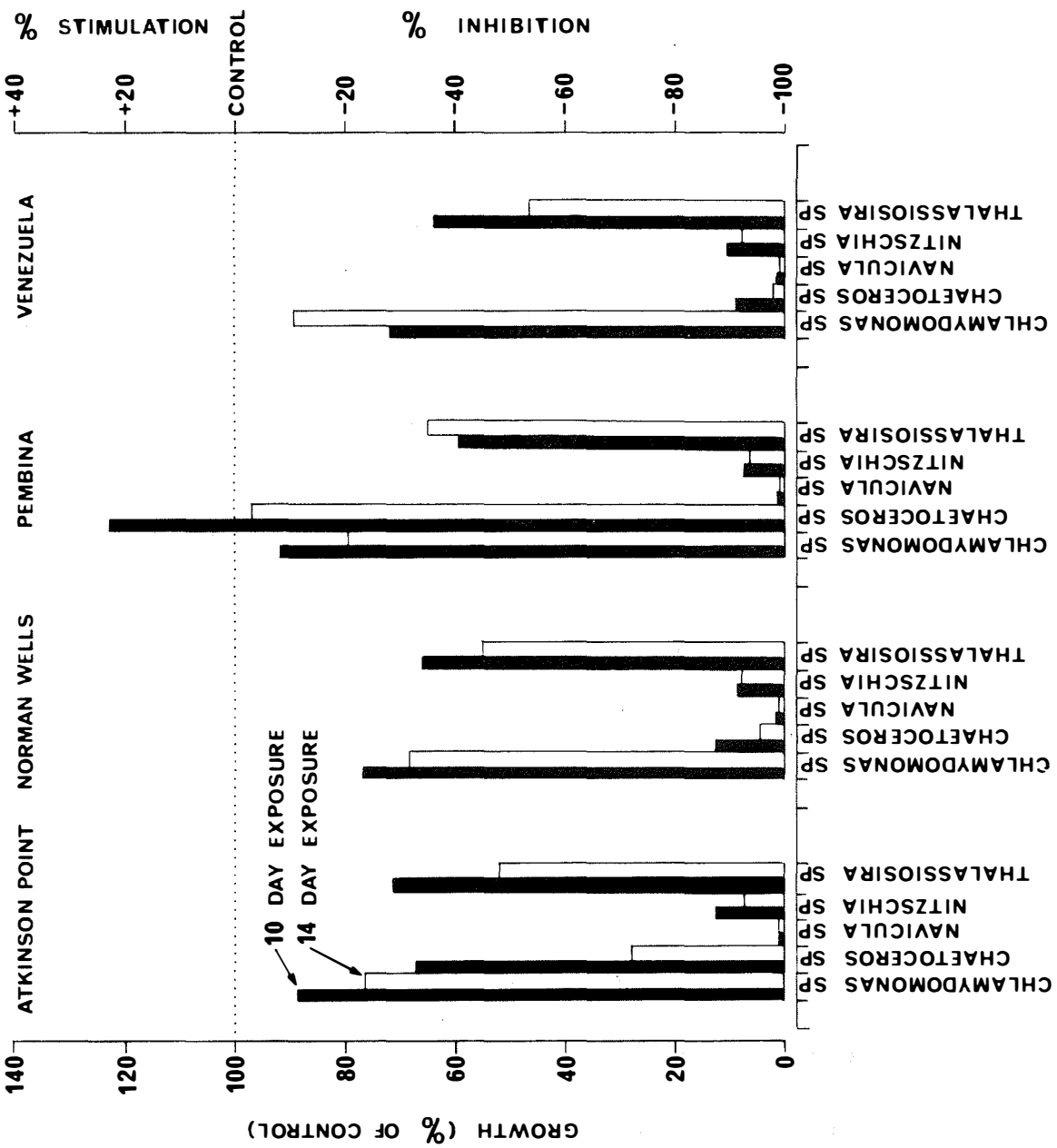

Fig. 29. Effect of crude oils (1 µl/100 ml) on the growth of phytoplankton in relation to exposure time at 5°C.

