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WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT

THIRD MEETING
Oslo, 21-28 June 1985

WCED/85/Info 7

BACKGROUND INFORMATION ON THE LOCATIONS TO BE SEEN ON SITE VISITS (21-22 June 1985)

* Ora Nature Reserve, Fredrikstad (21 June)
* RAIN Project, Birkenes (21 June)
* Elkem A/S, Fiskaa Verk, Kristiansand (21 June)
* Institute of Marine Research, Department of Aquaculture, near Bergen (22 June)
* Tapered Chanel (Tapchan), Wave Power Plant (NORWAVE A/S), Toftestallen (22 June)
* Multiresonant Oscillating Water Column (MOWC), Wave Power Plant (KVAERNER A/S), Toftestallen (22 June)

ORA NATURE RESERVE

Fredrikstad, 21 June 1985

IUCN: COMMISSION ON NATIONAL PARKS AND PROTECTED AREAS

World Directory of National Parks and Other Protected Areas

Protected Area Information Sheet

COUNTRY: Norway

1. Name of Area: Øra Nature Reserve.

Biographic Province: Boreonemoral

Numbers: 2.10.5.

Name:

2. Category: NR

3. Legal Protection: Strictly protected.

4. Date Established: 28. September 1979 by Royal Decree.

5. Geographical Location: Estuary close to Fredrikstad, Østfold County.

6. Altitude: 0 - 20m

7. Area: 1560 ha (230 ha land area).

8. Land Tenure: Privately owned.

9. Physical Features: The reserve comprises the estuary of river Glomma and nearby islands. More than one half of the estuary is 1/2 - 1 m deep water, and the bottom is covered with marine deposits and sediments from the river. Salinity differ greatly during the year.

10. Vegetation: The emergent vegetation is characterized by large reedbelts, with Phragmites communis, Scirpus maritimus and Scirpus tabernaemontani as dominant species.

11. Noteworthy Fauna: The reserve is a very important area for water birds, as resting place during migration, wintering area for ducks and swans, breeding area for ducks and waders and moulting area for ducks. The locality is a borderline for the distribution for several species and is therefore of special zoogeographical interest. The area with brackish water is unique in norwegian context and comprise a large number of fish species. (More than 30 species). Several species of aquatic invertebrates are not found any other place in Norway.

12. Zoning: None.

13. Disturbances or Deficiencies: None reported.

14. Scientific Research: Botanical, zoological and hydrological investigations.

15. Special Scientific Facilities: None.

16. Principal Reference Material: None listed.

17. Staff: None.

18. Budget: No informations.

19. Local Park Administration: Østfold County Governor

20. Name of CNPPA Co-ordinator: John Foster.

Date:

<u>RAIN PROJECT</u>

Birkenes, 21 June, 1985

JOINT CANADIANORWEGIAN PROJECT

RAIN

Reversing Acidification in Norway

NIVA

ecretariat NIVA, Norwegian Institute for Water Researc

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0314 Oslo 3, Norway

elephone (0472) 23 52 80

Participating and supporting institutions :

* Ontario Ministry of the Environment Canada (OME)
* Canadian Ministry of the Environment (CME)
* Norwegian Ministry of the Environment (MD)
* Swedish Environmental Protection Board (SNV)
* Royal Norwegian Council for Scientific and Industrial Research (NINF)
* Swedish University of Agricultural Science, Uppsala
* Norwegian Institute for Air Research (NILU)
* Central Institute for Industrial Research (SI)
* Norwegian Institute for Water Research (NIVA)

Background

Vigorous efforts to optain reductions in the emissions of acidifying compounds SO_2 and NO_x to the atmosphere are based in part on the premise that such reductions will restore acidified freshwaters.
Yet the magnitude and rate of response can only be postulated, for such large-scale reductions apparently have never been investigated. It simply is not known to what extent acidifiation is "reversible" or entails an irrevocable change in, for example, the base status of soils. The length of time required to achieve a new "steady state" following a change in deposition is also uncertain. Perhaps the pool of sulfur built up in the soils and vegetation during 50-100 years of acid deposition will require years or decades to be "bled" out of the system. Furthermore even if sulfur deposition is reduced, nitrate may take over as the acidifying agent. These questions can perhaps be answered satisfactorily only by large-scale whole ecosystem experiments.

The joint Canadian-Norwegian Project RAIN started during the summer 1983. The project comprises two parallel large-scale manipulations, at Sogndal and Risdalsheia, to determine the response of runoff water chemistry to changes in loadings of strong acids from the atmosphere (Figure 1).

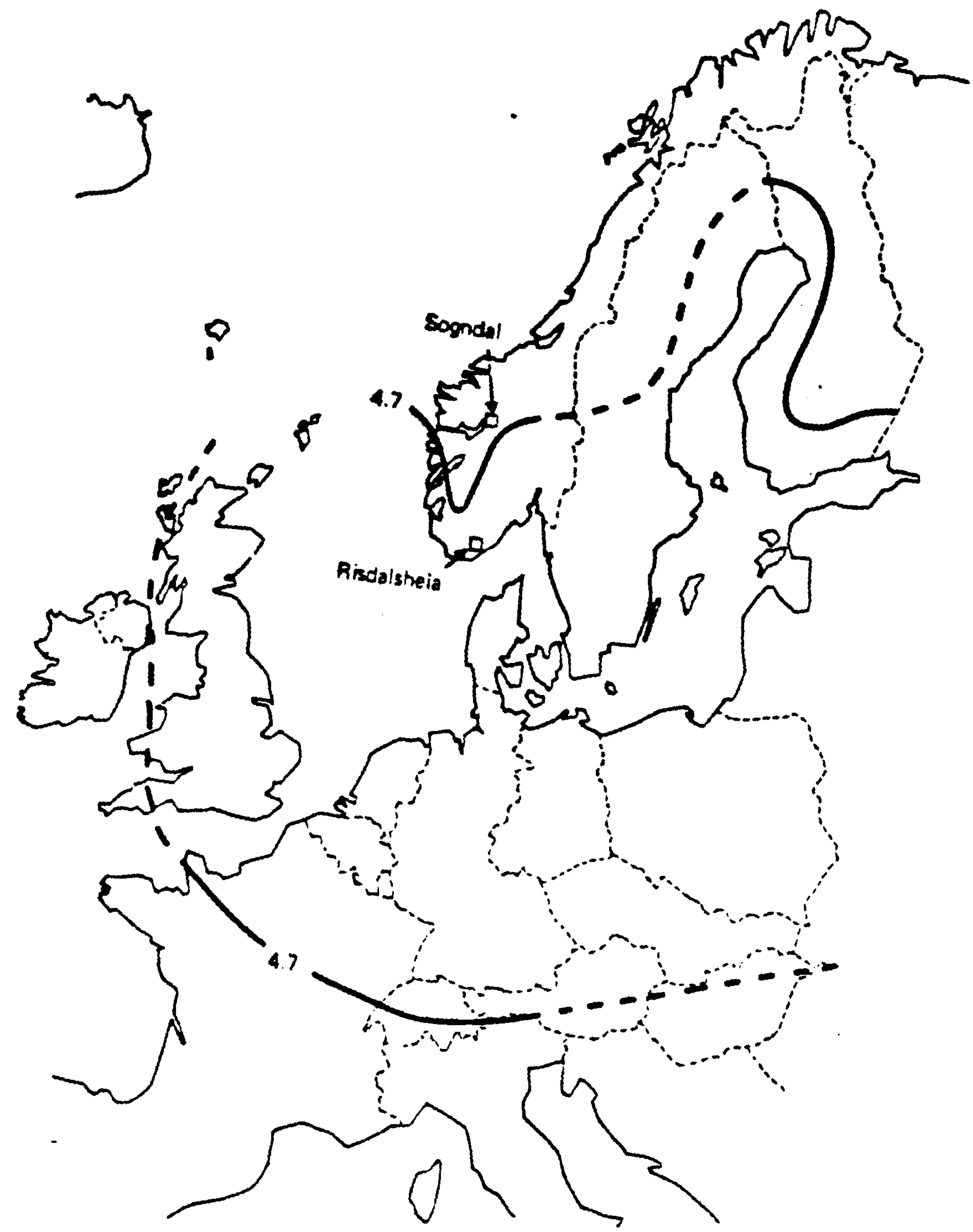


Figure 1. Location of the experimental catchments in project RAIN. Areas within the pH 4.7 isoline receive precipitation with a yearly weighted-average pH below 4.7.

Experimental design RAIN

Experiment 1 (Sogndal)

Acidify a clean area with acid precipitation, then stop treatment and observe recovery back to initial state.

An area in Sogndal, on the Kaupanger peninsula, inner Sognefjord (Figure 1), offers a suitable site for the acidification experiment (Foto 1-3). Here four well-defined catchments, 0.1-10 ha in size, are included in the experiment. The area located above treeline at about 900 meters elevation, has suitable water chemistry today;

pH	6.0	SO_4	0.9 mg/l
Ca	0.4 mg/l	NO_3	10 µg/l
Na	0.9 mg/l	TOC	1.5 mg/l.

Two of the four catchments is being treated with acid (sulfuric and nitric acid respectively) in amounts corresponding to the "natural" acidity of the precipitation in Southern Norway. The outflowing water from the catchments is continuously registered and water samples are taken for chemical quality control.

Experiment 2 (Risdalsheia)

Deacidify an impacted catchment by excluding acid rain with a roof and watering with pH 5.0 precipitation

Risdalsheia (Figure x), an area of granitic bedrock, thin and patchy soils and sparse forests offers a suitable site for this experiment. Risdalsheia is located near Birkenes where a gauged catchment with a 12-year period record of precipitation, air and streamwater chemistry is situated. Water chemistry in Risdalsheia is presently:

pH	4.0	SO_4	6.0 mg/l
Ca	0.6 mg/l	NO_3	300 µg/l
Na	4.0 mg/l	TOC	10 mg/l.

Two mini-catchments have been covered with roof of light-penetrating material. The bigger area (1000 m^2, called KIM-feltet) is sprinkled with deacidified precipitation containing, however, the natural amount of salts. The other roofed area (600 m^2, called EGIL-feltet) is watered with "natural" acid precipitation. The outflowing water from these two sheltered catchments is studied in detail, both quantitatively and qualitatively.

Participating institutions , their main responsibility and co-investigator

* Norwegian Institute for Water Research (NIVA)
  - project coordination, water chemistry, engineering, field experiment control;
  - R.F. Wright, E. Gjessing, M. Johannessen, K. Wedum, R. Storhaug, R. Høgberget, S. Andersen.

* Norwegian Institute for Air Research (NILU)
  - precipitation, soil chemistry;
  - A. Semb.

* Central Institute for Industrial Research (SI)
  - modelling, water chemistry;
  - N. Christophersen, H.M. Seip.

* Ontario Ministry of the Environment (OME)
  - water chemistry, aquatic biology;
  - P.J. Dillon.

* National Swedish Environment Protection Board (SNV)
  - water chemistry:
  - W. Dickson.

* Swedish University of Agricultural Science
  - soil chemistry;
  - E. Lotse

BUDGET

Expenses (x 1000) NOK	1983	Budget 1984	1985	1986	1987	1988
Personnel	407	790	320			
Analyses	122	150	140			
Roof and sprinkler device	175	2300	355			
Travel cost etc.	29	85	35			
Miscellaneous	18	75	50			
Total	751	3400	900	900	900	900

Financial support 1984 (x 1000) NOK	1984
Transfer (including interest) 1983	450
NTNF*	150
MD*	425
SNV*	65
OME & CME*	630
Participating Norwegian institutes (NIVA, NILU, SI)*	130
Bank loan	1100
Applications not comfirmed	450
	3.400

* See inside first cover.

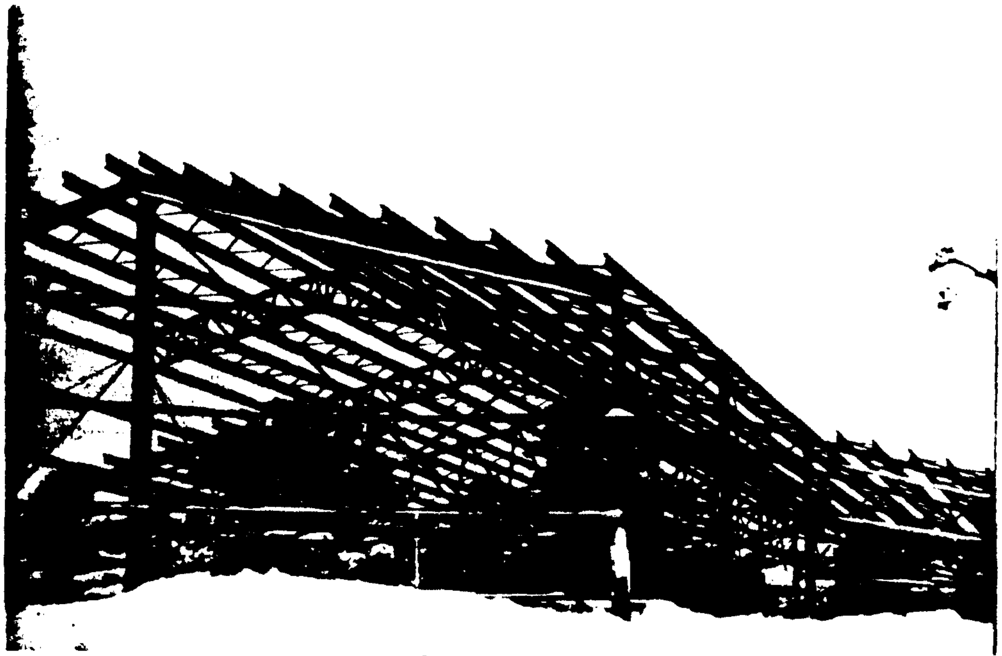
Sogndal
Experiment 1

Experimental area

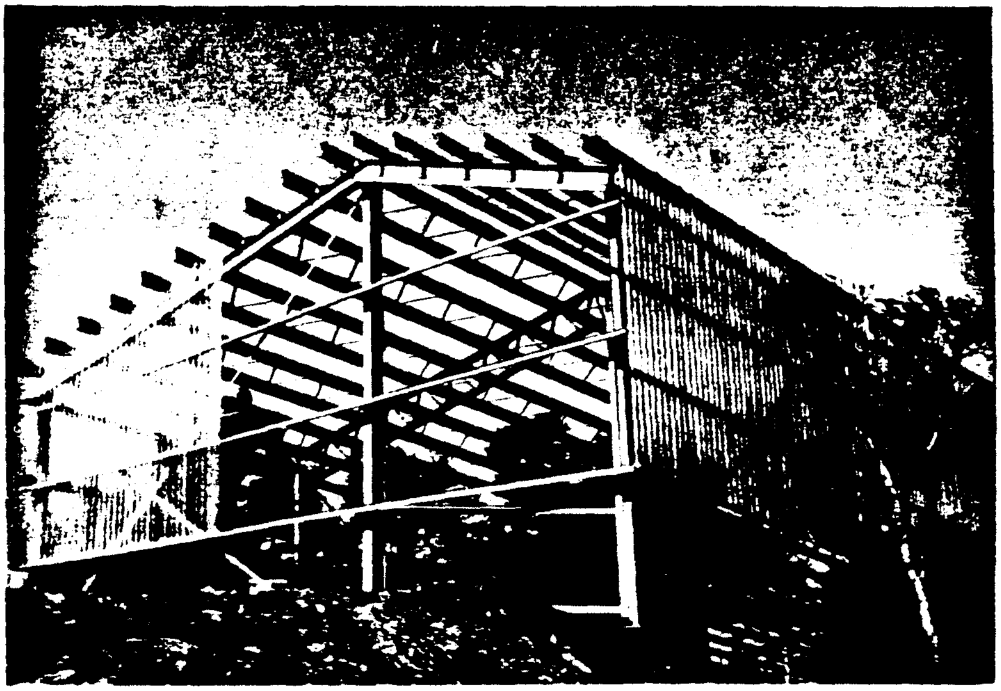
Half the annual »input» of acid is added on the snow during late winter

Testing the equipment

Risdalsheia
Experiment 2



The constructions are raised during winter time, leaving the snow cover of the catchment undisturbed



The »roofing» is nearly completed

The 1000 m^2 reference catchment

ELKEM A/S, FISKAA VERK

Kristiansand, 21 June 1985

The ES Group

Elkem a/s employs about 9,000 persons at more than 30 production plants in several countries. The group is engaged in aluminium, steel, ferro-alloys and pig iron production as well as mining and engineering, and is also producing a wide range of manufactured goods.
The company was formed in May, 1972 through the merger of Christiania Spigerverk and Elkem, and is organized in six divisions with a coordinating head office in Oslo.

