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ENVIRONMENTAL IMPACT OF WIND ENERGY UTILIZATION

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BY

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1. Introduction

Wind energy may be utilized by conversion into linear or rotational motion. An example of conversion into linear motion is the use of sails to propel ships. Conversion into rotational motion may be performed by stationary wind turbines. The rotating shaft power may be further transformed into pumping motion (for water pumping), electric power (by an electric generator) or heat (e.g. by hydraulic dissipation of the mechanical energy). Direct production of electric power is possible by using a wind driven ion generator. There are a variety of conversion devices, ranging from the classical sail types, windmills and panemones to modern aerodynamically shaped horizontal or vertical axis converters and advanced concepts. A technical description of the conversion methods and application of devices and systems based on wind energy is outside the scope of this book (but may be found elsewhere, e.g. in Sørensen, 1979). Here focus will be on the environmental impact of existing or proposed wind energy conversion devices, with emphasis on free stream turbines and occasional reference to sailships and advanced stationary converters.

In assessing the environmental impacts two further aspects have to be considered: the type of use and the support system required beyond the conversion device itself. The type of use is important for determining the range of alternative energy generation methods, to which the impacts of wind energy conversion should be compared. For rural irrigation purposes the alternative may be diesel-driven pumps, for main grid electricity production the alternatives may be coal or nuclear fuel use in central power plants, and so on. The specifications of the use also determines the support system required. If power has to be supplied on demand at any time, energy storage facilities or back-up systems that can be regulated at will have to be part of the supply system. The total assessment of environmental impacts should thus include manufacture and operation/maintenance of equipment, for conversion, storage and transmission as required by the actual application. In some cases, the impact of some components will be independent of the energy source used, and in such cases an assessment of alternative conversion methods may be performed in isolation, by assuming that the remaining parts of the system (e.g. transmission facilities etc.) will be identical for all the alternatives.

2. Safety hazards

A number of situations may be imagined, in which wind energy technology could affect the physical safety of human beings. Falls from high locations could be associated with the tower constructions characterizing many wind conversion systems. The accident probability is likely to have maxima during tower construction for large stationary turbines, during maintenance that has to be carried out at a height, and for sailships during manual setting from high masts. Most presently constructed wind conversion devices are made in such a way, that dangerous climbing is eliminated during routine operation (automatic setting of sails on sailships, maintenance-free constructions of stationary converters, inside stair access to nacelle of large turbines, etc.). However, during construction and repair hazards may still exist. They are of a nature common to most structures (tall buildings, masts for overhead transmission lines, and so on). Therefore the nature of the hazards is well-known, and measures to bring the risk down below given standards are generally known. However, in traditional construction industries, norms have been developed over long periods of time, and it should be made certain, that wind conversion devices are subject to appropriate standards and codes, or such standards have to be set, so that the fact that this is an emerging industry is not causing loopholes in existing regulation to be exploited in the interest of monetary profit.

This applies to accidents involving falls, capture by moving parts and other incidences not specifis to the wind conversion devices. It also applies to those accident modes, which are specifically associated with the nature of wind energy converters. As an example, failure of rotor-type converters may be considered in a little more detail.

Failure may occur in each component of the system: rotor blades, shaft, transmission or tower. Causes include fatigue of materials, corrosion, fretting or moisture ingestion, depending on the nature of materials used (e.g. metals, composites, wood). A number of loads on the converter may contribute to fatigue failure: Different wind velocities experienced by different parts of the turbine, changing speed and direction of wind, wind turbulence and gusts, accelerations and stresses on components, including aeroelastic and resonance effects, tower-rotor or blade-blade interactions, gyroscopic and centrigugal loads at speed changes and start or stop. Excessive loads may particularly arise in cases of failing controls, e.g leading to overspeed.

The engineering design principle for wind energy converters is safety throughout lifetime. Ensuring this requires not only a static calculation of the construction, but also a dynamical, aeroelastic calculation for the turbine under normal operation as well as under various abnormal conditions (brake failure, etc.). For a horisontal axis turbine, the main fatigue-producing motions of the blades are the flapping modes (in and out of the plane of rotation) and the lead-lag modes (in the plane of rotation).

Fig. 3 shows an example of the calculated variations in flapping and lead-lag amplitudes during one revolution for a blade on a two-bladed horizontal axis rotor of diameter 38m (Kottapalli et al., 1978). The model can include the effect of blade-tower interactions, which is seen to affect the maximum amplitude of the flapping mode considerably. For a discussion and comparison of a number of aeroelastic models see e.g. Spera(1978), Friedman(1978) and Raab(1980). The latter one includes the effect of the turbulent component of the wind, which in some cases can be substantial. Generally speaking, it is possible numerically to estimate the behaviour of horisontal axis rotors under normal operation with sufficient accuracy to allow safe distance to material failure situations, as it is similarly possible for the tower construction. The same applies to a number of cross-wind turbines, although the computational experience is smaller than for horizontal-axis machines.

More difficult is the anticipation of failure modes caused by abnormal situations, since the details of such events can rarely be known in detail. As mentioned a failure in the brake or control system may fall into this category, and also events caused by external factors, such as strikes by lightning, impact of various objects (birds, airplanes, etc.). In many cases the only defense against such events of failure (e.g. causing pieces of rotor blades to be expelled and traveling distances of hundreds of meters) is to site the wind energy converters away from dwellings and areas frequented by many people. This precaution is often easy to fulfill for large, electricity-producing converters, whereas the users of small machines often prefer to have the wind energy converter near to their house or farm. The approach must here be to minimise the risk of external failure causes, and to insist (e.g. by regulations) that the rotor is "failsafe" under all conditions not involving external causes of unknown character. Extreme winds are of course part of the design basis, as are extreme lightning intensities (for which ground-connected rods of sufficient current-carrying potential must be incorporated in the tower and wings).