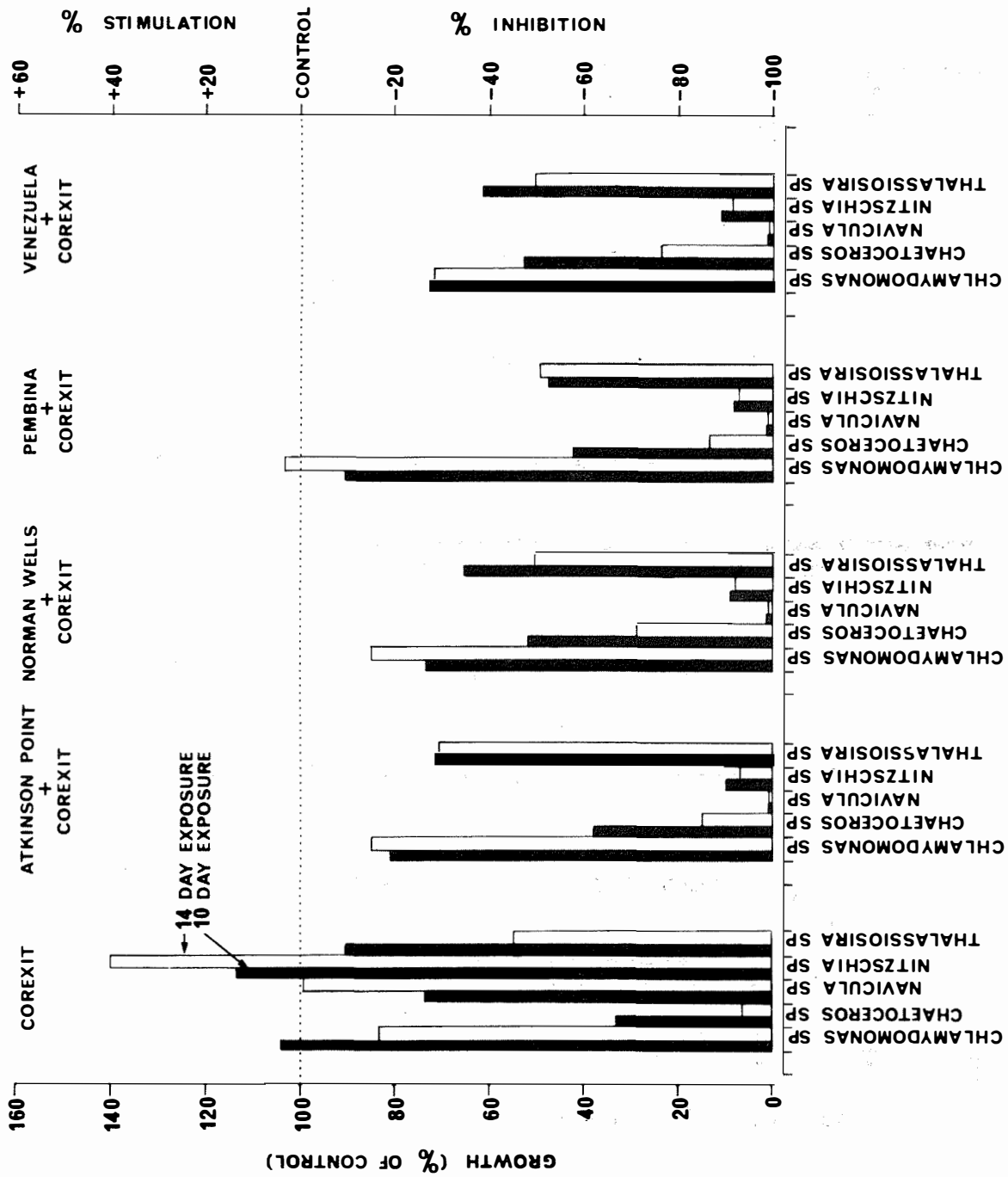

Fig. 30. Effect of Corexit and crude oil-Corexit mixtures (1 µl:1 µl/100 ml) on the growth of phytoplankton in relation to exposure time at 5°C.