Steel Division

The Steel Division comprises steel works in Norway and England and several plants which process steel into finished products.
Christiania Spigerverk in Oslo produces blooms, billets, reinforcing bars, merchant bars, wire rod, welded wire fabric, various reinforcing products for the prefabricating concrete industry, drawn wire, wire nails and other wire products, tools and other products.
Stål og Tau has five plants which produce steel wire ropes, fibre ropes, extrusions, drawn wire, wire nails and other wire products, chain, winches and other products.
Fonas produces bolts, screws, nuts, rivets and engine heaters.
In Manchester, England, the subsidiaries Manchester Steel Ltd. and Johnson & Nephew (Mill Street) Ltd. produce steel billets and wire rod. In Denmark, the subsidiary Lysbro Fabriker A/S produces tools for gardening, farming and construction.

Product Division

Elkem's Product Division consists of six companies with 12 production plants manufacturing a wide range of products. Three of the companies are fully owned by Elkem and three are partially owned. The companies and their products are listed below:

Istrail: Road transport material, timber handling equipment.
TrioVing: Locks, handles, hinges, door closers, window fittings, fittings for maritime use, ice skates.
Elkem-Rockwool: Mineral wool and expanded polystyrene for heat, cold, sound and fire insulation.
Noblikk-Sannem: Tin, aluminium and plastic packaging.
Norsk Glassfiber: Fibreglass mats, roving and other fibreglass products.

Ferro-Alloys Divisions

Elkem's Ferro-Alloys Divisions is one of the world's largest producers and exporters of ferro-alloys. The alloys are used as additives in the production of steel and other metals.
The division comprises four ferro-alloys plants: Bremanger Smelteverk at Svelgen on the west coast, Fiskaa Verk in Kristiansand, PEA in Porsgrunn and Salten Verk near Fauske in North Norway. In order to secure the necessary electric power, Elkem has participated in hydroelectric development at Salten and Bremanger. The division has a power generating capacity of 1470 million kWh.
The division also includes the iron ore mine Rødsand Gruber at Raudsand on the west coast. This mine supplies iron ore concentrates to Bremanger Smelteverk.
In Brazil, the division is engaged in the production of electrode paste, and in Iceland in the production of ferro-silicon.

Engineering Division

The Engineering Division is responsible for the exploitation of the company's experience and know-how, and is one of the world's leading designers and suppliers of electric smelting furnaces.
The Engineering Division markets the company's patents and processes, designs, specifications, equipment and engineering services.
The number of Elkem furnaces in operation or under construction around the world is approximately 340. The division also supplies Elpit soaking pits for electric heating of steel ingots, Magn-O-Matic equipment for control of steel billet surfaces, scrap pre-heating systems and other equipment for the steel industry throughout the world.

Mining Division

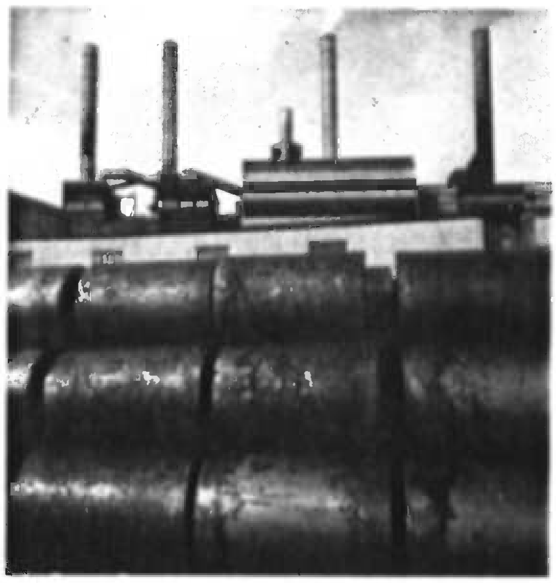
Elkem's Mining Division consists of the mines Norsk Nefelin at Stjernøy in North Norway, A/S Sulitjelma Gruber, also in the northern part of the country, and Skorovas Gruber in North-Trøndelag as well as a part-interest in Grong Gruber A/S, also in Nord-Trøndelag.
Norsk Nefelin produces nepheline syenite, a raw material for the glass and ceramics industry. The mine started production in 1961 and has been developed at a rapid rate.
Sulitjelma Gruber, where Elkem's share is 92%, produces blister copper, pyrites and zinc-concentrates. Skorovas Gruber produces copper and zinc concentrates.

Aluminium Division

In the aluminium sector, Elkem cooperates with Alcoa which is the world's largest aluminium producer. Elkem holds 55% of the shares in two smelters in Norway and Alcoa 45%. Elkem also has a 25% interest in two large plants in the United Kingdom and the Netherlands – Alcoa of Great Britain and Alcoa Nederland – which fabricate a considerable part of the metal produced by the two smelters.
The smelters are Lista Aluminiumverk and Mosjøen Aluminiumverk. Their total annual production capacity is approximately 170.000 tons.

ELKEM A/S

Fiskaa Verk



Fiskaa Verk in Kristiansand, the group's oldest ferro-alloys plant, was acquired in 1917. The production at Fiskaa Verk is concentrated on ferro-silicon, silicon metal and electrode paste. Other products are tamping paste, cupola paste, calcined anthracite and volatilized silica.

Elkem's large Research Centre is also located at Fiskaa Verk. It is continually working on the further development of the group's total range of processes and products.

Annual Production capacity:
100.000 tons of electrode paste and calcined anthracite
30.000 tons of silicon metal
20.000 tons of volatilized silica

PROBLEMS AND SOLUTIONS IN ENVIRONMENTAL CONTROL OF ELECTRIC FURNACES

by

Aa. Lømo and O.C. Bøckman

SUMMARY

We have to distinguish between pollution control for open and for closed furnaces. Gases from closed furnaces have been cleaned for more than 30 years, but high efficient venturi scrubbers have only been in use for the last 10-12 years.

Today it will also be necessary to clean the water coming from the venturi plants.

New high temperature filters for dry cleaning of CO-gases are being developed. A full size filter of this type will be started at Bremanger Smelteverk this automn.

In most countries the authoroties require cleaning of gases also from open furnaces.

Various types of filters are in use. Pulse jet type filter using Nomex, Bag House filters with shaking mechanism for cleaning of the bags and the most common type, Bag House filters using reverse air and with bags made of glass fibre.

Filters of the last type are designed by ourselves and installed in our own ferrosilicon plants. All together 12 filters of our own design are in operation today.

Filter for No. 9 furnace at Fiskaa Verk has been in operation since March 1976. The filter is operating well with more than 99% avalability.

PROBLEMS AND SOLUTIONS IN ENVIRONMENTAL CONTROL OF ELECTRIC FURNACES

by

Aa. Lømo and O. C. Bøckman

With regard to pollution problems in the ferro alloy industry we have to distinguish between cleaning problems for open and for closed type furnaces. That is, cleaning of burnt none explosive, none toxic gases from the open furnaces and CO-rich, toxic and explosive gases from the closed furnaces.

Cleaning of gases from closed furnaces is today a fairly straight forward matter without real problems. Gas cleaning plants have been built for many years. Rotary scrubbers of the Theissen and Buffalo types were quite common up to some 10-12 years ago. A substantial disadvantage with these installations were their high water requirements, which would amount to some 3-400 m^3/h for a smelting furnace of about 20 MW.

In a modern gas cleaning installation employed today, namely the high efficiency venturi scrubber, the water requirement for cleaning the same amount of gas is about 50 m^3/h, i.e. less than 20% of the water consumption for plants with rotary scrubbers.

There are two types of venturi scrubbers with which we have good experience. These two types are built by SF in Sweden and the Finish company Ahlstrøm, through their subsidiary Varkaus Bruk.

Fig. 1 and Fig. 2

The SF venturi gas cleaning plant consists of two almost identical venturi stages, each comprising an inlet duct, a mixing chamber and a diffusor.

The first stage is used as a cooler, humidifier and precollector, while the second stage is the main collecting unit.

According to the venturi principle the gas is propelled through the venturi by powerful fans and the pressure drop across the venturi throat with subsequent expansion causes the formation of a water-mist compatible with the particle size of the dust load in the gas. The high velocity of the gas and the water and the intimate contact between mist and dust particles provide the cleaning efficiency.

The dust content in the gas after the venturi is mainly governed by the pressure drop. With pressure drop across the first venturi of 2-2.5 kPa, the total pressure drop for the whole plant will amount to some 12-13 kPa.

With a normal pressure drop across the venturi and a raw gas dust load not exceeding 150-200 g/Nm^3, a dust load in clean gas of less than 50 mg/ Nm^3 can be expected.

The cleaning efficiency of the SF plant depends on maintaining a relatively constant gas flow through the venturi throat, that is the pressure drop must be kept constant. This is achieved by recirculating a variable amount of gas to the venturi throat in accordance with the variable load and gas production in the smelting furnace. A regulating valve in the shunt line is governed by the pressure variations in the smelting furnace.

The Finnish system (shown in figure 2) is based on a different principle, in as much as the gas flow is powered by pumps and water jets instead of fans. The water pressure is normally 24-25 bar. Developed originally for the cellulosis industry, the adaptation to smelting furnace use was done in 1964 in a cooperation with Elkem engineers.

According to our experience the performance of the two gas cleaning systems are quite equal, however, the water consumption of the Finnish venturi may be somewhat higher.

There are of course other types of wet gas cleaning equipment that can be used for covered smelting furnaces. However, our experience is that adaptation to smelting furnace service requires costly development work before success is secured.

Although the cleaning process in the above described systems is quite simple and virtually without technical problems, the operation leaves us with a waste product - the scrubbing water and sludge - which cannot be discharged in nature without special treatment.

Treatment of gas scrubbing water.

The effluent luquids from gas scrubbing plants attract more increasingly attention from the authorities, due to their complex chemistry and harmful effects on nature, human beings and animal life. Strict regulations are set up in many countries, in some countries no effluents whatever are permitted discharged due to scarcity of drinking water.

The gas scrubbing water will contain dissolved elements including heavy metals at different concentrations, depending upon smelting process in question. Scrubbing water from a FeMn furnace will for instance contain mostly dissolved Mn.

At the same time the scrubbing water will contain poisonous cyanides.

In addition to the dissolved materials the water will contain variable proportions of suspended matters, as functions of the concentrations of the dissolved material.

The acidity of the water, its pH-value, will vary with the reduction process and the ratio of CO/CO_2.

A chemical treatment of the scrubbing water with precipitation of the dissolved material and sedimentation of the suspended matters will produce a sludge that will contain all the material mentioned above.

The scrubbing water can either be recirculated to be used over again in the gas cleaning plant, or it can be discharged as waste, or a combination of the two. In both cases regulations may require sedimentation of the suspended matters, and - in the latter case - also an optimum degree of precipitation of the dissolved heavy metals as well as oxidation of the cyanides.

The treatment of the gas scrubbing water compatible with direct discharge, will require a substantial consumption of chemical reagents, besides being expensive with regard to water consumption. The cost of the chemical reagents will in most cases make such an alternative totally unacceptable.

Figure 3 shows a water treatment installation based upon recirculation of the water with sedimentation tank for removal of matters susceptible to sedimentation and with subsequent vacuum filter for separation of the sludge from the liquid. The cooling is being done by heat exchanger using sea water as cooling agent.

It is quite obvious that gas cleaning plants using venturi scrubbers and water treatment plant for cleaning and detoxification of the waste water is not a cheap solution. Neither with regard to capital cost nor with regard to operating cost. But at present it is the sole solution we have to this problem. However, we are working very hard to find another and hopefully improved solution to the problem.

During a period of two years we have gone through a number of tests with a dry, high temperature filter unit. We have tried out various types of filter elements, both ceramic and other type of materials. The test unit has been used on CO-rich gases from FeMn, SiMn and 75% FeSi. A full size test filter designed and constructed for closed operation will be in operation on a totally closed 8 MW 75% FeSi-furnace at Bremanger Smelteverk this automn. Needless to say, we are quite anxious to see the result of this full scale test operation.

Cleaning of gases from open furnaces

While the technology for cleaning of CO-rich gases from closed furnaces has been well known for the last 20-30 years, the technology for cleaning off gases from open furnces with a reasonable success has only been known for the last 6-8 years.

Early in the fifties we tested a bag filter, designed by ourselves, for the cleaning of silica fumes. We did not at that time attain a convincing solution. In 1966 a dry electrostatic precipitator was put into operation at Fiskaa Verk cleaning the fumes from a 9 MW furnace producing silicon metal. Due to extensive corrosion problems this method had to be given up. At the same plant a bag house filter was purchased in 1971 cleaning the fumes from a 12 MW furnace. The performance of this filter was not satisfactory and major parts were completely rebuilt. Mechanical details were improved and the bag cleaning operation was converted from shaking to reverse flow. Since then the filter operation has been satisfactory.

Based on the experience already achieved at Fiskaa Verk not only with the filtering process itself but also with dust handling system, and since we were now faced with the problem of installing filter units in all our own ferro silicon plants within the next few years, the decision was taken to design the filter ourselves. The next filter at Fiskaa Verk cleaning fumes from a 20 MW FeSi furnace was put on stream early in 1976. Before that we had successfully managed to design and construct a bag house filter which were started just before Christmas 1974 for an Italian customer. At present we have altogether supplied 13 large bag house filters of which 5 to our own plants.

Before dimensioning a filter for a customer certain information are required as for instance : See fig. 4 (a, b and c)

1. Type of smoke hood, i.e. semiclosed, low hood or conventional old type with flexible cables underneath smoke hood roof.
   The last one requires a spesific gas volume of at least 15 Nm^3/kWh. Low hood with cables above the smoke hood roof about 10-12 Nm^3/kWh. Semiclosed hood about 6-8 Nm^3/kWh and semiclosed hood combined with energy recovery about 3 Nm^3/kWh.

2. Raw material composition and in particular the type of the reducing agent f. inst. ratio coal/coke, wood chips etc.

We have developed a formula for heat content in the gas based on heat balance calculation and where certain correction is made for heat losses by radiation and convection from gas to air and watercooled furnace equipment. The correction has been checked against good measurements on a 12 MW silicon metal furnace. See fig. 5.

The gas temperature increases as silicon recovery decreases, and as content of volatile matter of reducing agents are increased. In modern furnace operation quite a proportion of coal and wood chips are used, to the effect that volatile matter contributes 15-40% to the heat of combustion.

The type of smoke hood and the spesific gas volume in Nm^3/kWh which can be drawn off through the hood has also a great influence on the gas temperature.

The size of the filter and the area of the filtering media will depend on the type of cleaning mechanism applied to remove the dust from the filter media.
There are three different methods commonly used today namely : Reverse air, shaking and pulse jet. See fig. 6.