With respect to the materials problems under the general heading "fatigue", the balance of failsafe construction and economic penalty may be improved by proper inspection techniques, that acknowledge the occurrence of cracks but detect them and allow repair before they lead to failure (Bridson and Worthington, 1980).

Presently, the prime candidates for storage in connection with electricity-producing wind converters are batteries and hydro systems with reservoirs (Sørensen, 1980). These systems may also involve safety hazards, such as dam failures for hydro systems. Approaches to minimizing risk include siting (or re-siting) of dams and significant human settlements in such a way, that no populated area will be flooded in case of dam failure, or alternatively an inspection, warning and evacuating system that will work. Future energy storage forms will have their particular sets of safety-related environmental problems. Hydrogen storage, for instance, may involve a gas explosion risk, that may require a separation of the system, so that the bulk of the hydrogen is stored far from populated areas, and only small amounts are transmitted to the load centers for re-conversion to electric power, e.g. in fuel cells, at any given time.

3. Health hazards

Few health effects are associated with the operation of wind turbines, which does not require use of toxic substances beyond lubrication oils and similar small scale usage of moderately harmful chemicals. Health impact of noise created by wind turbines will be discussed in the following section. The main risks of chemically induced substances of possible toxicity is likely to be associated with the construction phase: use of epoxy and glues in blade manufacture (e.g. glass fibre or laminated wooden materials), dust and chemicals induced into the air during erection of concrete towers, and the health hazards associated with steel manufacture, for steel to be used in transmission and generator parts, as well as for tower and blades in some constructions.

4. Noise

The rotor type wind energy converters may give rise to noise associated with the interaction between the moving and static parts and the wind, as well as mechanical noise in the power transmission and conversion machinery (gear-boxes, generators, etc.). The mechanical noise associated with power transmission may present a health hazard for persons working in the nacelle of large turbines during operation, and to a lesser extent to people on the ground. In the case of noise exposure to the general public, smaller wind energy generators may be of more concern, since they are typically sited close to dwellings, while large converters producing electric power for a general grid system are typically sited at considerable distances from areas occupied by people. In any case, sound insulation of transmission machinery is feasible, and the present standards for occupational and general exposure (which are different in different countries) can be met in all cases. Typical limiting standards are 85-90 dB(A), while recommended guideline noise levels are around 75 dB(A) for an 8 hour working day (Keast, 1978). dB(A) is a measure of noise on a logarithmic (decibel) scale simulating the human perception of noise levels in the audible range by use of a frequency-dependent weighting factor (the "A-filter").

For external noise, i.e. noise experienced by a person on the ground outside the premises of the energy conversion plant, standards recommended are from 70 dB(A) in industrial areas and down to 35 dB(A) for residential and recreational areas during nighttime (Danish Dept. Envir.,1974). The noise from wind turbines must be confined to the night-time values if operated during night. If operation during certain night hours is prohibited, the total energy production decreases, and measures to keep the noise down so that the machine can be operated would usually be economically warranted.

Noise levels not presenting an established health hazard may nevertheless be annoying to people. Fig. 5 gives an impression of intervals of noise levels perceived as "highly annoying" by various percentages of people surveyed in a number of situations. Noise levels that will cause most sleeping people to wake up range from 40 to 90 dB(A), depending on stage of sleep and individual differences. Some ten percent may even wake up from light sleep at brief sounds in the range from 0 to 30 dB(A) (Keast, 1978). Conversation at normal level of voice is possible at a noise level of 40 dB(A) over distances up to 20m. This distance decreases linearly with noise level in dB(A), and reaches zero at 80 dB(A). Prolonged exposure to noise causes a transient (or at worst permanent) increase in the treshold for perceiving sound. For 24 hours exposure at 82 dB(A), the treshold shift as measured two minutes after exposure is 35 dB, and for noise levels above 82 dB(A) for prolonged periods the possibility of acoustic trauma exists (Keast, 1978).

In contrast to the noise caused by mechanical parts of power transport and conditioning, which can be brought below any conceivable standards by proper design, then the noise created by the interaction between the turbine and the wind itself is of a more fundamental character and it cannot be arbitrarily reduced. This "aerodynamic noise" has several components. First there is the static noise caused by the interaction between the wind and the tower and rotor parts even in a condition of no movement. This noise is similar to the one found in connection with all structures or obstacles (houses, trees, masts, etc.), but it may depend strongly on the type of wind converter construction, such as use of large-diameter hollow tower, slender pole-type tower of metal or concrete, with rough or smooth surface, or metal grid tower constructions.

Secondly, noise caused by the motion of the rotor must be considered. It consists in part of noise of frequency equal to the rotational frequency or multiples of this, and in part of broadband noise caused by the interaction between the turbulent component in the wind and the rotor blades. There are several mechanisms linked to the rotational frequency, including the periodic shedding of vortices from the air foils and rotor-tower interactions, particularly if the rotor is placed downwind.