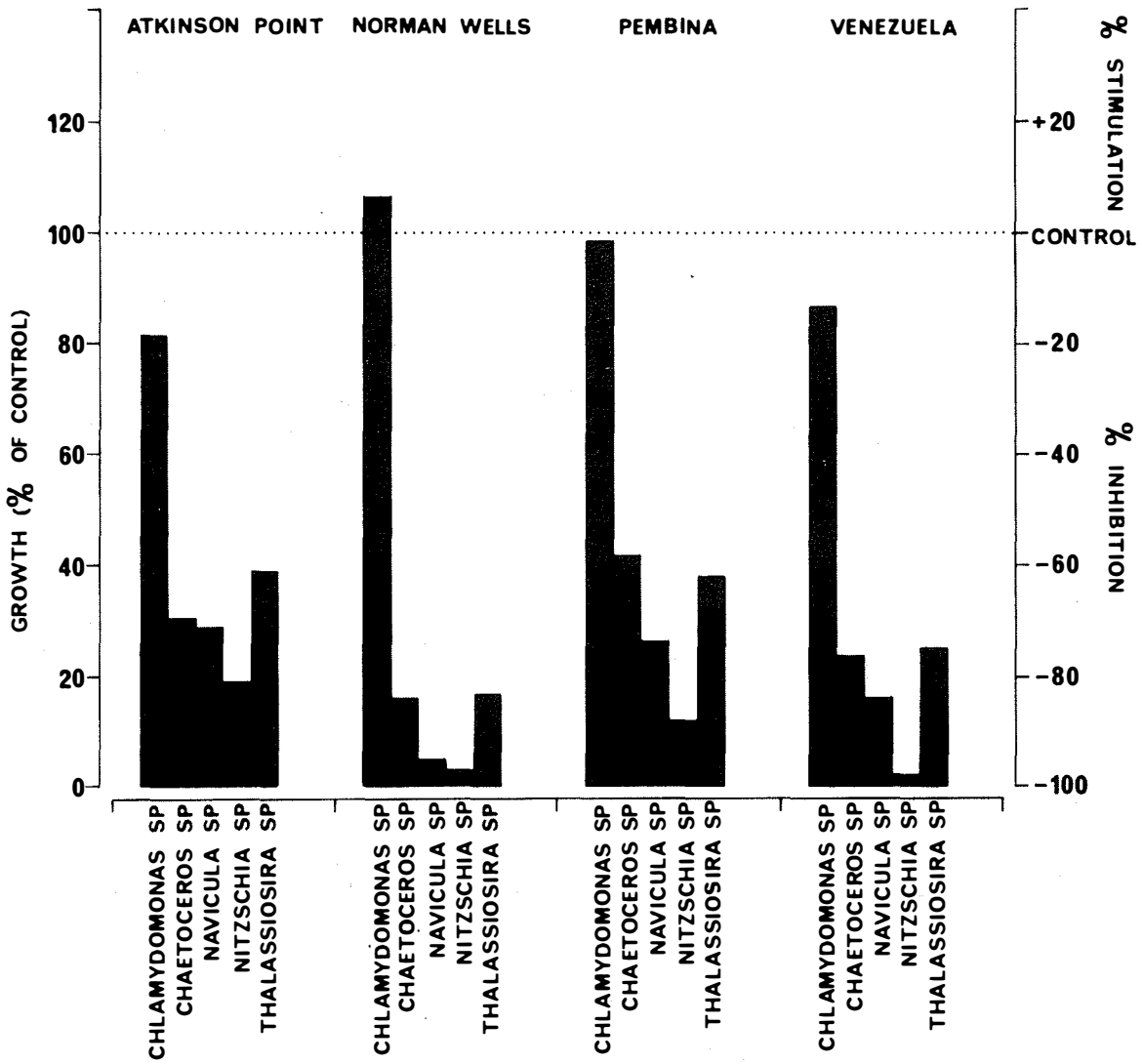

Fig. 31. Effect of crude oils (1 µl/100 ml) on the growth of phytoplankton at 10° C (10 day exposure).