The pulse jet method is used in the high ratio filters or in filters having a rather high filtering velocity, for instance about 100 m^3/h per m^2 filter media usually expressed as filtering velocity in m/h. Normal bag size is about 3 meters length and 10 cm diameter. Some manufacturers are using bags up to 5 meters length and 20 cm dia. The pulse jet filters are all working with an underpressure i.e. with the fans on the clean gas side. Filter media is normally Nomex with max. operating temperature 200-220°C

Filters using shaking as cleaning method can either be pressure type filter or filter working with underpressure. Normal bag size 6 meter length 20 cm diameter. Bag material normally Nomex. Filtering velocity about 40-50 m/h depending on the frequency of the shaking.

The reverse air system is used in the large open bag houses which are always working as pressure type filters i.e. with the fans on the dirty gas side. Due to the gentle handling of the bag material during reverse air, glass fibre bags can be used. The advantage with this material is the high temperature resistance with working temperature up to 260-270°C. Normal bag size applied for bag houses in the ferro alloy industry is 9-10 meters length and about 30 cm dia.

Normal filtering velocity for glass fibre bags when cleaning FeSi-furnace using reverse air system is 30-40 m/h. However, if same bag house is using Nomex instead of glass fibre bags the filtering velocity can be increased to 40-50 m/h.

When we are referring to filtering velocity and are quoting certain figures one should bear in mind that filtering velocity alone without at the same time giving the corresponding pressure drop across the fabric is meaningless. Therefore the correct way to express the capacity or performance of a filter is to quote filter resistance (American : Filter drag) expressed in

$$\frac{\text{mm WG}}{\text{m/h}}$$

For instance pressure drop 200 mm WG. equal to ~ 2 kPa. filtering velocity 40 m/h.
The filter resistance $= \frac{200}{40} = 5$.

Main requirements for a good filter.

For the filter operation the most important requirement is reliability and high operating time. The design ought to be simple and rugged, with easy access for inspection and maintenance. Of special importance, defective bags should easily be detected and blanked off or replaced. For efficient operation of the filter these are mandatory requirements.

In addition, cost of investment and operation should be reasonable, especially consumption of energy. Space requirements may be important. Low noise level, especially from the fans, is most desireable.

Below we shall describe the ES bag house filter to see how it meets these requirements. As an example we can look at the filter installed at No. 9 furnace at Fiskaa Verk.

The filter is designed for a gas volume of 300 000 Nm^3/h, giving a specific gas flow of 15 Nm^3/kWh for a 20 MW furnace with old type smoke hood. The filter is prepared, however, to be devided longitudinally into two separate filters of half the size. This to be able to adapt the filter to new conditions if future rebuilding of the furnaces at Fiskaa Verk is feasible.

L a y o u t

See fig. 7. The coarse particles mainly coke and a small amount of silica dust, altogether about 5%, are separated out in a battery of cyclones acting as precollectors. Two fans between the precollector and the filter supply the gas to the main duct of the filter. Through inlet valves to each of the 14 compartments the gas enters the hoppers and further on to the bags for filtration. The bags are elastically suspended between hopper and a grated floor in the top of the filter. The dust is deposited inside the bags. The cleaned gas passes through the bags and rises by natural draught up through the three stacks. (Roof ventilators along the ridge of the roof may also be used).

For cleaning the bags, one compartment at a time is taken off stream by closing the inlet valve. By a special fan, the reverse air is drawn from the compartment and discharged to the main duct. With the bags partly collapsed the filter cakes are released and fall down into the hopper. The dust is transported by a screw conveyor to the one end of the hopper where it is taken through a rotary feeder down to a chain conveyor. At the end of the chain conveyor the dust is pneumatically transported to a storage bin.

The bags are made of glass fibre cloth, they are 9, 1 m long and approx. 300 mm in diameter. Seven equally spaced rings of stainless steel are sewed into each bag. The rings shall prevent the bags from collapsing under reverse flow conditions.

Each compartment has 160 bags arranged in 2 x 4 rown of 20 bags in each row. On both sides and in the centre walkways give access to all bags within two bag reach.

At the level of the hoppers the filter building walls have ventilation openings. Fresh air from these openings passes up through the grating floor surrounding the hoppers and is mixed with the filtered gas and leaves through the stacks.

Between compartments partition walls extend from the roof down to a level 2 m above the grating floor between the hoppers. This arrangement gives easy access for inspection of the bags, see fig. 8.

When a compartment is taken out of operation, for instance for bag replacements, gas temperature in this compartment will drop and natural draught is reduced. To prevent gas from neighboring compartments to enter the compartment out of operation, this compartment may be completely separated at the top by a hinged flap.

To each compartment a door from the tunnel at level of upper grating floor gives easy access to this floor. This door may be used as fresh air inlet to a compartment out of operation.

In this way good working conditions are established for inspection and maintenance in a compartment out of operation, even when the other compartments are on stream.

A central control room contains the instruments, alarms, sequence controls and other equipment necessary for automatic or manual operation of the filter. From this control room the pelletizing plant (see below) is also operated. Gas temperature and bag pressure are continuously recorded.

Fan control

The fans have to be controlled in order to adjust the fan operation to the furnace need for ventilation, and in order to protect the fan motors from overload. Three possible ways of controlling the fans are presently used :

1. Controlling the fans by inlet guide vanes. This is a simple and rugged method, fairly inexpensive. At Fiskaa Verk this alternative is chosen.

2. Fan speed controlling by using hydraulic coupling between motor and fan.

3. Variable speed motor. Usually a slip ring motor controlled in cascade is used.

Combined energy efficiencies for motor and controlling method are shown in fig. 9. Guide vane controlling and speed control by hydraulic couplings show low efficiencies at reduced gas volume flow, and large losses may occur. The variable speed motor in question, on the contrary, shows high efficiency at all speeds. Such a motor is expensive, however, and in each case it is a question of balancing investment against operating cost.

Controlling principle may be to keep constant motor load. In this case, however, a cold furnace will get a better ventilation than a hot furnace. Introducing the temperature of the gas in the control loop, to the effect that motor load is reduced when gas temperature drops, will save energy and give less strain to equipment. Especially when using variable speed motor this way of controlling is favourable.

Experiences

What are our experiences with this filter, and how do they meet the requirements mentioned earlier ?

Reliability of operation may best be illustrated by stating that downtime caused by faults in the filter itself is about one per cent.

The filter has an open structure which facilitates inspection and maintenance work. Well ventilated, the filter atmosphere is acceptable at inspection points. All bags are easily inspected during operation of the filter. Defective bags are easily detected and blanked off. When a certain number of defective bags have been disconnected, the compartment is isolated and bags replaced by new ones, while the other compartments are still operating. (In Norway this is a requirement by The State Pollution Control Authority.) When replacing bags you do not get in touch with the dirty side of the bags, which is inside of the bags.

The filter has been in operation for three years. The period is too short to establish the lifetime of the bags. The same type of bags, however, have been in operation for more than six years in the filter for the 12 MW furnace, and are still in good shape. Conservative estimate is then at least sixe years as average lifetime of the bags.

The fans operate at the dirty gas side of the filter, but this has not caused any trouble. It is reported from other installations, however, that coarse particles in the gas stream have caused fan wheel wear. This is not the case by us, probably because of the efficient precollectors.

The filter may seem voluminous. Compared with high ratio filters, however, we feel that the following considerations are valid.

A high ratio filter is bound to use Nomex, with the limitations this impose. A fair comparison would then be against a bag house also equipped with Nomex bags. The higher filtration velocity possible in a bag house when using Nomex instead of glass fibre, will reduce the size of the bag house considerably.

The large volume of a bag house is in part caused by the great height of the building. In fact, the two types of filter do not differ so much in demand for ground area.

Nevertheless, so far we have preferred to use glass fibre bags, because of greater temperature flexibility and because of uncertainties of sulfur attack on Nomex. In addition, glass fibre bags are substantially less expensive.

Our fans produce some noise. Speed controlled fans are less noisy, a fact in favour of this control method. The noise may be reduced, however, by using silencers specially developed for this purpose by our consultants on noise problems.

Pelletizing plant

Only half the job is done when the fumes are cleaned, the other half is to dispose the percipitated dust. The bulk density of the dust is low, hence large volumes are involved. For a 20 MW furnace the volume of dust produced each day will be in the order of 100 m^3.

Three ways of disposal are possible :

1. Return to furnace.
2. Other applications.
3. Landfill.

Return to furnace has been tested, but do not seem promising.

Fiskaa Verk has thoroughly looked for other applications. Some customers have been found interested in using the silica dust in their own production. But the market cannot obviously absorb the large volume of dust produced when all smelting plants are forced to clean their fumes. In addition, transport expences are high and price is low.

Some places, therefore landfill of silica dust will be the only possible way to get rid of the dust. To reduce the volume and to produce a condition suitable for landfill, the dust is pelletized. Tests of landfill show good stability of the masses and that drain is no danger for plant life.

If return of silica dust to the furnace still should be contemplated, the dust has to be pelletized also for this purpose.

A pelletizing plant therefore, is a natural extension of the filter plant. A pelletizing plant is built at Fiskaa Verk with sufficient capacity to pelletize the complete volume of dust produced. Many of the filter plants delivered by ES to customers are also combined with pelletizing plant.

The silica dust may be pelletized using water only, or with the addition of a binder. By using a few per cent Portland cement as a binder very strong pellets are obtained.

INSTITUTE OF MARINE RESEARCH

DEPARTMENT OF AQUACULTURE

near Bergen, 22 June 1985

Reared blue mussels

Institute of Marine Research
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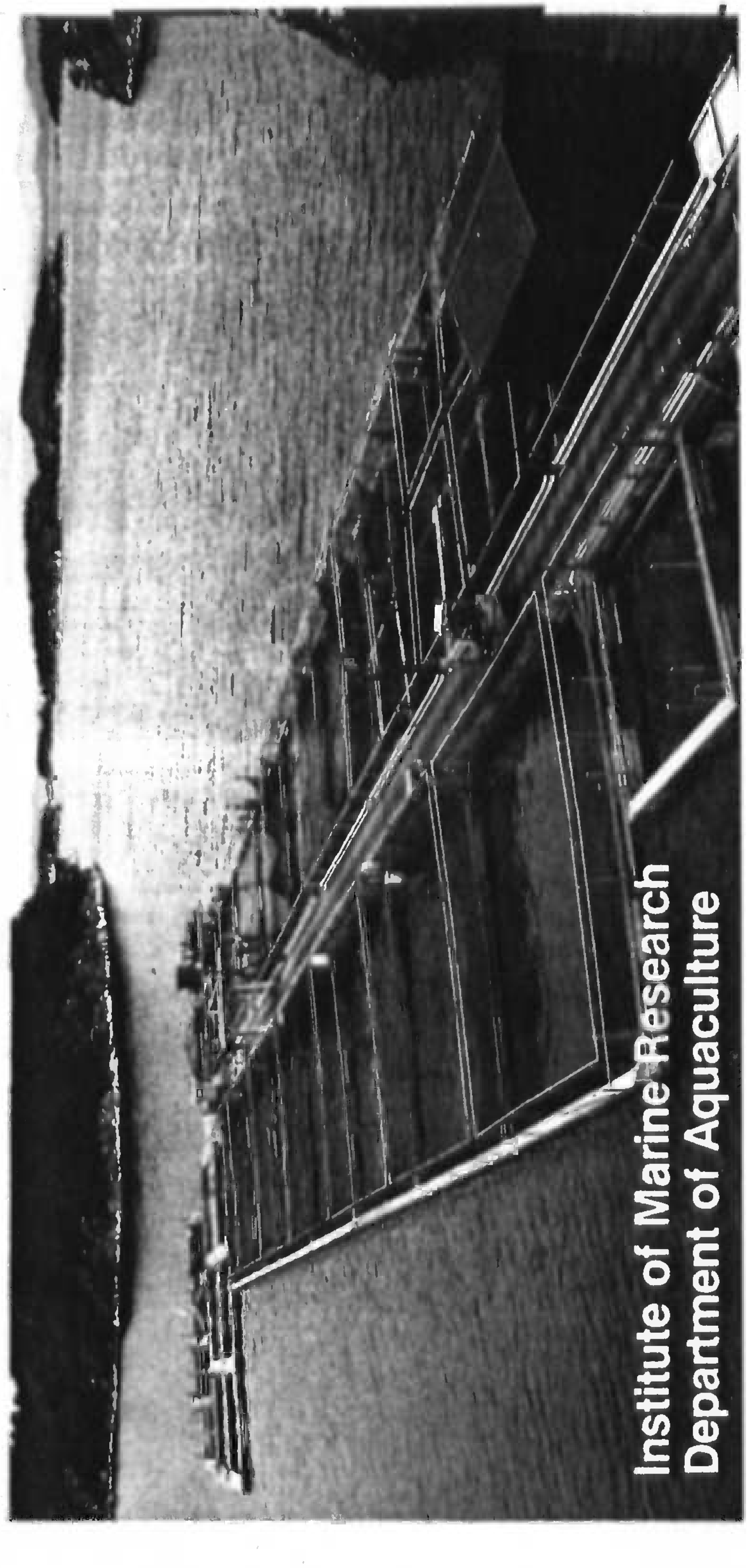


Department of Aquaculture

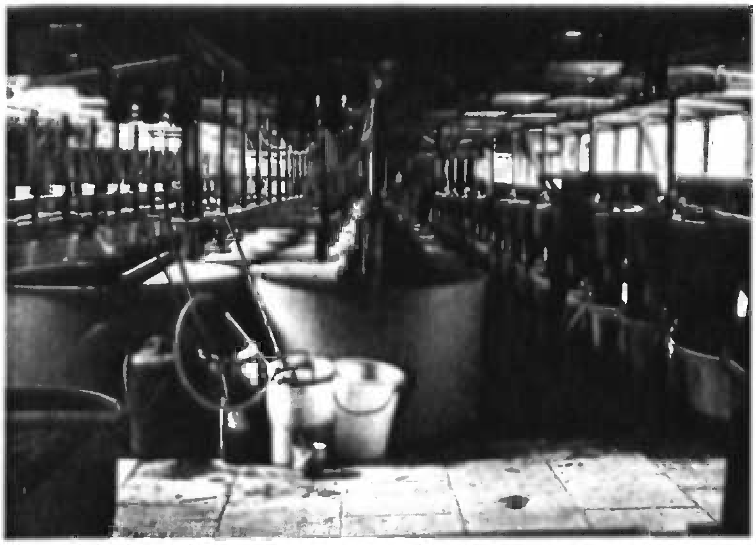
In 1972 the Institute of Marine Research established a research group for aquaculture. By now this group has grown into a department in the institute in Bergen and two affiliate aquaculture stations.

The Department is involved in investigations in the fields of genetics, pathology, nutrition, physiology, behavior, general culture of marine organisms as well as farming techniques. There is extensive cooperation with other institutions, such as the universities of Bergen and Tromsø. As a part of the Institute of Marine Research the Department of Aquaculture also functions in an advisory role in the Directorate of Fisheries.

Among the products of the research, the development of methods to combat salmon lice and vaccines against vibriosis are noteworthy, along with successful attempts to hatch and raise cod larvae and improved salmonid hatching rates through the use of hatching substrates. Methods of water recirculation and treatment in the hatchery and farm ponds are also upgraded.

The most important projects presently undertaken by the department are: genetic variation in the production characteristics of farmed fish; nutrition investigations in salmonids; cultivation of fingerlings of marine fish and the development of appropriate feeds; release of salmonids and cod; discovery and exploitation of suitable areas for farming oysters, mussels and other bivalves; behavioral investigations with smolt in the wild and in cultivation; development of methods for pond-rearing smolt in freshwater; improvement of water quality and water treatment i.e. for hatching salmonids; testing and developing new farming equipment; examining the pollution and environmental impact of a fishfarm; intensive rearing of cod and, finally, investigations into the pathology of fish in farms, particularly the development and testing of vaccines. Research is also conducted in population genetics and diseases of natural fish stocks.