Several measurements of noise levels near existing wind turbines have been performed. At a distance of 50m from a Danish turbine from 1957 (rotor diameter 24m, fixed rotational frequency 30.2 r.p.m.), the aerodynamic noise at a windspeed of 15 m/s was 10 dB higher than the noise level associated with the transmission system (Danish Dept. Energy, 1978). The latter was 50-52 dB(A) due to an inappropriate gear construction. For the more recent US MODO construction (1975), the total noise was found to be 20 dB(A) at the foot of the tower, falling to 10 dB(A) at a distance of 90m (Rogers et al., 1977; Sørensen, 1980b). This machine has a rotor diameter of 37m and a rotational frequency of 40 r.p.m. The noise measurements were performed at wind speeds between 5 and 8 m/s. It is concluded that audible noise is not a problem in connection with large wind generators. For smaller machines near farms or other houses, there would typically be other structures around, which produce aerodynamic noise (e.g. trees), and the main concern would be to keep noise from transmission to an acceptable level.

In many cases, wind turbines create the largest noise intensity outside the audible frequency range. Infrasound, i.e. sound of frequencies lower than the lower limit of human perception, is emitted in association with the vortices shed by the blade tips (and to some extent roots) of a wind turbine rotor. The dominant infrasound contribution, however, is from the interaction of vortices formed by the passage of wind around the tower structure with passing blades, in the case of downwind rotor mounting. For the US MOD0 machine described above, signals in the range 90-100 dB and of frequencies near 1 Hz have been measured close to the turbine (Rogers et al., 1977). For the larger MOD1 machine, which also has the rotor downwind and has a steel lattice tower construction, infrasound intensities at a house located over 500m away has caused annoyance to such an extent, that night-time operation has been restricted. On the other hand, no infrasound problems has occured for the similar size machine at Tvind (Denmark), which has dwellings situated 50-100m away from the turbine, and which is also a downwind machine. This indicates, that tower structure is a major factor in reducing the infrasound intensity. The Tvind machine has a concrete tower with three sections of different diameter, such that the unfolding vortex sheets will interfere and lose coherence after short traveling distances.

The health impacts of infrasound are somewhat different from those of audible noise. Generally speaking, the tresholds for annoyance as well as for health hazards are about 40 dB higher for the frequency range 0.1-5 Hz (Rogers et al., 1977). Thus it should be possible to construct downwind horizontal axis turbines without annoyance problems (as in fact the Tvind machine shows), and of course the problem may be substantially reduced by placing the rotor upwind.

Noise problems are usually addressed in terms of distance between turbine and areas occupied by people. Therefore, it is important to know the mechanisms of sound propagation. While sound propagation in homogeneous air leads to quadratically decreasing intensity with distance, the effects of ground reflection and transmission through obstacles (walls, vegetation, etc.) may substantially modify the propagation. The same is true for inhomogenuity of the atmosphere, such as the one associated with the temperature and wind speed profiles and their changes during time. They usually cause a reflection of sound as if there were a ceiling above the turbine, and more pronounced upwind from the machine than downwind. During nighttime inversions (i.e. positive temperature gradients upwards) this ceiling may disappear. It is clear, that the effect of complex sound transmission may be to establish regions away from the rotor with intensities higher than the one expected from the simple model of propagation in homogeneous air.

In comparison with alternative ways of energy production, the use of wind energy may dramatically reduce the noise production, as for example when replacing a diesel engine by sails in a ship.

5. Interference with telecommunication

Wind energy converters may cause distortion of telecommunication signals, either due to reflections on the structure or due to modulation caused by the electrical properties of moving parts.

Television interference may be discussed in terms of two parameters. One is the scattering cross section or effective area of the turbine blades with respect to scattering of electromagnetic waves. The other one is a treshold modulation or maximum amplitude of the interfering signal, which will be judged as acceptable (Sengupta and Senior, 1978). The interference between the scattered part of the signal and the direct one is responsible for the observed distortion of audio or video reception.

The scattering, which is dominated by specular reflection from the broad face of the blades, corresponds to effective areas of 8-25% of the rotor swept area, depending on blade material. The highest value is for metal blades, the lower one for composite materials such as glass fiber. The effect of adding metal strips to blades made of composite materials, for lightning protection, is of the order of 20% increase in the effective scattering area. These estimates are deduced from measurements performed on the US MOD0 by Sengupta and Senior(1978).

The effect of interference with a rotating object of a given radio or TV signal is an amplitude modulation showing up as a repetitive pulsed distortion. All other things being equal, the amplitude of the modulation increases with frequency, thus being small for FM radio signals and large for the highest (UHF) TV channels. The distortion depends on the directions of turbine blades (e.g., yaw angle) and the relative directions to turbine and sender as seen from the point of reception. The signal path may furthermore be indirect (in mountain regions or due to other obstacles). Measurements performed 150m from the US MOD0 has led to the establishment of a maximum amplitude of the interfering signal as being 2.6 dB (15%) in the most critical direction and for TV channel 50. In other directions or for lower frequencies the modulation treshold is higher. For instance, a value of 16 dB was found for a healthy FM signal (signal to noise ratio over 15 dB).

The aim of the study by Sengupta and Senior was to set standards for calculating the extent of interference zones for a given wind turbine construction. If houses are located within this zone, a feasible solution may be to provide them with cable connections to aerials placed outside the interference zone. This solution has been used by the Danish Department of Energy(1978), which found an interference zone extending to ten rotor diameters from the turbine, for the machine mentioned in section 4 above.