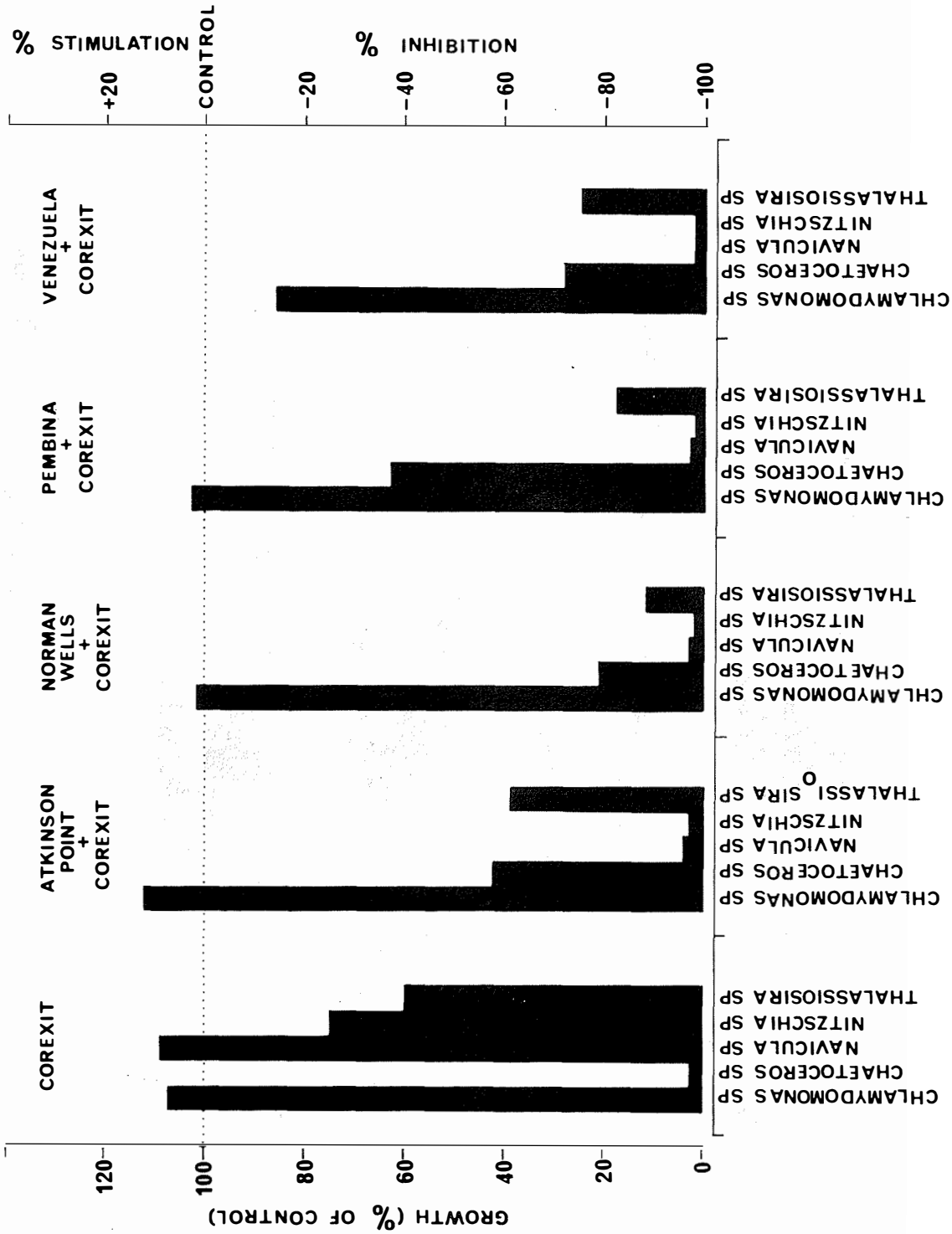

Fig. 32. Effects of Corexit and crude oil-Corexit mixtures (1 µl:1 µl/100 ml) on the growth of phytoplankton at 10°C (10 day exposure).