Bergen, laboratory for fish pathology



Matre, parr and smolt tanks

The necessary laboratory work of the projects takes place either in Bergen or at one of the stations. Field work is conducted at the stations, in the small fjords adjacent to Austevoll Aquaculture Station, at some commercial installations and in Kvernavatnet, a coastal lake in Austevoll.

The department's activities are financed partially by a budget from the Ministry of Fisheries and partially by foundations and councils (the Norwegian Council of Fisheries Research, the Oil and Fish Fund, Norwegian Fisheries Research Fund). Some of the activities are supported by special grants from the Ministry of Fisheries, the Ministry of the Environment and the Ministry of Municipal and Labor. Companies and organisations, such as ELF Aquitaine Norway A/S, Norsk Hydro, the fishfarmers organizations etc., also contribute significant-amounts.

Matre Aquaculture Station

The purpose of Matre Aquaculture Station was to contribute to the development of Norwegian aquaculture, particularly the raising of salmonids. Construction of the station has been more or less continuous since 1971 and led to the timely inclusion of an experimental station for fisheries research.

The station has access to five different water types: from the Matre River, cooling water from the Matre Power Station, recirculated water, brackish water at the river mouth and seawater.

The stations hatchery has a capacity for 2.4–3 million salmonid eggs, while fry and older fish can be maintained in the approximately 200 fibreglass tanks and the floating cages of various shapes and sizes. At the disposition of the station are a lab for water and general food analyses, a small feed kitchen, a freezer and cooler room, a classroom for up to 60 people and facilities including sleeping rooms and kitchen.

Recording of fish larvae behavior

Stripping of female brood fish

Austevoll Aquaculture Station

This station meets the requirements of experimental investigations in marine aquaculture. The first stage of construction was complete in 1978 and the station now consists of a small analysing laboratory, a wet lab, a feed kitchen and freezer, a feeding hall with 60 tanks and a large sea installation with netpens of various sizes as well as floats for research in mussel culture. The wet lab has containers for growing rotatoria and for the hatching and start feeding of marine animals and bivalves.

The seawater supply comes from 50 meters depth where the salinity and temperature are fairly constant year round. The seawater used for hatching and for larvae experiments is filtered and disinfected by ultraviolet irradiation.

Field experiments on the massproduction of larvae of marine organisms, particularly cod and oysters, take place in a small fjord adjacent to the station. A brood stock of halibut will form the basis of an attempt to farm this commercially interesting species.

Aquaculture

Norway has a marvellous coastline replete with fjords, bays, sounds and straits. For those who approach from the sea this can appear barely navigable but once shoreward of the skerries and islands there is shelter from bad weather and storms. The topography of this coast is also special by international standards.

A northbound coastal current originating in the Baltic Sea mixes with the freshwater of a number of rivers and with the enormous watermass of the Transatlantic Current. A rich bloom of algal species and phytoplankton occurs particularly in spring. The areal transfer of biological energy can be compared with production on cultivated land.

We Norwegians have generally taken these resources for granted, rejoicing in the beauty of the fjords and the pleasure of the richness of the fisheries. But we have neglected to exploit this richness through cultivation.

Norwegian fishfarming has nonetheless directed attention to the exploitation of our coastal areas, where the farming of salmon and trout has shown that the location can be used for more than just recreation, transportation and small catches. Industry in particular has become interested in the potential of our coastal waters. Although the pioneers of fishfarming toiled with primitive techniques and insufficient know how, and despite large losses, they possessed great optimism and laid the foundation for a new and hitherto unparalleled primary industry. There still remains a number of problem areas in salmon farming, such as disease prevention and treatment, appropriate utilization of the foodstuffs and the environmental impact of the fishfarms. In addition to these problems, interest has been focussed in new areas, the most important of which is the exploitation of other species by cultivation, such as cod, plaice, turbot and halibut. This requires the development of economical methods of stockfish production. Such techniques combined with cheaper and better smolt production in salmonids could form the basis for a new type of fishery. The fishery of released fish or sea-ranching can mean better use of the coast's grazing areas. Examples from other countries show that such resource management can lead to a steady increase in yield if balance is achieved between the home environment and the area of release.

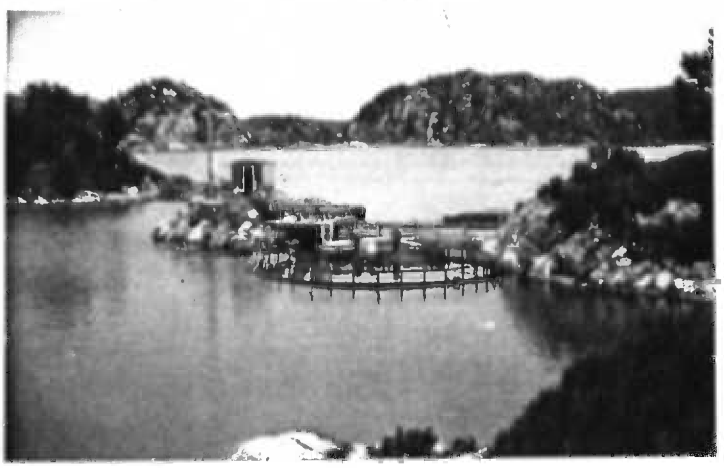
An additional use of the sea's production can be found in the farming of bivalves and the raising of kelp and seaweed. These organisms take their nutrients directly from the sea and are an inexpensive natural product. Although oyster farming has a long tradition in Norway this industry has not yet reached its potential level of output. Meanwhile, interest has been growing in the cultivation of mussels which, despite criticism and instances of poisoning is hoped to expand into an industry for coastal Norway.

In the Far East algae farming is a booming business. Many of our local species are well-suited for cultivation so that with proper management this resource could yield significant amounts of protein to supplement both animal and human diets.

Innumerable problems await a solution. The Department of Aquaculture of the Institute of Marine Research has taken on some of these problems and many have been solved with positive results.

We are hoping for a deeper understanding of the coast's potential and a greater interest in the sea's natural products. The larders of the sea hold many delicacies.

Rearing of cod fry in an enclosed small fjord



TAPERED CHANEL (TAPCHAN)

WAVE POWER PLANT, NORWAVE A/S

Toftestallen, 22 June 1985

October 1983

TAPCHAN

WAVE POWER PLANTS

NORWAVE A.S

Forskningsveien 1, Blindern
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TAPERED CHANNEL WAVE POWER PLANTS

In many parts of the world the energy content of the ocean waves is considerable and the cost of traditional electricity is high. This makes wave power an interesting proposition. The critical problem is the development of efficient and reliable methods for converting wave energy into electrical energy. In general, such energy conversion devices must meet the following requirements:

* The conversion efficiency should be insensitive to variations in wave height, frequency and direction.

* The construction itself should be able to cope with extreme weather conditions.

Most of the devices proposed for wave energy conversion involve the exposure of moving parts and machinery to adverse off-shore conditions. As a result, production and maintenance costs for these devices are high.

To overcome these problems, NORWAVE A.S and the Central Institute for Industrial Research, Oslo, Norway, have developed a novel method for wave energy conversion: the TAPERED CHANNEL WAVE POWER PLANT(TAPCHAN). TAPCHAN POWER PLANTS are now offered by NORWAVE A.S on a commercial basis.

1. THE TAPCHAN POWER PLANT

The TAPCHAN POWER PLANT combines the following features:

* The wave energy is converted to potential energy in an on-shore water reservoir.

* The generation of electricity is carried out by standard hydroelectric power plant technology.

* The conversion device is entirely passive and has no moving parts.

* High energy conversion efficiency is maintained over a broad range of wave heights, frequencies and directions.

The principle of operation of the NORWAVE TAPCHAN can be explained by dividing the system into the following sub-systems: (see fig. 1.)

* A collector designed to concentrate the wave energy and optimize collection efficiency for a range of frequencies and directions.

* An energy converter in which the energy of the collected waves is transformed into potential energy in a water reservoir.

* A water reservoir for storage of the converted energy. The reservoir also serves to average out short-term fluctuations in the wave energy level.

* A conventional hydroelectric power plant for electricity generation.

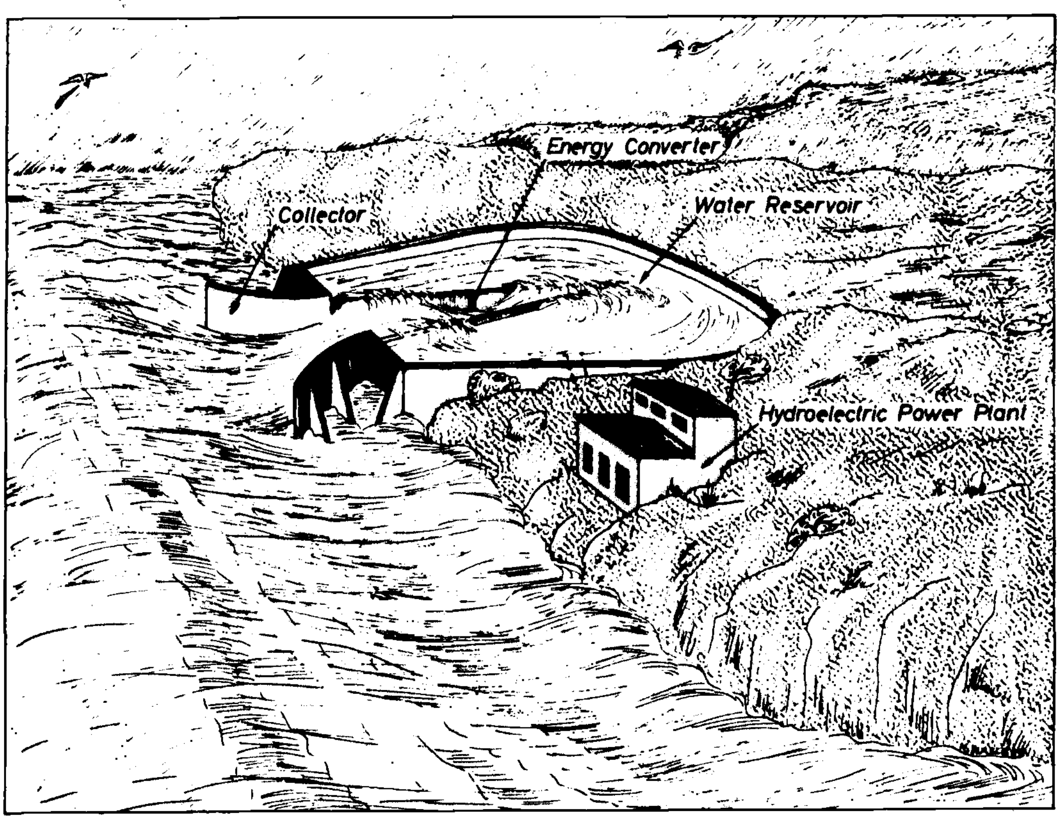

Fig. 1

(a) <u>The wave energy converter</u>

This stage is the unique part of the TAPCHAN POWER PLANT. It consists of a gradually narrowing channel with wall heights equal to the filling level of the reservoir (typical heights 3-7m). The waves enter the wide end of the channel and, as they propagate down the narrowing channel, the wave height is amplified until the wavecrests spill over the walls. The gradual narrowing of the channel causes a continuous sideways spill-off as the wavecrests move along. As a result, the wave energy is gradually transformed into potential energy in the reservoir. The advantage of this conversion method is that it is entirely passive, and almost completely insensitive to variations in wave height and frequency.

Various models of converters have been thoroughly tested in a wave flume as well as in a wave tank and shown to behave according to specifications. Typical figures for the conversion efficiency are in the range of 65-75 %.

(b) <u>The collector</u>

The collector serves the dual purpose of concentrating the incoming waves before they enter the converter, and matching the converter to the local wave climate in an optimum manner. The horn shaped collector is designed so as to optimally collect the wave energy over a range of incoming wave frequencies and directions.

In some cases it is desireable to modify the local wave climate (i.e. increase the energy density) by using offshore lens elements for wave focusing. Such wave lenses act as a pre-collector, and must be adapted to the collector stage.

(c) The reservoir

The main function of the reservoir is to provide a stable water supply for the turbines. The reservoir must be large enough to smooth out the fluctuations in water spill-off due to the individual variations in the waves propagating down the tapered channel. This is achieved with a small reservoir. Storage capacity for less than one hour's operation of the turbines is ample. The reservoir should be as small as possible, the lower limit being determined by the technical requirements of the water turbines.

(d) The hydroelectric power plant.

Well established techniques are used for the generation of electric power. The water turbine driving the electric generator is of a low head type such as a Kaplan, or a tubular turbine. It must be designed for salt water operation, and should have good regulation capabilities. Otherwise, there are no special requirements for the power station and its equipment.

2. DESIGN OF A TAPCHAN POWER PLANT

The TAPCHAN POWER PLANT is based on a concept which is adaptable to a large spectrum of external conditions. Plants of sizes between 0,5 MW and 300 MW can be constructed.

A TAPCHAN POWER PLANT is individually designed to ensure an optimal configuration. The capital costs of the plant and the unit cost of power, i.e. average production cost per kWh. in a year, should be minimized.

Normally, NORWAVE will start with a feasibility study in order to evaluate the possibilities for an economical utilization of the available wave power in a region. The economy of any wave power plant is highly dependent upon local variations in the wave energy. Key parameters, such as capital cost per installed kW and unit cost, vary with installed machine capacity, dimensions and shape of converter etc. Thus, optimization of plant parameters is a very important part of the design.

NORWAVE and partners have developed the theoretical basis and adequate design tools for optimization, design, and performance analysis of TAPCHAN POWER PLANTs. With our Wavetrack computer program, the local wave climate is analysed. The Wavetrack results are used together with results from well established procedures for site selection to determine the most advantageous plant location.

Computer programs are important tools in the optimization and design of the power plant and its sub-systems. One example is a program for design of optimum size and shape of the collector stage of the system. With a given spectrum of sea waves as input, this program calculates the detailed wave patterns and the overall transmission efficiency of converters of various shapes. (See figs. 4 - 10). The output data from the program are important parameters used in a computer-aided optimization procedure in which plant parameters (dimensions of converter and reservoir, installed machine capacity, etc.) are determined to give optimum overall performance of the TAPCHAN POWER PLANT.

NORWAVE has found that great cost reductions can be achieved by a thorough and intelligent optimization and design. Optimization of potential TAPCHAN POWER PLANTs has resulted in reductions in unit costs of power by factors of between 2 and 4. The unit cost of power from some actual TAPCHAN POWER PLANT propositions has been calculated to less than 2 new pence per kWh. (about 3 U.S. cents).

This figure compares favourably with most other energy costs, and indicates that our TAPCHAN WAVE POWER PLANT in many cases might be the right device for the supply of electric power.

3. PARTICIPATION BY NORWAVE A.S IN WAVE POWER DEVELOPMENT

NORWAVE A.S is a company formed by former staff members of the Central Institute for Industrial Research, (SI) to develop and market products based on wave phenomena. The NORWAVE employees and their SI colleagues have carried out a major research programme on ocean waves since early in the seventies. One notable result is the renowned focusing wave power plant, in which specially designed water wave lenses are used to convey the wave energy into a focal area, where the converter is placed. This concept is well suited for large wave power plants, producing several hundred megawatts.

During the later years SI and NORWAVE A.S have concentrated on the development of smaller wave power plants. The result of this effort is the TAPCHAN WAVE POWER PLANT which now can be constructed on a commercial basis.

NORWAVE A.S and its partners in Norwegian industry combine some of the world's most advanced scientific expertise on wave power, with extensive international experience in the design and construction of hydroelectric power plants, as well as large offshore structures.