The presence of wind energy converters may interfere with other forms of telecommunication. Examples are the microwave communication links used by the telephone companies and the navigational systems used by commercial aircraft authorities. The analysis of these problems have been addressed by Sengupta and Senior (1978), which in the case of current navigational systems find that the interference is at a maximum when the rotor is not moving, and decreases when the blades are turning.

6. Impact on ecosystem

The impact of wind energy conversion systems on the ecosystem may derive from the extraction of materials used in the construction (e.g. iron mining), from the operation of the converter itself and from other parts of the system, such as transmission and energy storage facilities. Free-stream wind turbines are not particularly intensive in materials use, as compared with other energy conversion equipment. For this reason, no specific discussion of the impact of materials extraction phase will be attempted here.

The operating wind turbine may present a hazard for birds and airborne insects. Some windy sites, e.g. near seashores or large lakes, are also of vital importance for migrating bird species. Migrating songbirds normally fly at an altitude of 150-450m, while waterfoul and shorebirds occupy higher altitudes (Rogers, et al., 1977). Many nocturnal migrant birds have been killed by tall buildings, towers, transmission lines and other structures without moving parts. A major factor is lights, on the obstructing tower or elsewhere, since light may strongly distract certain birds from avoiding collision courses. Experimentation is underway to determine the color and pattern of intermittancy, which will minimise the bird disorientation, e.g. in connection with airplane warning lights on tall structures.

Since wind turbines usually do not extend to heights above 150m, impact probabilities depend on the "tail distribution" of migrating birds being down at low altitudes. In particular, the presence of bird rest areas nearby may highly enhance the risk of passage in the height of the turbine blades.

It is likely, that a stationary wind turbine presents a higher risk than a rotating one, because the birds may sense the motion and take evasive action. A survey around the first US MODO wind turbine (Maximum height about 50m) discovered one case of a bird probably killed by the rotor tower and two probably killed by the nearby meteorological tower. The turbine was not operating during a large fraction of the four migration seasons covered by the study. Bird kills by a 150m cooling tower of a nuclear power plant in the same state mounted to between 44 and 103 per season (Rogers et al., 1977). It would thus appear, that height and solidity are important factors in determining the risk to birds.

The MODO study further investigated the behavior of the birds approaching the turbine. The migration traffic rate ranged from zero (off-season, precipitation) to 10.6 birds per hour and per meter crossed perpendicular to the direction of flight(clear night in spring migration season). The average for a clear night was 3.4 $h^{-1}m^{-1}$. Of a series of birds heading towards the rotating turbine, six out of nine took evasive action and avoided a course penetrating the area swept by the rotor. Three other birds headed on a straight course between the turbine blades, without incidence. This supports the theory, that many birds will sense the danger sufficiently in advance, and further stresses the fact, that the blades of large wind turbines are slowly moving objects, which may not present a hazard even for birds flying between them. This is different for small wind turbines, which if sited in suburban regions may present a danger to garden birds. This study also indicates, that the open nature of the obstacle may give better chances for evasive action than the solid obstacle of the cooling tower mentioned above.

Records of bird killing, e.g. in connection with light towers, has shown very irregular patterns, with the major contribution to total number of kills occuring at years intervals in specific situations of high migration rate, heavy fog or mist and specific wind direction. This situation occurred during the MODO study but no strikes were observed. The migration rate was 4.9 $h^{-1}m^{-1}$ and the turbine was operating during 4 hours.

Flying insect populations were released near the turbine, but no conflict could be deduced (Rogers, et al.,1977).

Thus the possibility of an impact on the ecosystem from the wind turbines themselves seems small. It is therefore conceivable, that the highest potential impact will be associated with the energy storage systems, which would be associated with wind energy systems, either for use far from grid systems or for supplying a major part of the energy in a given system. Likely storage systems could be batteries or pumped hydro installations, or back-up systems regulated in anti-phase with the wind turbines, e.g. hydro turbines or fossil generating systems. Batteries have a limited lifetime, and discarded batteries constitute a form of chemical waste, which must be properly managed, in order that it does not interfere with ecosystems. The environmental problems associated with fuel-based systems are well-known and in fact among the reasons for wanting to introduce renewable energy sources. Thus, the use of fossil generators in a transition period for back-up should be seen in the perspective of a systematically declining fraction of the total energy supply being provided by these fuels.

Hydropower and its use in combination with wind energy conversion is a different problem, because hydro energy is a renewable source which may find permanent place in future energy systems, due to its versatility as storage or back-up for intermittent sources, in particular the short time needed for switching and the reservoir options for truly long-term energy storage. It is therefore very important to keep the environmental impacts of hydro installations in mind, ranging from the effect of sedimentation, dam construction, water table changes on ecosystems, hydrology and evapotranspiration to the safety hazards of dam failure and social impact of land transformation and re-settlement methods.

7. Work environment

The work conditions for operators of wind energy systems are generally good, with respect to variations of tasks and possibility of participation in decision making and function in work groups of modest size. Also repair and maintenance services offer a generally varied and challenging work situation. Typically, one team would be servicing a number of units installed in arrays or more dispersed. A good fraction of the work is likely to be outdoor activities, and some repair work on outside parts of tower or blades may involve unpleasant climbing and high altitude stays possibly under adverse weather conditions. Safety precautions would be similar to those used by scaffold construction workers.