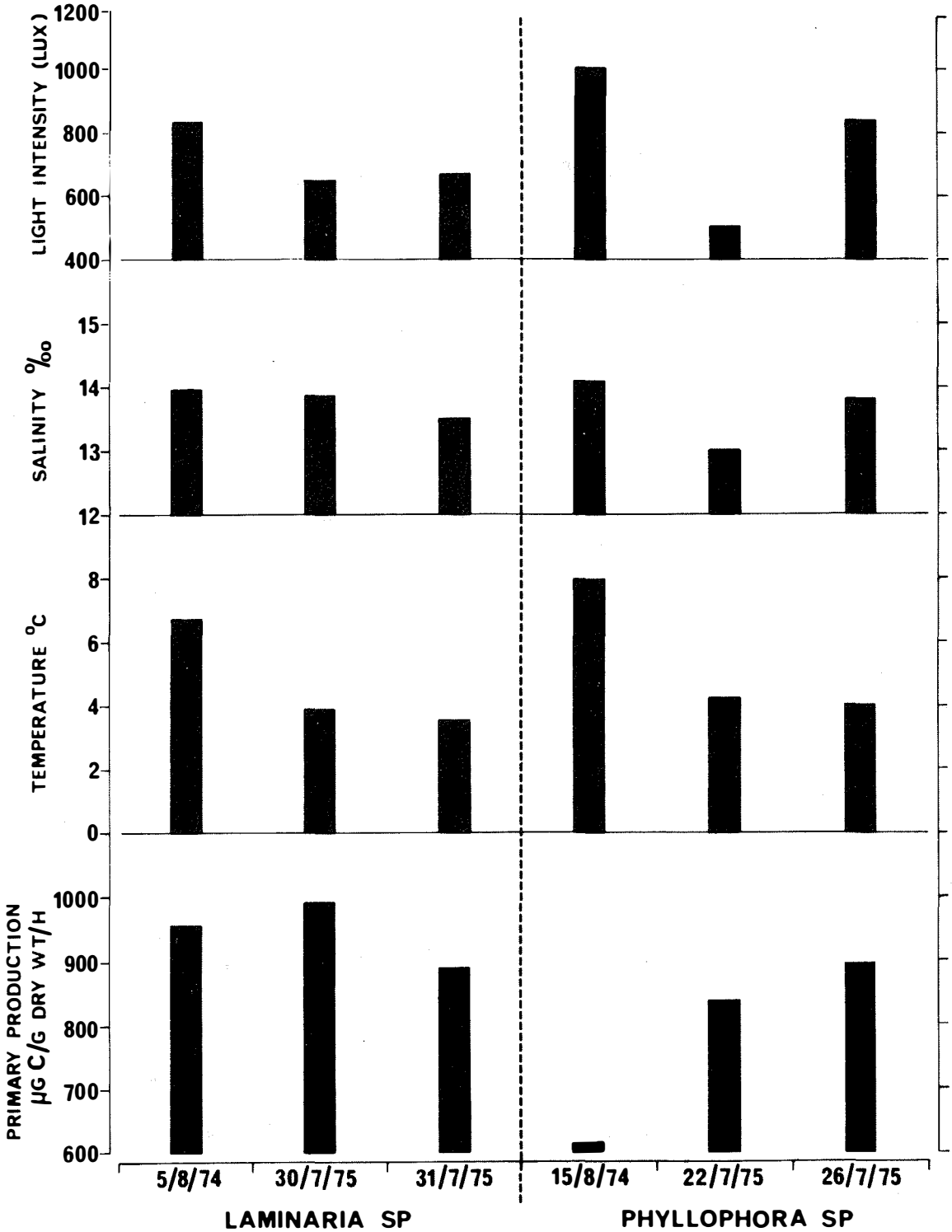

Fig. 33. In situ net primary productivity of seaweed in relation to light intensity, salinity and temperature at Eskimo Lakes station 507 at 2 metres during summers of 1974 and 1975.