NORWAVE A.S can assist in connection with any activity related to the development of wave power. This assistance can range from cooperation with local companies on special activities, to taking full responsibility for any part of the design and construction of a TAPCHAN POWER PLANT. This includes turnkey delivery of the complete power plant.

For further information and references, please contact

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MULTIRESONANT OSCILLATING WATER COLUMN (MOWC)

WAVE POWER PLANT, KVAERNER A/S

Toftestallen, 22 June 1985

KVÆRNER BRUG's MULTIRESONANT OSCILLATING WATER COLUMN

Kværner Brug A/S has since 1975 carried out extensive research and development work on wave power utilization, and are now in the final stage of building a wave power prototype excavated in a shelf in a cliff on the Norwegian coast.

The work on the prototype started in spring 1984 at Toftestallen in an area called Øygarden, near the city of Bergen, on the Norwegian west coast. The prototype is planned to be in operation in the autumn of 1985.

Kværner's wave power concept - the Multiresonant Oscillating Water Column (MOWC) - is based on the resonance principle. A fixed construction made of steel or concrete is placed either off or on the coast. The construction is basically half a U-tube. The waves enter the construction at the bend of the U-tube and hence make the water column in the U-tube oscillate. The natural frequency of a water column in a U-tube is dependent on the U-tube dimensions. A large U-tube will have slow oscillations while a small will have fast oscillations. The U-tube construction will be dimensioned such that the water column will have a natural frequency which is the same as the frequency for most of the waves where the wave power unit is situated, hence the resonance effect will be achieved for these waves. By giving the wave entrance for the unit a special shaped addition, a so called harbour, the water column will have two natural frequencies near each other. The resonance effect will then be expanded to cover a wider frequency band for the incoming waves.

The oscillating water column will respectively suck and blow air through an air turbine which in turn drives a generator which produces electric power.

The significance of the air turbine is that the rotor will rotate in the same direction independent of the direction of the air stream. For wave power stations where the air changes direction, this is of great importance. By using this kind of turbine one does not need rectifying valves and complicated control systems to direct the air stream to the correct side of the rotor depending on the direction of the air stream.

A model of the air turbine is tested at the Technical University in Trondheim and the efficiency is higher than for similar turbines. The turbine will be built by Sørumsand Verksted, another company in the Kværner Group. The weight is estimated to 9 tonns and with a runner diameter of 2 metres. The speed of the turbine will be betewwn 1 000 and 1 500 rpm. and will be capable of delivering up to 500 kW. The production of the turbine is fairly simple but due to the high speed care has to be taken in balancing the runner and other rotating parts.

The building site is a vertical cliff facing the sea, where a lot of the waves are reflected. The result of this is an increase in the wave height near the cliff without a change in wave frequency. This implies an increase in the energy output from the wave power plant.

The construction work started in the summer of 1984. A shelf in the cliff (10.5 x 12 x 11.3 m - L x B x H) was blasted away leaving only a rock wall towards the sea so the founding of the oscillating chamber could be carried out in dry surroundings.

In November 1984 the foundation work was finished and the rock wall blasted away. The 11 metre high steel tower was build nearby and brought to the construction site, in three parts, by boat and lifted in place and bolted togehter with the concrete foundation. The tower has a dimension of 7 metres at the bottom and 3.5 metres at the top.

In the tower there is now mounted a measureing device for measureing the construction's ability to suck and blow air into the tower, and hence decide the energy output from the construction. A rough estimate gives a yearly production of 1.9 GWh. Furthermore extensive tests are done on the construction in order to find the force that the sea exerts on it. In the autumn of 1985 the air turbine and a generator will replace the measuring device in the tower and the wave power plant will produce electricity to the local Electricity Board.

Kværner Brug A/S
1985-03-21

TRONDHEIM, Norway 22.-24 JUNE 1982
The Second International Symposium on
WAVE ENERGY UTILIZATION

THE KVÆRNER MULTIRESONANT OWC

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Abstract

This paper reports on the development of Kvaerner's multiresonant oscillating water column.

The work is not yet finished, but theoretical and experimental results so far show a significant increase in energy production when the absorber is designed to have several resonances within the frequency span of the incoming wave spectrum.

The multiresonant characteristics are achieved by having walls protruding from the opening of the oscillating water column (OWC), thus giving "harbour" resonance effects in addition to the basic resonance of the OWC itself. The interaction between absorbers in a row will further increase energy production.

Introduction

The oscillating column concept (OWC) where a confined "water body" is used as a piston to displace water and generate a wave, is probably the most multinational of the wave energy absorber concepts, worked on in Great Britain, Japan, Canada, USA etc. and also in Norway.

The point absorber principles have been advocated strongly in Norway, in particular by Mr. Budal and Mr. Falnes. Also in the OWC project we have bent towards using high resonance amplification thus reducing geometrical dimension, although compromises are believed to be the most attractive.

The resonance effects utilized have been the normal resonance oscillations for a OWC, not phase controlled as in the buoy point absorbers. Instead, one has tried to achieve good energy absorption over a wide wave frequency range by making OWC systems where one either changes the OWC's resonance frequency continuously and tunes it to the peak of the incoming wave spectrum, or has two or more resonance peaks within the frequency span of the incoming wave spectrum.

During the years 1978-80, our work concentrated on the development of an OWC with continuous variable resonance frequency. During 1980 we shifted to an OWC with several fixed resonance frequencies.

The selection between continuous variable or several fixed resonance frequencies will be a trade-off between simplicity versus energy production. The same of course is the case in selecting between phase control and "natural resonance".

Up to this point the main emphasis in our OWC development has been placed on mechanical simplicity, for the sake of inexpensive and safe operation and maintainance, which favour the multiresonant OWC we will report on here. The main part of this work has been done at the Norwegian Hydrodynamic Laboratories (NHL) under a contract with Kvaerner Brug A/S.

1.1 Description of the design and working principle of Kvaerner's multiresonant OWC (KMOWC)

The general design of the KMOWC is shown in Figure 1.1. The KMOWC differs from the conventional OWC under development other places, in that it has a "harbour" in its front towards the sea. This harbour which actually is concrete walls protruding from the main structure gives rise to new eigenvalues (resonances) in the absorber's response to the incoming wave.

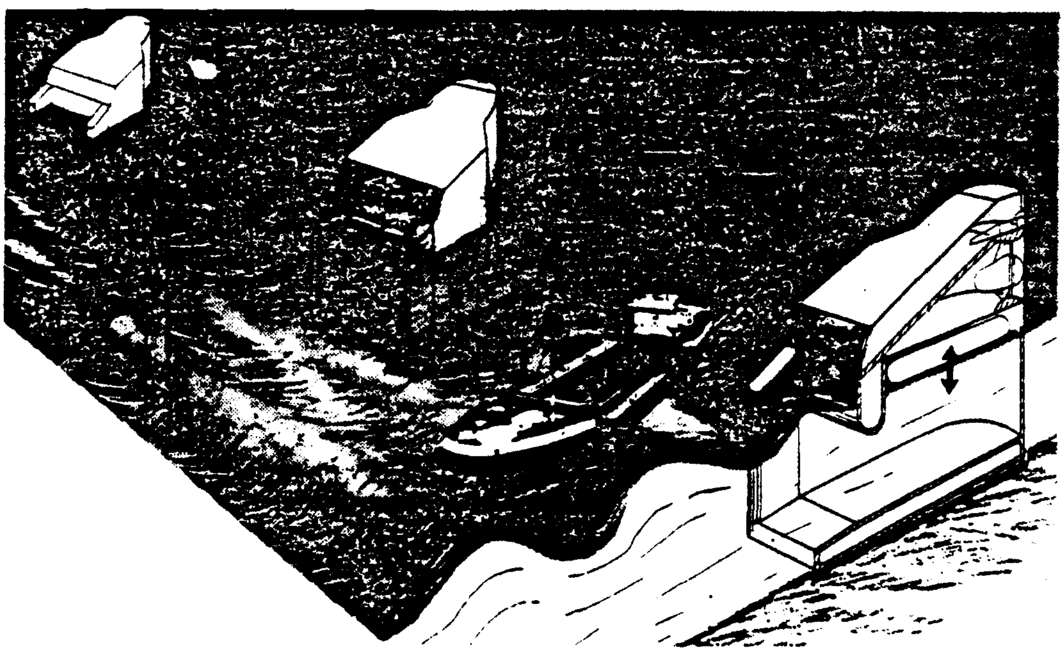

Figure 1.1 Kvaerner's multiresonant OWC, artist's impression.

If the columns works alone, i.e. interaction between columns can be disregarded, the effect of the harbour is go give rise to a series of new resonance frequencies. The two important resonance frequencies for energy production are shown in Figure 1.2.

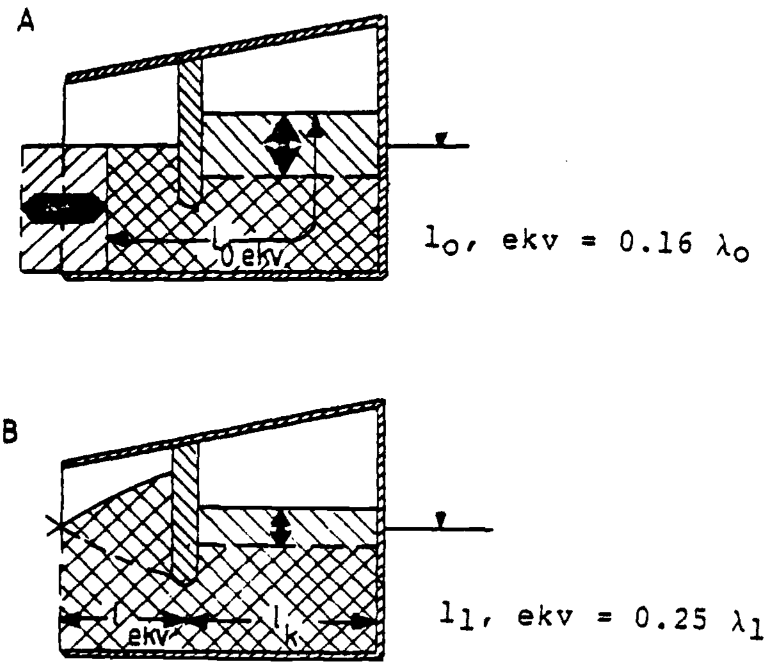

Figure 1.2 Resonance oscillations in the water column with harbour. Fig. A shows, in principle, the normal water column resonance picture. Fig. B shows quarter-wave resonances introduced by the harbour.

Figure 1.3 shows the influence of the harbour on energy absorption.

In a row of columns, where interactions also must be taken into account, the picture is somewhat complicated as one gets extreme values when the distance between the columns equals an integer multiple of the wave length. This is treated in Section 2.

In practical design, however, the distance between the columns will be selected shorter than most of the wave lengths one wants to absorb energy from.

The main emphasis in the work with the KMOWC so far has been to

- prove that the "harbour resonance effect" works and does increase energy production,
- build a computerized theoretical model, and calibrate this experimentally, so that continued optimization can be done with the theoretical model.

The program is scheduled to be finalized in the middle of 1983.

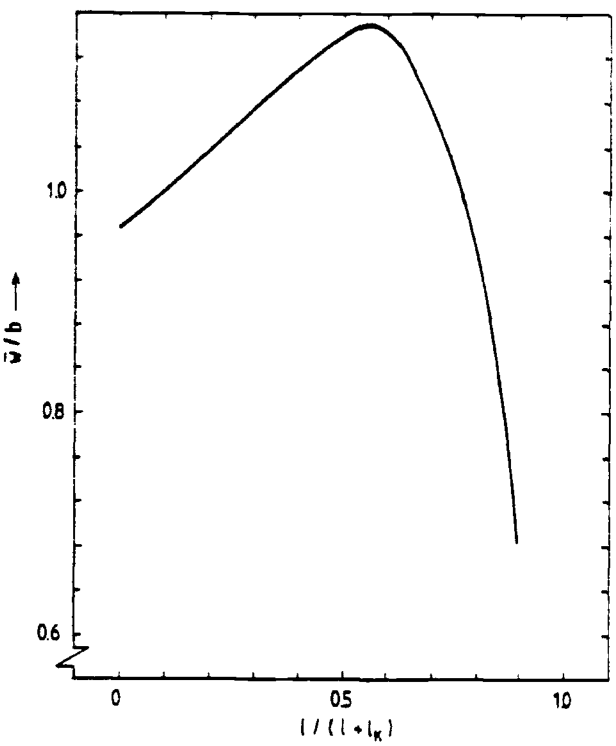

Figure 1.3 Absorption width over harbour width at varying harbour lengths. In the example shown, total length $l+l_k$ is kept constant. First peak in absorption length at $\lambda_o \cong 0.16\, l_o$ekv, is kept constant and coincides with the peak in the incoming wave spectrum. The result is for a single column, optimally damped, in open sea and deep water.

Theory

2.1 The model

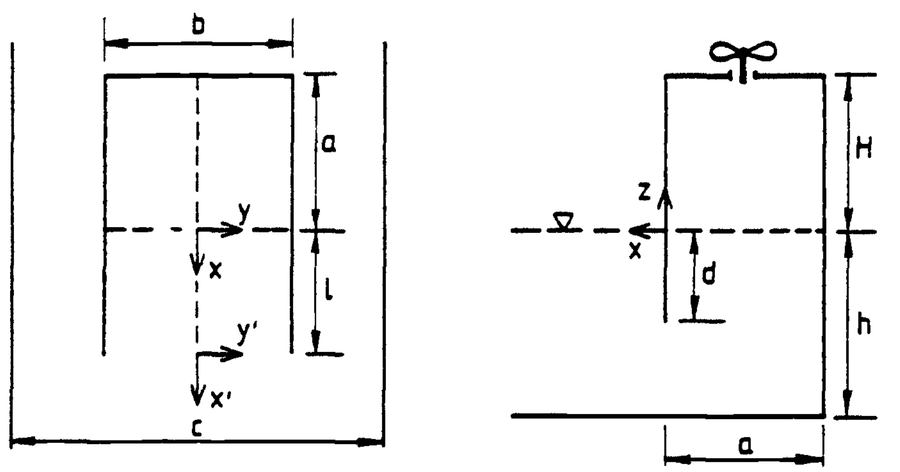

Figure 2.1 Oscillating water column with harbour.

We consider a model system as shown in Figure 2.1. The pressure chamber has length a, width b and height H above the water surface, and is separated from a harbour of length l by an infinitely thin barrier of depth d. The harbour has the same width b as the chamber and the system is placed symmetrically in a channel of width c or in the open sea. In either case we consider monochromatic waves with normal incidence and assume a constant water depth h.

We find it convenient to develop the theoretical description of this system in three stages. In the first instance, we consider the problem of a closed rectangular harbour on the open sea or in a channel. Secondly, we deal with the case of an infinitely wide barrier in front of a totally reflecting wall. The methods developed for these two problems are then finally coupled into a description of the complete model system.

2.2 The harbour problem

Consider a rectangular harbour of width b and length l placed on an open sea of constant depth h, corresponding to the case d = h in Figure 2.1. Factoring out the time dependence $\exp(i\omega t)$ we take the incident wave to propagate along the negative x axis and have amplitude $\hat{\eta}_i(x') = \hat{\eta}_o \exp(ikx')$. We assume that the wave amplitude

$$(2.2.1) \quad \hat{\eta}_H(x) = \hat{\eta}_o(\xi_H/2)[\exp(ikx) + \exp(-ikx)]$$

inside the harbour is constant across the width b. Here ξ_H is the wave amplification at the back wall x = 0, and the derivative $\hat{\eta}'_H(x) = \partial\hat{\eta}_H(x)/\partial x$ is zero at this point.