8. Visual environment

The visual impact of wind energy systems are in part from the converters, in part from transmission systems and in part from support facilities such as energy storage. Transmission lines in connection with electricity producing converters may be required in addition to those associated with the transmission of power to load locations. This would be true, if arrays of wind energy converters are placed in high wind areas very far from the power usage regions. Also conventional steam power plants have this problem, because they require large quantities of cooling water and therefore are typically sited at seashores or major rivers, and away from load areas (among other things to reduce impact of pollutants from the fuel-based plants). There is considerable motion to replace overhead transmission lines by underground cables, in populated or recreational areas. The energy storage, if part of the system, also may present a visual impact, such as it is the case for a large dam and the landscape changes induced by hydro reservoir construction.

The wind energy converter itself may possess artistic or functional beauty, as witnessed by many sailships and windmills. The design of modern wind energy converters in some cases has considered this aspect, in other cases not. If large numbers of wind turbines shall become accepted as part of our visual environment, their design and incorporation in the physical surroundings are important factors. Several studies have been made or are on the way, which assess the visual impact of wind turbine arrays in considerable depth. Figs. 6-9 gives an example of such a study (Birk Nielsen, 1980). 161 wind energy converters have been placed in arrays near the Baltic coast of Denmark(Fig.6), on reclaimed land presently used for agriculture. This land use would not be altered by the wind turbines, assumed to have a rotor diameter of 50m and a minimum spacing of 7 rotor diameters. Fig. 7 indicate four positions and view angles in the area, from which the visual impact of the turbines have been illustrated in Figs. 8 and 9. The conclusion is that wind energy converters have a substantial impact on the landscape, but that this impact need not be negative. It can indeed help to underline the characteristics of the landscape.

Siting of wind turbines at sea has also been considered, partly in order to minimize the discussion of visual impact, but more seriously in order to take advantage of better wind conditions at sea, and to be able to utilize wind energy in cases, where land areas are so densely populated that no suitable sites can be found.

9. Microclimatic impact

Concern could be raised for microclimatic modifications in the region surrounding wind energy converters. The energy extraction is of course connected with a slowing down of the wind, which may lead to changed precipitation and evapotranspiration patterns downwind, and conceivably to changes in temperature and concentration of minor atmospheric constituents as well.

The optimum energy extraction is in a simple theoretical model, considering only streamwise flow, achieved for a windspeed reduction downwind from the rotor to a third of the incident windspeed (see e.g. Sørensen, 1979). Usually, the windspeed reduction is not uniform over the area corresponding to the rotor swept disc. The incident wind profile, i.e. windspeed as function of height, is also not uniform, but may approximately be described as a logarithmic or power law profile. Measurements have been performed in a number of cases, on model wind turbines in a wind tunnel (in order to achieve incident wind conditions independent of time) and on actual machines. Fig. 10 gives an example of the measured vertical profile, before and at various stages after the passage through the turbine area. The data are from a wind tunnel experiment (Alfredsson et al., 1980). It is observed that initially, there is no modification of windspeed near the ground, but that after a while, during the restoration of the profile around hub height, energy is transferred into the region behind the rotor from below as well as from above. Still, the decrease in windspeed 4-8 rotor diameters behind the turbine is very modest near the ground. This may be taken as an indication, that changes in microclimate, which is sensitive mostly to conditions very close to the ground, will be very small.

This picture has been confirmed by actual measurements at the US MOD0 (Rogers et al., 1977). Within 0.75 rotor diameter of the machine a 5% rainfall deficit has been deduced, in cases where the rotor is not operating. The deficit decreases and almost disappears when the rotor is turning. No significant variations were observed in air temperature, concentration of carbon dioxide, and the reduction in windspeed had generally disappeared 2-3 rotor diameters away. It is expected that this distance would be smaller for field measurements than for wind tunnel experiments, due to the natural variability of the free wind, which tends to make it impossible to distinguish wake effects from the stochastic fluctuations in the natural wind regime.

If it is permitted to extrapolate the above results, the indication would be, that even for extended arrays of wind turbines spaced perhaps as close as 5-10 rotor diameters apart, there would be no significant microclimate changes, and use of the land areas between the wind energy converters, e.g. for agricultural purposes, would not be affected by the presence of the wind converter arrays.

This conclusion is likely to hold only for simple free-stream rotors. There have been proposals of a number of socalled "advanced" wind energy conversion systems, which are all designed to concentrate the wind energy flux from a large area into a smaller area, where they can be utilized e.g. by a turbine (although this is not the only method proposed). The concentration of wind power and potential for a large energy extraction in a small region may change the conclusions concerning microclimatic impact. Should any of these advanced concepts pass from the research stage into a stage of possible practical utilization, a specific study of the microclimate impacts would be called for.

10. Global climatic influence

Wind energy utilization would have to be on a truly large scale before global climate impacts could be imagined. This is because the formation and dissipation of wind energy is part of the solar energy cycle and driven by the very strong forces associated with the differential solar heating of the atmosphere and the induced physical requirement for poleward transport of energy. However, the fraction of solar energy needed to maintain the general circulation in the atmosphere is very small. It is estimated to average 1.2 x 10^{15}W (see e.g. Sørensen, 1980) or 0.7% of the solar radiation at the top of the atmosphere. This equals the amount of kinetic energy in air motion lost by friction, and in an equilibrium situation also the amount of new kinetic energy created on the basis of "available energy", i.e. potential and internal (heat) energy than can be converted into motion as a result of pressure and temperature differences in the atmosphere. It thus also equals the rate of formation of new "available energy" by absorption of solar radiation. The equilibrium value of total kinetic energy in the atmosphere is in this model estimated at 7.7 x 10^{20}J, while the equilibrium value of "available energy" is 2.8 x 10^{21}J (Lorenz, 1967).