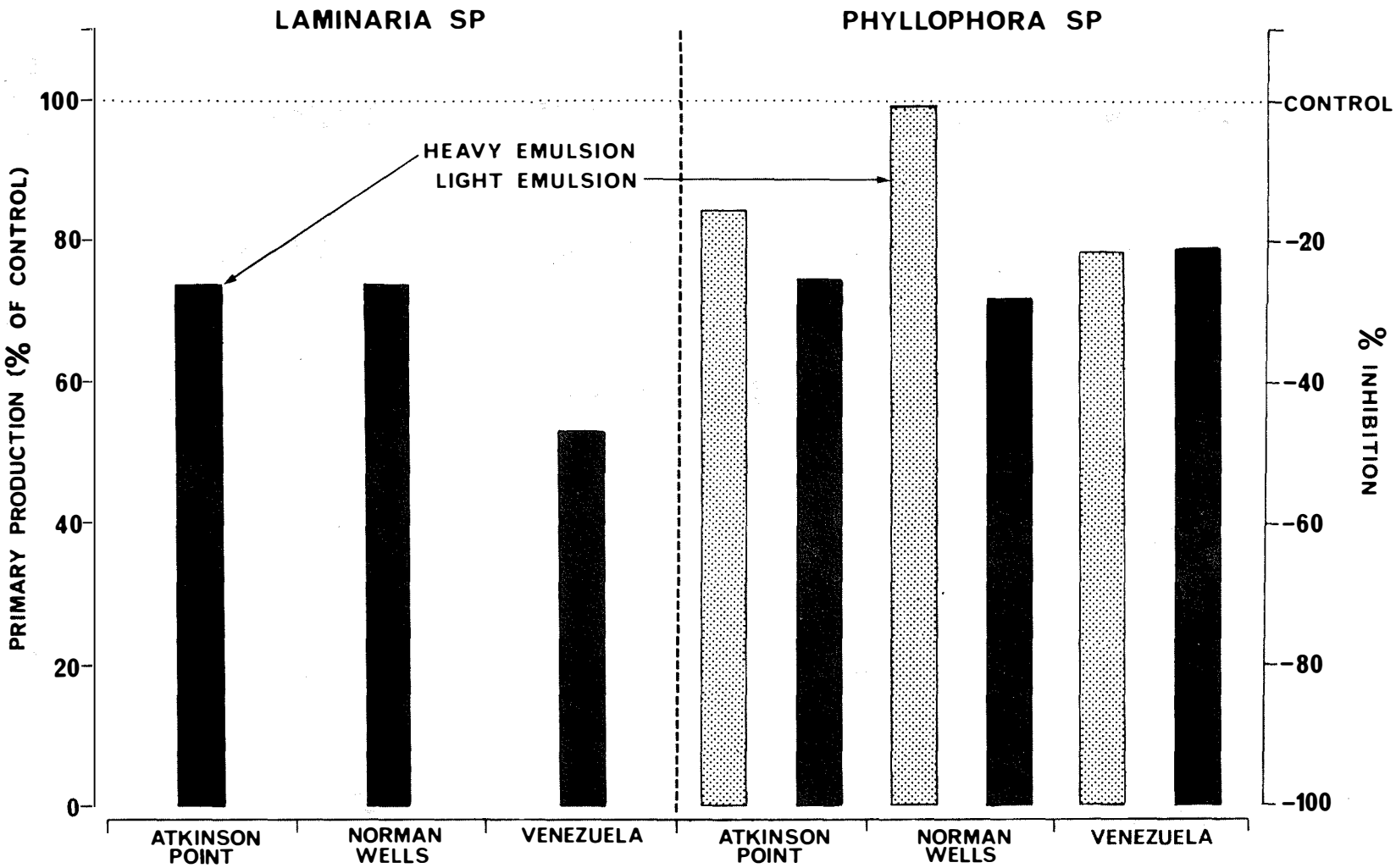

Fig. 34. Effects of light and heavy concentrations of crude oil-seawater emulsion on primary productivity of seaweed at Eskimo Lakes station 507 at 2 metres during August, 1974.