The harbour mouth is treated as a source of radiated waves. Assuming a constant source strength C across the mouth we write the radiated wave ($x' \geq 0$) as

$$(2.2.2) \quad \hat{\eta}_{rad}(x',y') = (i/k)C\, g_o(b,x',y'),$$

$$g_o(b,x',y') = (k/2)\int_{-b/2}^{b/2} dy''H_o^{(2)}\{k[x'^2 + (y'-y'')^2]^{\frac{1}{2}}\},$$

where $H_n^{(2)}$ is a Hankel function and $\partial\hat{\eta}_{rad}/\partial x' = C$ at $x' = 0$, $-b/2<y'<b/2$. By matching the harbour wave amplitude and its derivative to the corresponding quantities for the incoming plus radiated wave at the mid-point of the harbour mouth ($x'=y'=0$) we can write the wave amplification at the back-wall of a harbour of length l as

$$(2.2.3)\quad \xi_H(l) = (1+G_o)[\cos(kl) + i\, G_o \sin(kl)]^{-1},$$

$$G_o(\alpha) = g_o(b,0,0) = \alpha\{H_o^{(2)}(\alpha)$$

$$+ (\pi/2)[\,\mathbf{H}_o(\alpha)\, H^{(2)}(\alpha) - \mathbf{H}_1(\alpha)\, H_o^{(2)}(\alpha)]\},$$

where $\mathbf{H}_n$ is a Struve function and $\alpha=kb/2$. In the absence of the radiation function G_o we would obtain the usual quarter-wave resonances for harbour lengths $l=(n+\frac{1}{2})(\lambda/2)$, $n=0,1,\ldots$, the resonances now become finite and get shifted to lower frequencies.

For a harbour which is placed symmetrically in a channel of width c rather than on the open sea the radiation function becomes

$$(2.2.4)\quad G_o(b,c) = (b/c)\{1+2k\,[\sum_{m=1}^{M-1}(\sin\gamma_m/\gamma_m)(k^2-\beta_m^2)^{-\frac{1}{2}}$$

$$+ i\sum_{m=M}^{\infty}(\sin\gamma_m/\gamma_m)(\beta_m^2-k^2)^{-\frac{1}{2}}]\},$$

$$\beta_m = 2\pi m/c,\ \gamma_m = m\pi b/c,\ M-1<c/\lambda<M,\quad \lambda = 2\pi/k.$$

This gives rise to channel resonances at frequencies for which $c=n\,\lambda$, $n = 1,2,\ldots$.

In Figure 2.2 we show the calculated wave amplification for a specific harbour of model dimensions placed on the open sea and in a wide channel. The open-sea results serve to define the general level of the amplification, and the channel then causes a fine structure around this level. In this figure we deliberately choose a large channel width in order to illustrate the connection between the open-sea and channel amplifications. In a wave-power station consisting of a row of devices the distance between the latter would be of the same order of magnitude as the important wave lengths.

2.3 The barrier problem

We look at the problem of an infinitely wide barrier of depth d placed at x = 0 in front of a totally reflecting wall at x = -a. For consistency with section 2.2 and 2.4 we take the incoming wave to be $\hat{\eta}_i(x) = \hat{\eta}_0 \exp(ikx')$, $x' = x-l$ and write the wave amplitude for $x \geq 0$ as

$$(2.3.1)\quad \hat{\eta}_A(x)=\hat{\eta}_o\exp(-ikl)\sum_{n=o}^{\infty}[\exp(ikx')\delta_{no}+(ik/m_n)a_n\exp(-m_n x)],$$

where the quantities a_n are unknown coefficients and m_n is one of the eigenvalues satisfying the condition $m_n\tan(m_n h)=-(\omega^2/g)$; in particular $m_o=ik$. For $-a\leq x\leq 0$ (the chamber region in the complete model) we

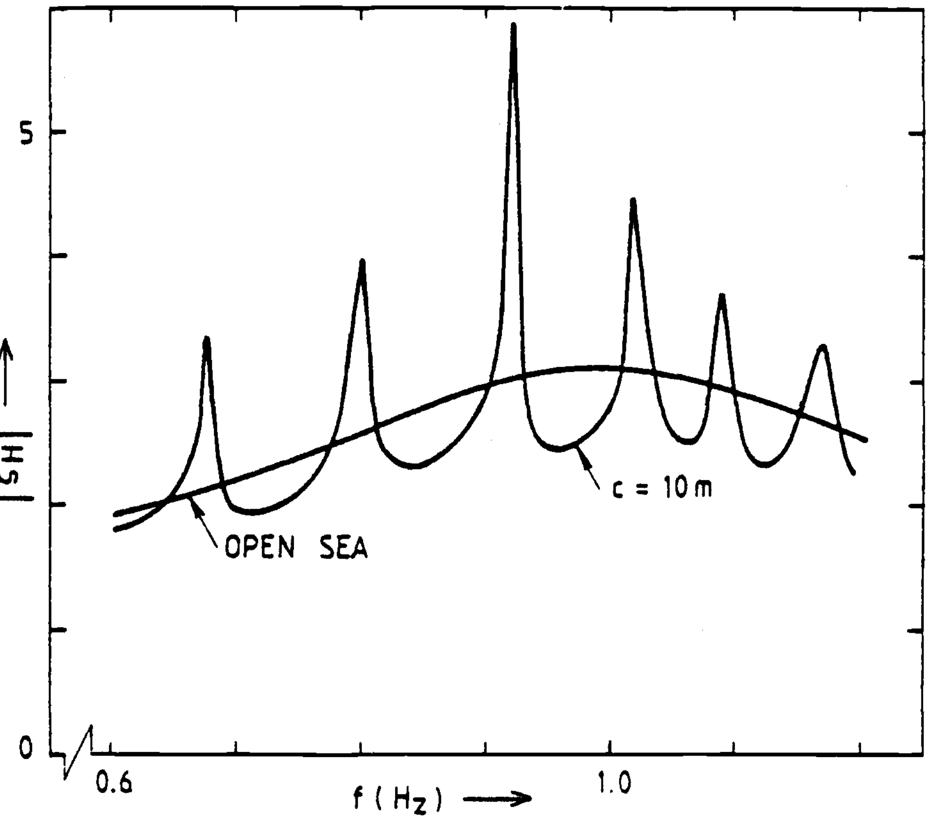

Figure 2.2 Wave amplification at the harbour wall for a harbour on the open sea and in a channel c = 10 m wide. The harbour dimensions are b = 0.417 m, l = 0.150 m, h = 0.385 m.

write

(2.3.2) $\hat{\eta}_c(x)=\hat{\eta}_o\exp(-ikl)\sum_{n=o}^{\infty}[\delta_{no}-(ik/m_n)a_n]\cosh[m_n(a+x)]/\sinh(m_n a).$

The corresponding velocity potential $\hat{\phi}(x,z)$ then satisfies the boundary conditions (a) $\partial\hat{\phi}/\partial z = 0$ at $z = -h$, (b) $\partial\hat{\phi}/\partial z = (\omega^2/g)\hat{\phi}$ at $z = 0$, (c) $\partial\hat{\phi}/\partial x = 0$ at $x = -a$, (d) $\partial\hat{\phi}/\partial x$ is continuous at $x = 0$. In addition, at $x = 0$ $\hat{\phi}$ should be continuous for $-h < z < -d$ and $\partial\hat{\phi}/\partial x$ should be zero for $-d < z \leq 0$. If the expansions (2.3.1-2) are terminated at $n = N$ this means that the coefficients $a_1, \ldots, a_n$ can be obtained from the linear equations

(2.3.3) $\sum_{n=1}^{N}(\delta_{ln}+e_{ln}f_n)a_n = -\mu_o e_{lo}, \quad l = 1,2,\ldots,N,$

and the amplitude for the reflected wave is then

(2.3.4) $a_o = 1 - \mu_o e_{oo} - \sum_{n=1}^{N} e_{on}f_n a_n.$

We have here

$$(2.3.5)\quad f_n = (ik/m_n)(\mu_o/\mu_n) - 1,$$

$$\mu_n = 1 - \exp(-2m_n a),$$

and the dependence on the barrier depth d appears in the integrals

$$(2.3.6)\quad e_{ln}(d) = \int_{-h}^{-d} e_l(z)e_n(z)dz / \int_{-h}^{o} e_l^2(z)dz,$$

$$e_n(z) = \cos[m_n(z+h)]/\cos(m_n h).$$

In terms of the coefficients a_n the average wave amplitude in the chamber region $-a \leq x \leq 0$ is $\xi_o\,\hat{\eta}_o$, where

$$(2.3.7)\quad \xi_o = \exp(-ikl)\sum_{n=0}^{N}(\delta_{no} - a_n)(ik/m_n)(m_n a)^{-1}.$$

For given values of h, a and d the resulting values of ξ_o as a funtion of ω show resonance peaks which become sharper and get pushed towards lower frequencies as d increases.

In addition, we are interested in looking at the case in which there is a periodic excess pressure $p(t) = \hat{p}\cdot\exp(i\omega t)$ in the region $-a \leq x \leq 0$, but no incident wave. We write the corresponding wave amplitude in this region as

$$(2.3.8)\quad \hat{\eta}_C(x) = -\hat{\eta}_p \sum_{n=0}^{N} (ik/m_n)b_n\cosh[m_n(a+x)]/\sinh(m_n a),$$

where $\hat{\eta}_p = (g\rho)^{-1}\hat{p}$, and the coefficients $b_1,\ldots\ldots,b_n$ are determined by the linear equations

$$(2.3.9)\quad \sum_{n=1}^{N}(\delta_{ln} + e_{ln}f_n)b_n = -\mu_o g_l,$$

$$g_l(d) = -\tfrac{1}{2}\int_{-h}^{-d} e_l(z)dz / \int_{-h}^{o} e_l^2(z)dz,$$

the left-hand sides of the equations thus being the same as those of (2.3.3). The coefficient for the lowest mode is now

$$(2.3.10)\quad b_o = -\mu_o g_o - \sum_{n=1}^{N} e_{on}f_n b_n.$$

The response of the system to the excess pressure can then be measured in terms of an impedance which per unit width is defined as

$$(2.3.11)\quad \tilde{Z} = -i\omega a(g\rho)^{-1}\langle \hat{\eta}_C(x)/\hat{\eta}_p\rangle = i\omega a(g\rho)^{-1}\sum_{n=1}^{N} b_n(ik/m_n)(m_n a)^{-1}.$$

2.4 The pressure chamber with harbour

We treat the complete model system in Figure 2.1 by a method which is a combination of those employed in section 2.2-2.3, matching the velocity potential and its derivative at the barrier ($x=0$) as well as the harbour mouth ($x=l$, $x'=0$). The quantities ξ_o (the average wave amplitude in an open chamber divided by the amplitude of the incoming wave) and $\tilde{Z}$ (the impedance per unit chamber width) can still be written as in eq. (2.3.7) and (2.3.11), with coefficients a_n and b_n ($n=1,\ldots,N$) given by linear equations of the type (2.3.3) or (2.3.9). The difference is that the quantities f_n in eq. (2.3.5) should now read

$$(2.4.1)\quad f_n = (ik/m_n)(\mu_o/\mu_n)(1+h_n) - 1,$$

$$h_n = \tfrac{1}{2}(G_n-1)\mu_n \exp(-m_n l)[\cosh(m_n l) + G_n \sinh(m_n l)]^{-1}$$

where G_o is given by eq. (2.3.3) or (2.2.4) and the other radiation functions are

$$(2.4.2)\quad G_n(\alpha_n) = (2/\pi)K_o(\alpha_n) + \mathbf{L}_o(\alpha_n)K_1(\alpha_n) + \mathbf{L}_1(\alpha_n)K_o(\alpha_n),$$

$$G_n(b,c) = (b/c)[1 + 2m_n \sum_{m=1}^{\infty} (\sin\gamma_m/\gamma_m)(m_n^2+\beta_m^2)^{-\frac{1}{2}}],$$

$$\alpha_n = m_n b/2$$

for the open-sea and channel cases respectively. Here K_n and $\mathbf{L}_n$ are the usual Bessel and Struve functions. The expressions (2.3.4) and (2.3.10) for the zero-mode coefficients should now be written

$$(2.4.3)\quad a_o = (1+e_{oo}f_o)^{-1}(1-\mu_o e_{oo} - \sum_{n=1}^{N} e_{on}f_n a_n),$$

$$b_o = (1+e_{oo}f_o)^{-1}(-\mu_o g_o - \sum_{n=1}^{N} e_{on}f_n b_n).$$

We assume that the pressure chamber is equipped with a linear turbine, the air volume per unit time through the turbine being $\hat{q} = C_t\hat{p}$, where C_t is the turbine constant and $\hat{p}$ the excess chamber pressure. Due to the compressibility of the air the effective turbine constant should be written as $\Lambda = C_t + i\omega V_C(\kappa p_o)^{-1}$, where $V_C = abH$ is the chamber volume, p_o is the atmospheric pressure and $\kappa = 1.4$ for adiabatic compressions.

Following Evans [2] we can now obtain the average chamber wave amplitude $\langle\hat{\eta}_C\rangle$, the chamber excess pressure amplitude $\hat{p}$ and the average extracted power P from the expressions

(2.4.4) $\langle\hat{\eta}_C\rangle/\hat{\eta}_o = \Lambda(\Lambda + Z)^{-1}\ \xi_o$,

$$\hat{p}/\hat{\eta}_o = i\omega A_c\ (\Lambda + Z)^{-1}\ \xi_o,$$

$$P/|\hat{\eta}_o|^2 = \tfrac{1}{2}\ (A_c\omega)^2\ |\xi_o|^2\ \mathrm{Re}(\Lambda)\ |\Lambda + Z|^{-2},$$

where $\hat{\eta}_o$ is the amplitude for the incoming waves, $A_c = ab$ is the chamber area and $Z = b\tilde{Z}$. Allowing optimum impedance matching we obtain the maximum power

(2.4.5) $P_{max}/|\hat{\eta}_o|^2 = (1/8)(A_c\omega)^2|\xi_o|^2/\mathrm{Re}(Z)$

at $\Lambda = Z^*$. In the more practical case where the turbine constant C_t is limited to be real the maximum power becomes

(2.4.6) $P_{max}/|\hat{\eta}_o|^2 = \tfrac{1}{2}\ (A_c\omega)^2|\xi_o|^2\ C_o$

$$\times\ \{[C_o + \mathrm{Re}(Z)]^2 + [\mathrm{Im}(\Lambda) + \mathrm{Im}(Z)]^2\ \}^{-1}$$

$$C_o = \{[\mathrm{Re}(Z)]^2 + [\mathrm{Im}(\Lambda) + \mathrm{Im}(Z)]^2\}^{\frac{1}{2}},$$

$$\mathrm{Im}(\Lambda) = \omega V_C(\kappa p_o)^{-1}$$

at $C_t = C_o$.