Energy extraction by wind conversion devices may be represented as an increase in the frictional loss of kinetic energy. The total human energy conversion today is over two orders of magnitude lower than the 1.2 x 10^{15}W frictional loss, so the wind energy utilization really has to be large in order to significantly increase this number. In this case a new equilibrium may establish itself, with the transfer rates equal to the elevated frictional loss. The equilibrium values of total kinetic and available energy will then change, but a detailed atmospheric model is required for estimating the amount of change, taking into account changes in horizontal as well as vertical energy transport in the atmosphere, as function of geographical position and height.

11. Summary

Most of the environmental impacts of wind energy conversion at a level which could be reached in the forseeable future can be meaningfully assessed. Considering first the converter alone, it is evident from the short survey made above, that the impact in most areas would be considerably less than that of current energy systems, compared on a basis of equal energy production. The impacts that do exist are also generally of a different nature than the pollution and radioactivity risks associated with conventional alternatives. Generally the impacts of wind energy conversion are not associated with long latent periods or small probability-large consequence events.

It is true that the experience, particularly with large-size units, is only a few converter-years. This may have special relevance for the accident risk, where mishaps associated with prototype units may have to happen, before adequate regulative standards can be enforced. Again, at this stage the consequences of such accidents are modest, and no long-range effects are involved.

With respect to environmental impacts of transmission and energy storage systems, these are common to all energy systems, but are of course often proportional to the amount of storage and transmission needed for each system. Wind energy systems are likely to require slightly more transmission capacity than current systems, but only for massive penetration of wind in the energy systems will substantial amounts of storage be required (Sørensen, 1979). In many region the storage needed for large-scale utilization of wind energy can be provided by hydro power systems already available. (Sørensen, 1980) In this case no additional environmental impacts are introduced, but of course the burden of relieving such impacts (i.e. the costs) should be shared by the wind and hydro systems.

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Figure captions

Fig. 1. Man working in nacelle of Tvind turbine during construction in 1978 (the Tvind wind energy converter, erected at Ulfborg, Denmark, has a rotor diameter of 56m)

Fig. 2. Tower failure of commercial wind energy converter in the 20 kW range.

Fig. 3. Calculated amplitudes of flap and lag during one revolution, with and without tower shadow (Kottapalli et al., 1978)

Fig. 4. Cross-wind rotor (for residential heating) mounted in atrium yard of one-family dwelling at Skive, Denmark (Team KUDU)

Fig. 5. Summary of 12 social surveys of noise annoyance (based on Keast, 1978)

Fig. 6. Siting proposal for 161 wind turbines (indicated by dots) near Rødby, Denmark

Fig. 7. View angles for the illustrations in Figs. 8 and 9, The area is identical to the one in Fig. 6

Fig. 8. Visual impact of wind converter array, as viewed from angle 1 (upper part) and 2 (lower part) of Fig. 7 (Birk Nielsen, 1980)

Fig. 9. Visual impact of wind converter array, as viewed from angle 3 (upper) and 4(lower) of Fig. 7 (Birk Nielsen, 1980)

Fig. 10. Wind profile modification by wind turbine, based on wind tunnel measurements. Abscissa: Wind speed relative to the one at top of wind tunnel. Ordinate: Height relative to hub height, taken equal to rotor diameter. Curve a is profile upwind from rotor, curves b,c and d are profiles 2,4 and 8 rotor diameters downwind from rotor (based on Alfredsson et al., 1980)