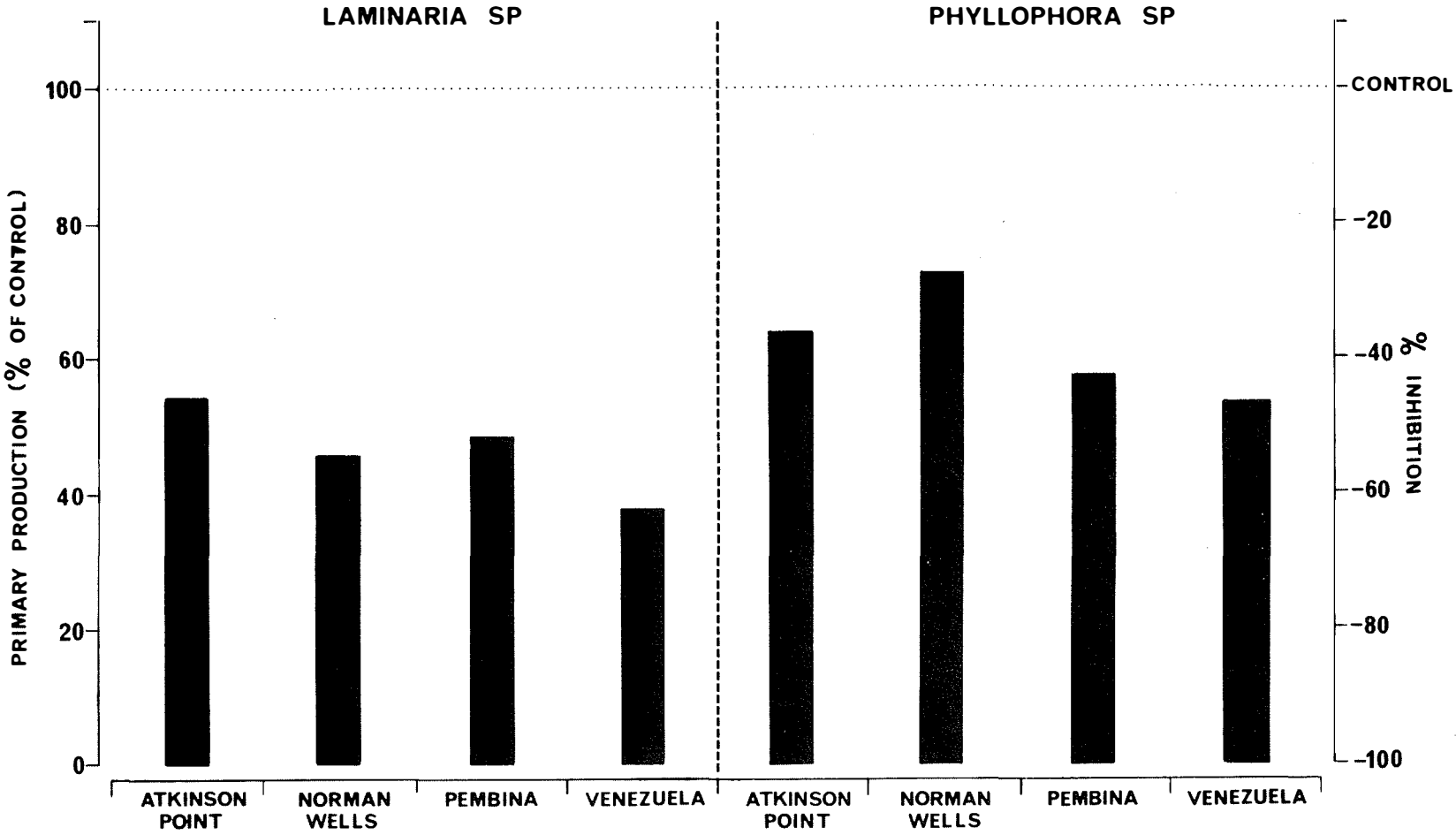

Fig. 35. Effects of crude oil on primary productivity of seaweed at Eskimo Lakes station 507 at 2 metres during July, 1975.