The present results are greatly simplified if we consider the deep-water limit and at the same time let the barrier depth d approach zero. We then obtain the expressions

(2.4.7) $\xi_o = \xi_H(l + a)\ [\sin(ka)/ka]$,

$$Z = 2(b/\rho)(i/\omega)\sin(ka)[\xi_H(l + a)/\xi_H(l)],$$

where $\xi_H(l)$ and $\xi_H(l + a)$ are the back-wall wave amplifications for closed harbours of length l (the actual harbour length) and $l + a$ (harbour length plus chamber length) respectively, see eq. (2.2.3). Neglecting the small correction due to the compressibility of the air we now find the excess pressure amplitude in a closed chamber ($\Lambda = C_t = 0$) to be $\hat{p} = (\hat{\eta}_o/2)g\zeta\xi_H(l)$, the pressure thus being proportional to the closed-harbour wave amplitude in front of the barrier. In our model the deep-water, $d = 0$ absorption width at optimum impedance matching is $w_{max} = b|\ \tfrac{1}{2}\ (1 + G_o)|^2/\mathrm{Re}(G_o)$, and is therefore independent of the harbour length l. This is no longer the case for a real turbine constant C_t, as shown in Figure 2.3 for a specific

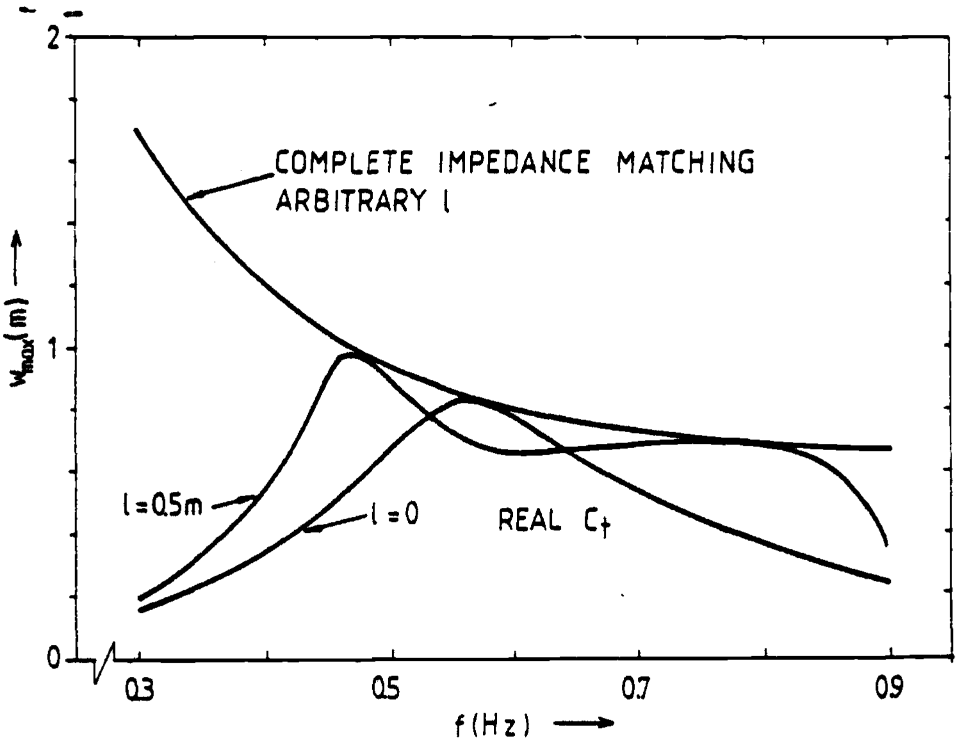

Figure 2.3 The theoretical maximum absorption width as a function of frequency with and without complete impedance matching. The system is placed in a deep open sea and has dimensions a = 0.8 m, b = 0.6 m, H = 0.5 m, d = 0 m.

system of model dimensions, placed on the open sea.

To obtain the absorption widths of Figure 2.3 one would need a frequency dependent turbine constant C_t. In Figure 2.4 we have shown some theoretical absorption widths corresponding to real and frequency independent values of C_t, using the same geometry as in Figure 2.3. The $l = 0$ curve is obtained by using a value of C_t which gives $w = w_{max}$ at the peak. For $l = 0.5$ we have required $w = w_{max}$ at either of the two peaks in Figure 2.3 (curve 1 and 3) and also considered an intermediate case (curve 2). The actual choice of C_t would of course depend on the incident wave spectrum.

We refer to the experimental section for a comparison of theory and experiment for systems in a channel.

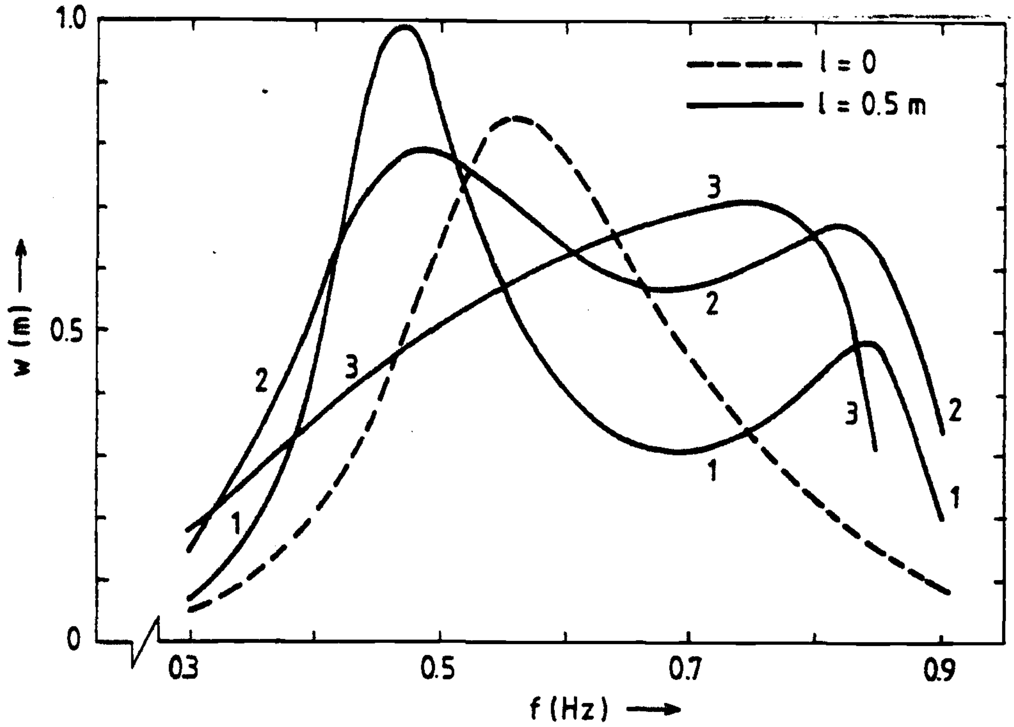

Figure 2.4 Some theoretical absorption widths for real and frequency independent turbine constants C_t. The geometry is as for Figure 2.3.

Experiments

3.1 Comparison of theory and experiment

The theoretical limits of energy absorption for an oscillating water column of finite width have been examined in section 2.

The main emphasis has so far been put on results for the open sea case, with no interaction between neighbouring devices, as to make clear the effect of the harbour alone.

In the case of an array of equally spaced devices, we will expect to obtain an increase in energy production, both from the harbour, and from advantageous interaction between devices.

The experimental work has two main objectives:

- to calibrate the theoretical model under varying conditions,
- to demonstrate the optimum design and absorption efficiency.

It still remains to test the device in a wide basin to obtain results for the open sea case. So far, we have examined the water column with harbour in two different wave flumes, under conditions corresponding to device spacings of approx. 80 and 150 m.

Geometrical parameters as the harbour length, the area of the air chamber and the depth of the barrier between the harbour and the air chamber, have been varied.

In this section we will give the experimental results and compare them to the theoretical prediction.

Figure 3.1 shows the theoretical and experimental energy absorption relative to incident wave energy across the flume width. The experimental points are obtained in regular waves. The damping is optimal both in the experiments and in the theoretical curve.

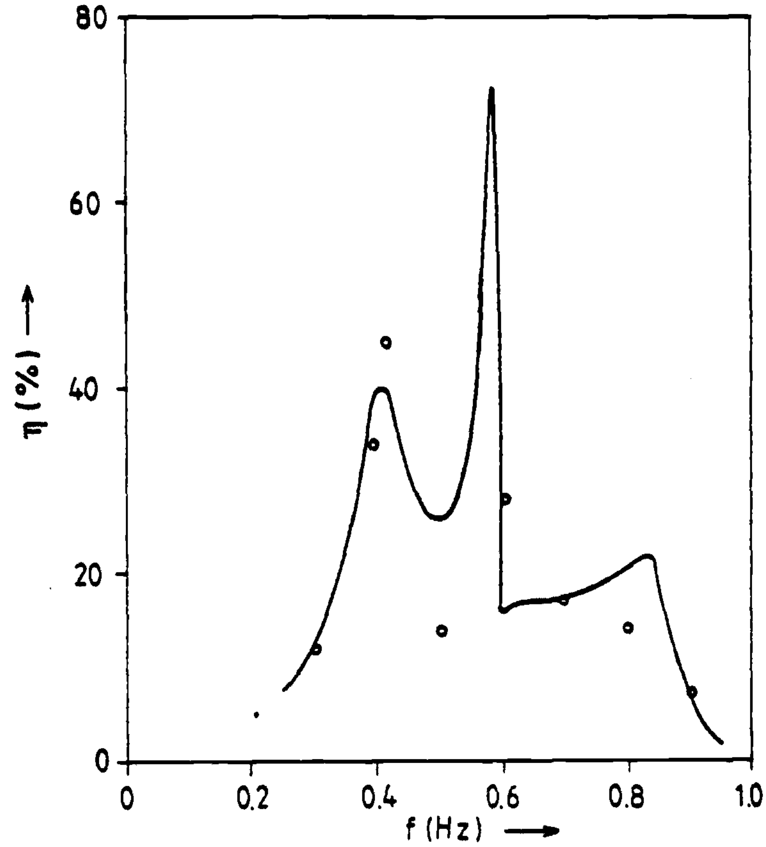

Figure 3.1 Absorption efficiency at optimal damping.
o - experiments in regular waves,
- - theoretical curve.

The theoretical curve has got a peak for a wave length slightly longer than the flume width, and then an abrupt decrease in efficiency when the wave length becomes equal to the flume width. This could not be fully examined by experiments in regular waves because of the strong cross wave build-up in the flume. Other tests in irregular waves show the same qualitative results as the theoretical curve (Figure 3.2).

Because we work with a non-tuneable device with a fixed damping, although depending both on frequency and wave amplitude, we are not

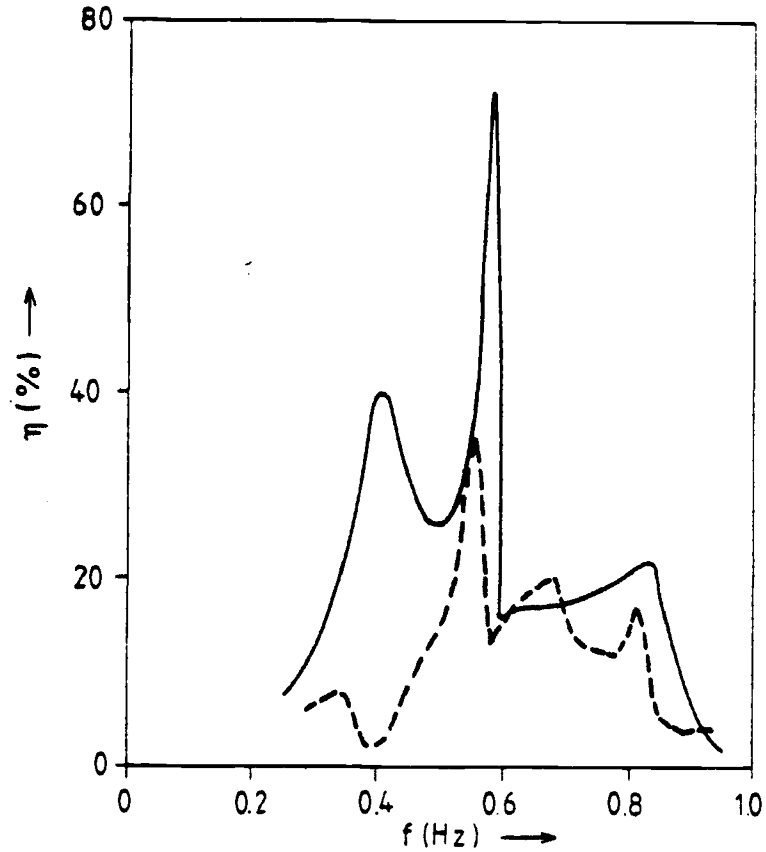

Figure 3.2 Absorption efficiency at fixed damping.
--- Results from experiments in irregular waves, relatively strong damping,
—— Theoretical curve for optimal damping at all frequencies.

able to achieve the optimum energy absorption at all frequencies.

Figure 3.3 shows the device efficiency when damping is optimal at the resonant frequency of the column, obtained from experiments in irregular waves. The theoretical curve for optimal damping in the whole frequency range is shown for comparison.

3.2 Absorption efficiency in a spectrum

In the last experiments shown in Figure 3.4, the resonant frequency of the water column was adjusted to make the energy absorption curve fit an average available energy spectrum [3]. The appropriate scaling of the model is then about 1:40 and the prototype water depth 30 m. Device spacing would be 150 m.

The maximum absorption efficiency is from our experiments 60% of the incident energy across the wave flume, which gives an absorption width of 2.6 times the maximum device width. Because the damping is

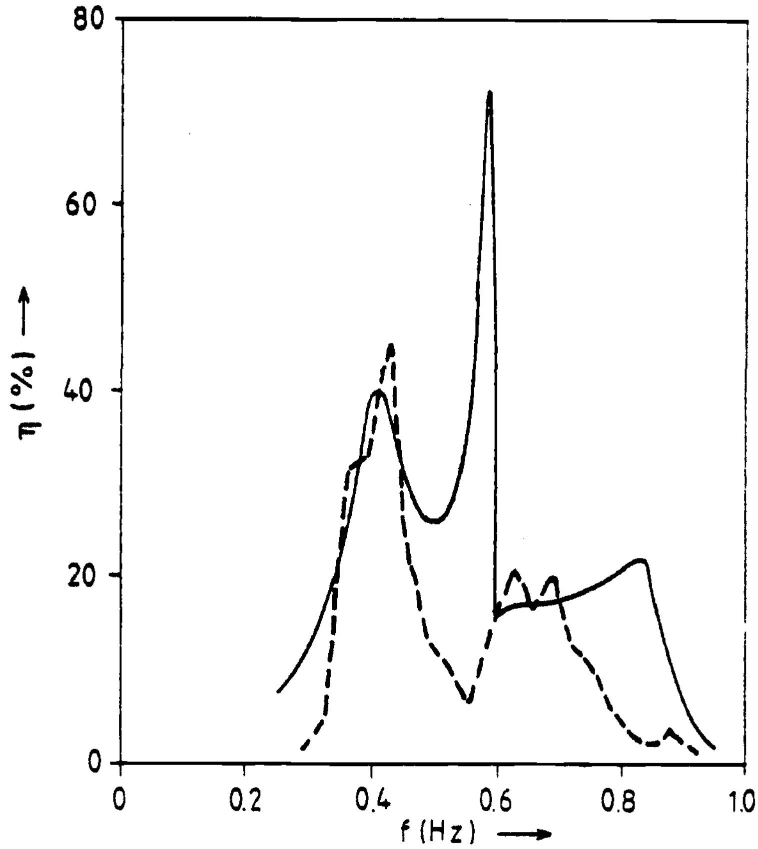

Figure 3.3 Absorption efficiency at fixed damping.
--- Results from experiments in irregular waves, damping is optimal at column resonance.
—— Theoretical curve for optimal damping at all frequencies.

optimal only in parts of the frequency range, this number is reduced to 1.2-1.4 times the maximum device width in our chosen average spectrum.

If we normalize the absorption width against the inner harbour width instead of the maximum device width, we get a maximum absorption width ratio of 3.6 at the column resonance.

The maximum of 60% efficiency is in agreement with results derived theoretically by Dr. Evans, who would predict an efficiency of 57%. The work of Dr. Evans which will be presented at this conference, is based on theory for harbours which in contrast to our design, are narrow compared to their length, so the agreement is in fact much better than expected.

In figure 3.4 the energy absorption of an OWC without harbour and with a fixed damping is shown in comparison to the OWC with harbour.

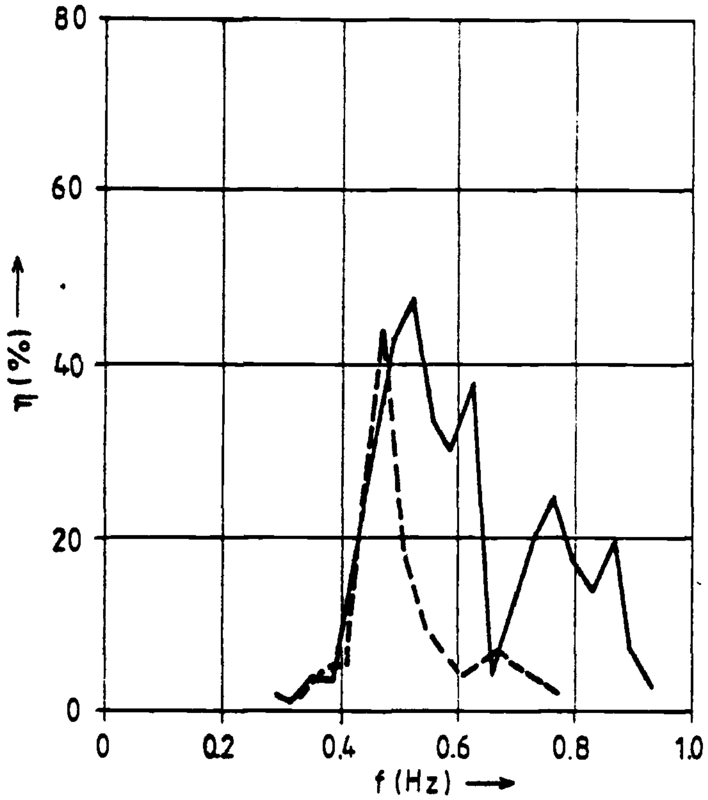

Figure 3.4 Pneumatic energy absorption, relative to incoming wave energy flux across the flume width from experiments in irregular waves. The curves show the efficiency at that choice of orifice which gave the best energy output integrated over our test spectrum [1].
—— with harbour,
--- without harbour.

In a wave spectrum the absorption width of the OWC without the harbour would be approx. 0.7 times the device width, or slightly less than for a pure two-dimensional device.

All Figures above are from tests with normally incident waves. So far, the model has not been tested in a wave basin with oblique waves or directional spectra.

3.3 Experimental set-up and method

A sketch of the wave flume and the experimental set-up in the 3.8 m wide flume is shown in Figure 3.5. By this set-up incoming, reflected and transmitted waves from the beach in the frequency range between 0.3 and 2 Hz can be resolved, which makes it possible to resolve also second harmonics in radiated waves, as the frequency range of main interest in our scale is between 0.4 and 0.8 Hz.

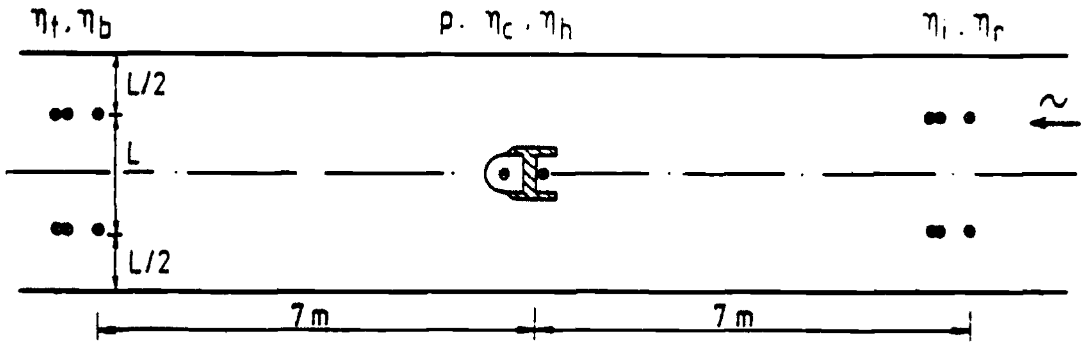

Figure 3.5 Experimental set-up. Total length of the wave flume is 65 m, flume width is 2L = 3.8 m. Wave elevation measurements at points marked ⊗ were carried out by two wire probes.

The model tested is shown in Figure 3.6. The maximum model width is 0.875 m, which is 23% of the flume width, while the inner width of the harbour and column is just 16.5% of the flume width, because a large curvature is needed to reduce vortex shedding at the harbour mouth.

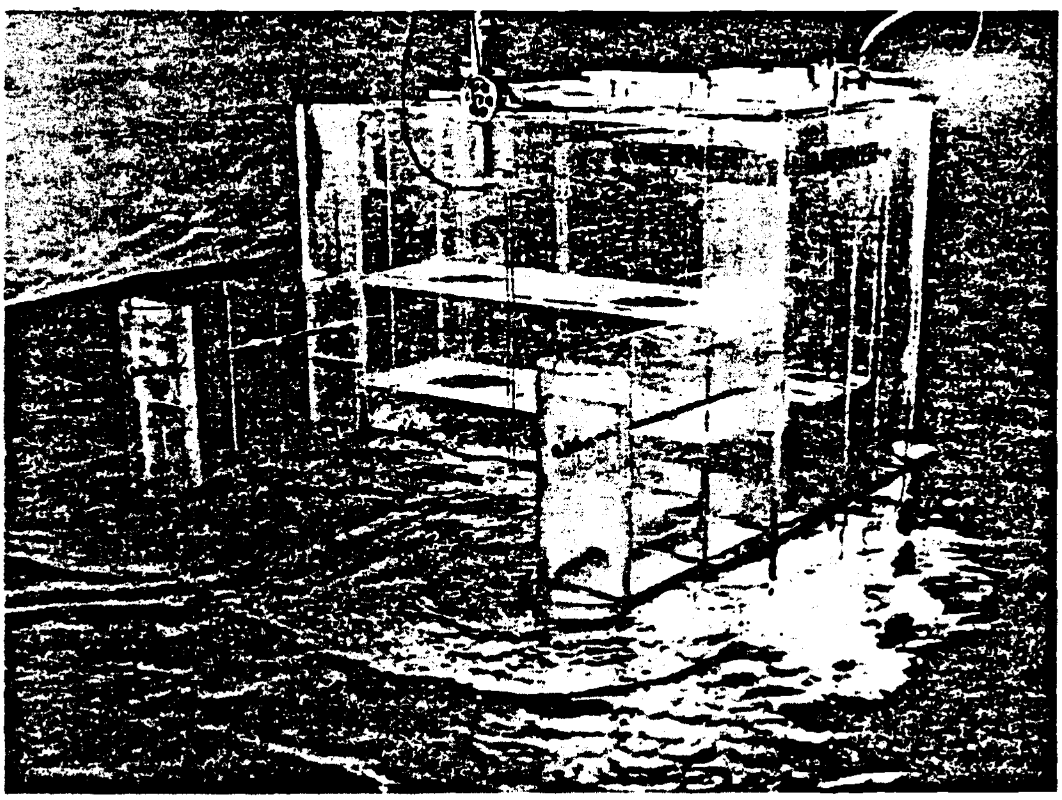

Figure 3.6 The model tested.

The energy absorption from the water column was obtained by pumping air through an orifice at the top of the air chamber. Energy absorption is calculated from measurements of pressure drop across the orifice. The flow, and accordingly the energy absorption, could be calculated from measurements of the water level in the column. The two methods gave good overall agreement, but using the latter method, one has to assume a horizontal water level, or measure at a node point of cross wave disturbances in the chamber.

In introductory tests of responses it was shown that the physical model was in effect linear in the amplitude range of interest. Accordingly, to be able to cover as many parameter combinations as possible in the model tests, it was decided to run most of the tests in irregular waves generated from two different wave spectra. One of the spectra would give a scaled energy flux distribution as found from wave rider measurements off the Norwegian coast, and averaged in time and place. The other reference spectrum gave approximately half the total energy flux, and had a more even distribution in frequency (Figure 3.7).

At certain frequencies the responses obtained in irregular waves were compared to results from tests in regular waves. By also comparing the results of the runs with the two different spectra, we could check both the linearity of the physical model and the data evaluation including FFT of all wave elevation and pressure time series.

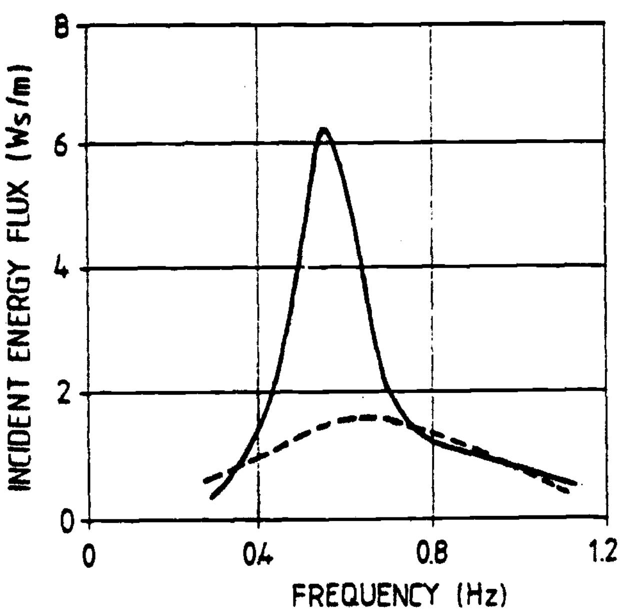

Figure 3.7 Test spectra in model experiments.

We did not in these experiments introduce limitations as a maximum allowed pressure drop or oscillation amplitude. The fact that hydrodynamic losses in the water column and the harbour is a non-linear effect, of course breaks our "linear" model at large amplitudes.

Figure 3.8 and 3.9 show energy accounts at the resonant frequency of the water column obtained in harmonic waves. In Figure 3.8 no external damping is applied and so all energy dissipation in the wave flume and at the structure is due to hydrodynamic losses. During the experiments it could be observed that the vortex build-up at the mouth of the harbour was very strong at large amplitudes of oscillations.

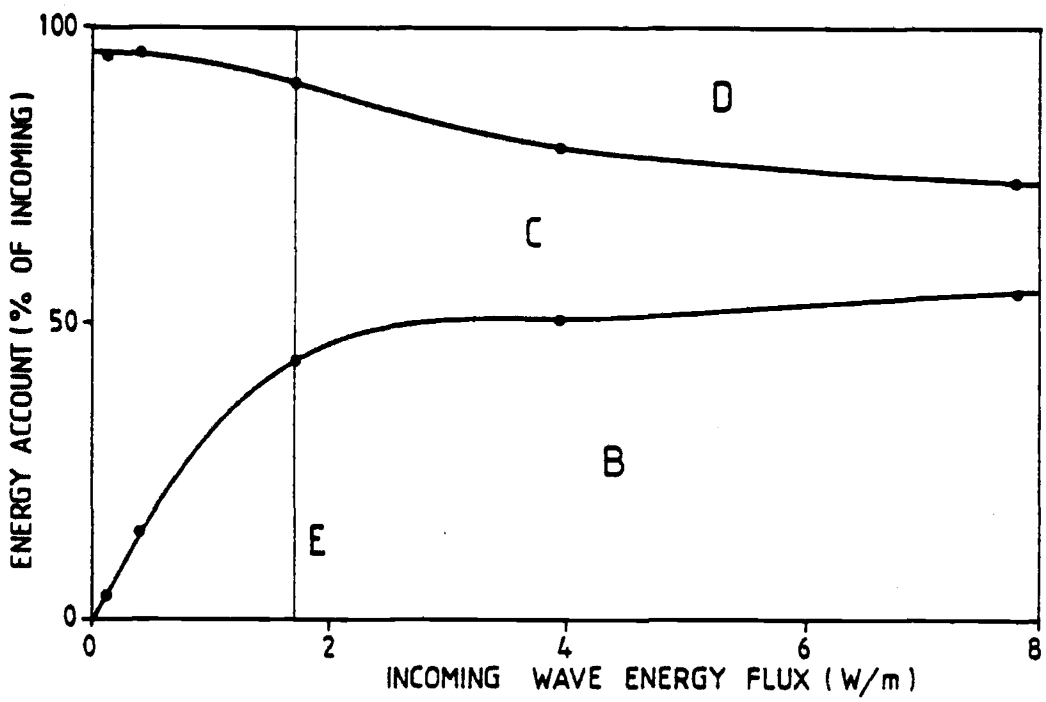

Figure 3.8 Energy account in percent of incoming wave energy flux. Experimental results from tests in regular waves at the resonant frequency of the water column - no external damping. Regions: B - total losses in wave flume between probes and in oscillating water column. C - reflected wave energy, D - transmitted wave energy. Line E coincides with the largest amplification in Figure 3.9.

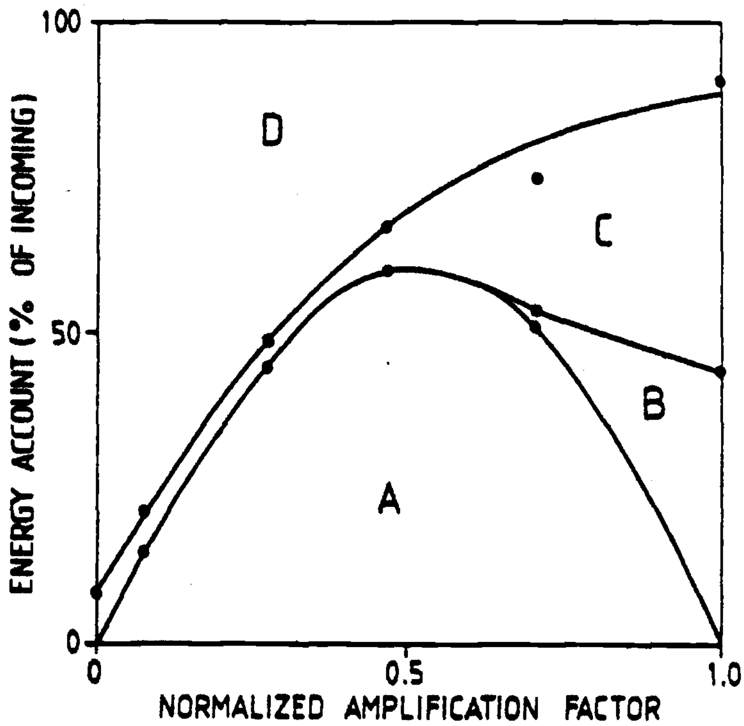

Figure 3.9 Energy account in percent of incoming wave energy flux. Experimental results from tests in regular waves at the resonant frequency of the water column with varying external damping. Regions: A - pneumatic energy absorption, B - unaccounted losses between wave measuring probes, C - reflected wave energy, D - transmitted wave energy. The column oscillation amplification is normalized to 1 in case of no external damping

Discussion

Both theoretical and experimental models used show that introducing several resonance frequencies increase energy procution per unit. Experimental and theoretical results are in good agreement, although there are discrepancies in minor details.

An area where work still in in its beginning is directional response, an area where too little is known also about the incoming waves.

Economical optimization of spacing between units seems to be an area which can give gains. So far indication is that wider spacing than earlier anticipated gives better overall economy. Further work, theoretically and experimentally is needed here.

Economical optimazation with regard to hydrodynamic losses are worked at - but again the state of knowledge concerning losses in oscillating current under the condition one works under in an OWC wave power absorber is unsatisfactory.

Cost effectiveness of the harbour has proven high in the evaluation ordered by the Norwegian Ministry of Petroleum and Energy as OWC with harbour gives cost per unit energy that is substantially lower than for OWC without harbour.

Direct comparison with alternatives as a phase controlled OWC has not been undertaken.

Our preliminary conclusion, however, is that the harbour concept will prove to be a positive contribution in regard of simplicity, ease of operation and maintainance.

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