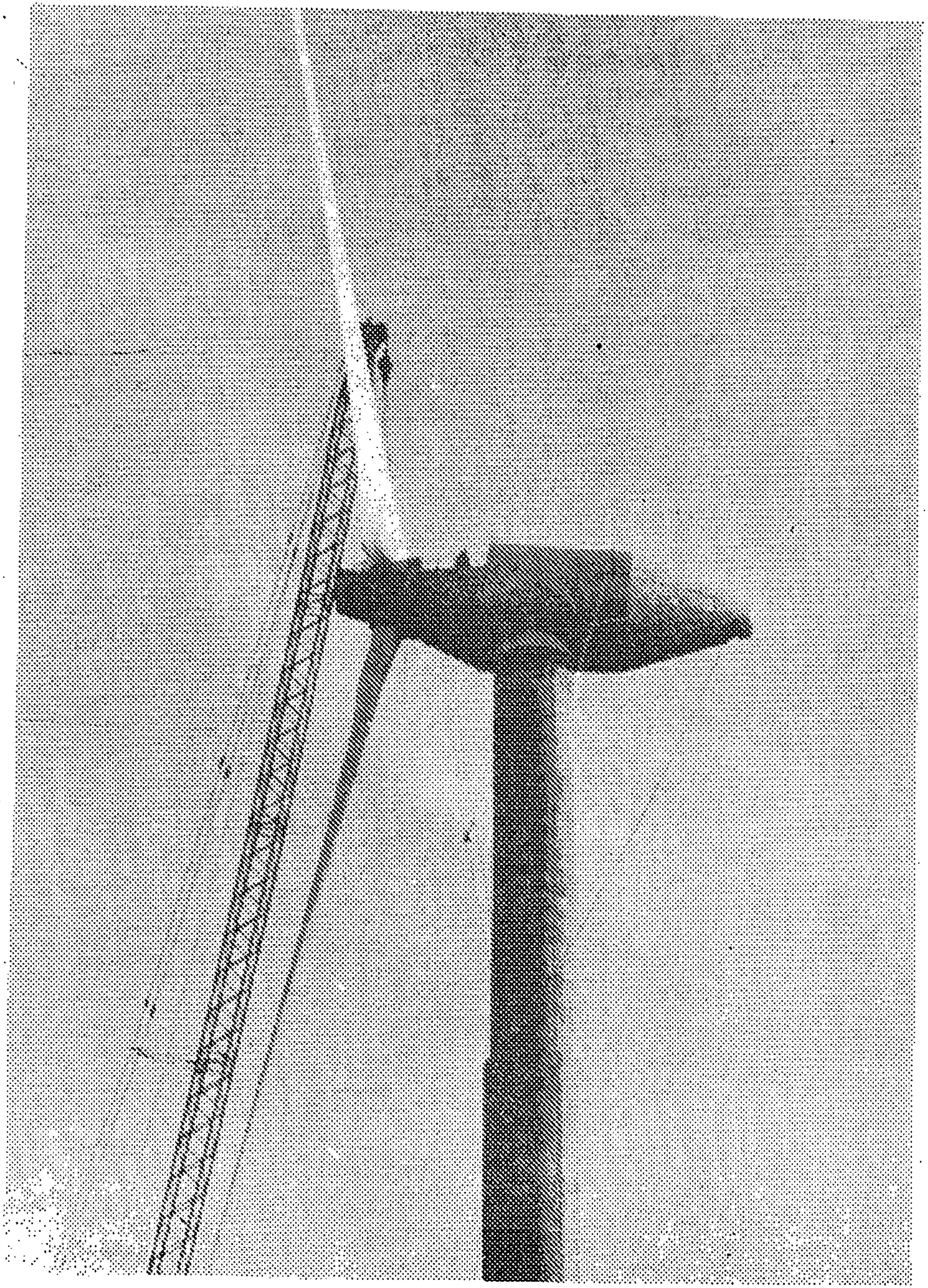


FIG 1

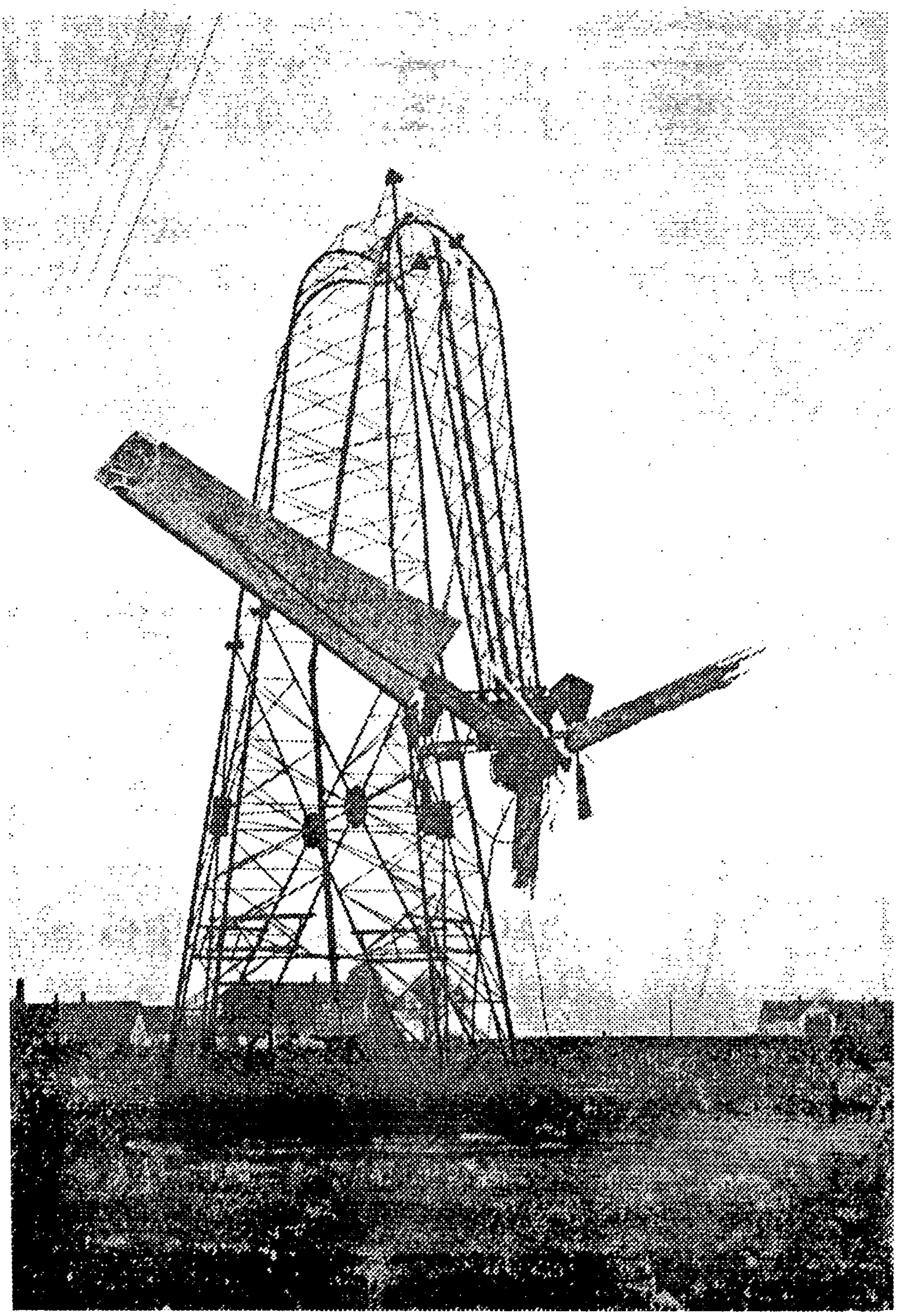
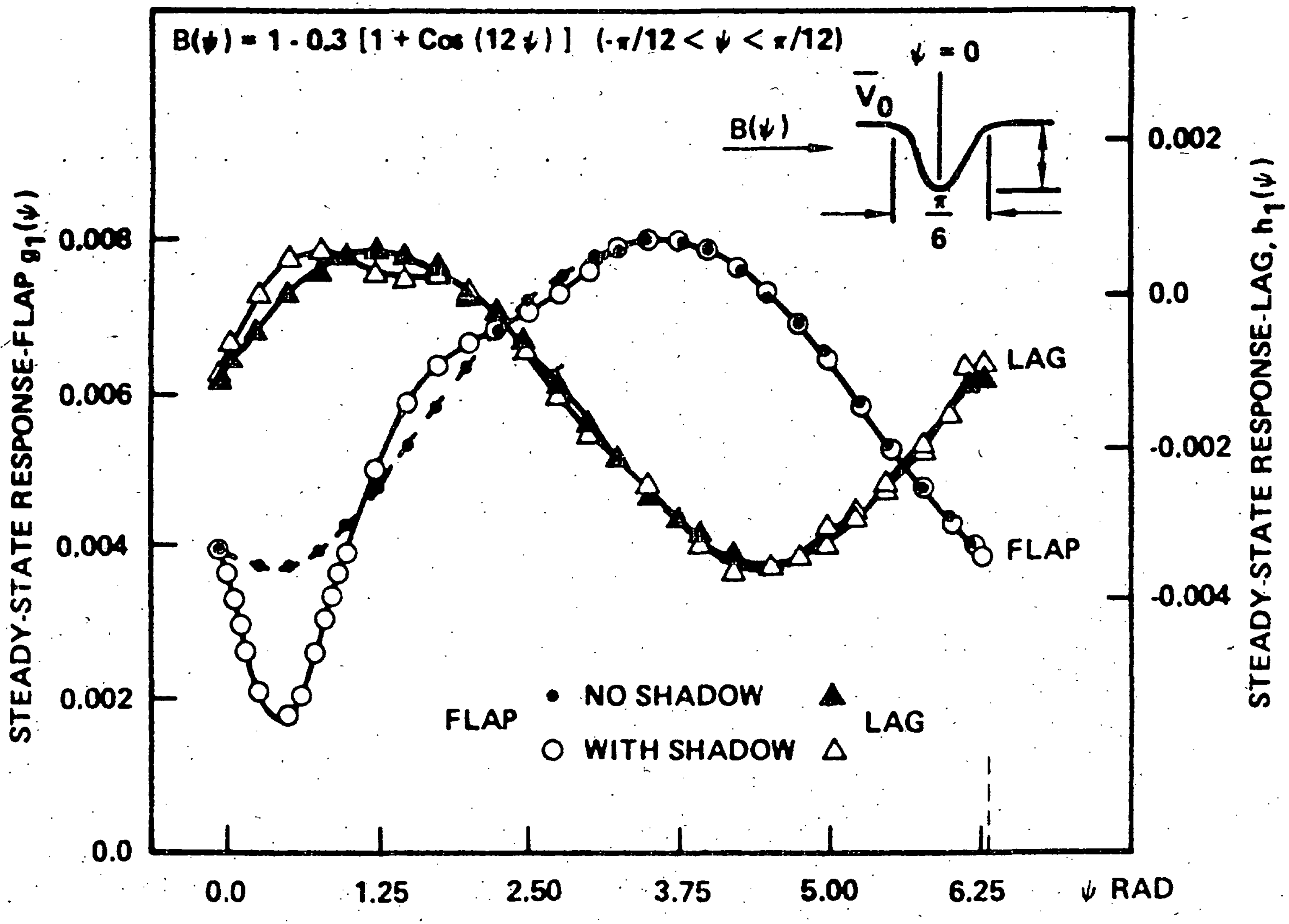


FIG 2



B(ψ) = 1 - 0.3 [1 + Cos (12ψ)] (-π/12 < ψ < π/12)
ψ = 0
$\overline{V}_0$
B(ψ)
π/6
STEADY-STATE RESPONSE-FLAP g1(ψ)
0.008
0.006
0.004
0.002
0.0
STEADY-STATE RESPONSE-LAG, h1(ψ)
0.002
0.0
-0.002
-0.004
LAG
FLAP
FLAP
● NO SHADOW
○ WITH SHADOW
▲
△
LAG
0.0
1.25
2.50
3.75
5.00
6.25
ψ RAD

FIG 3

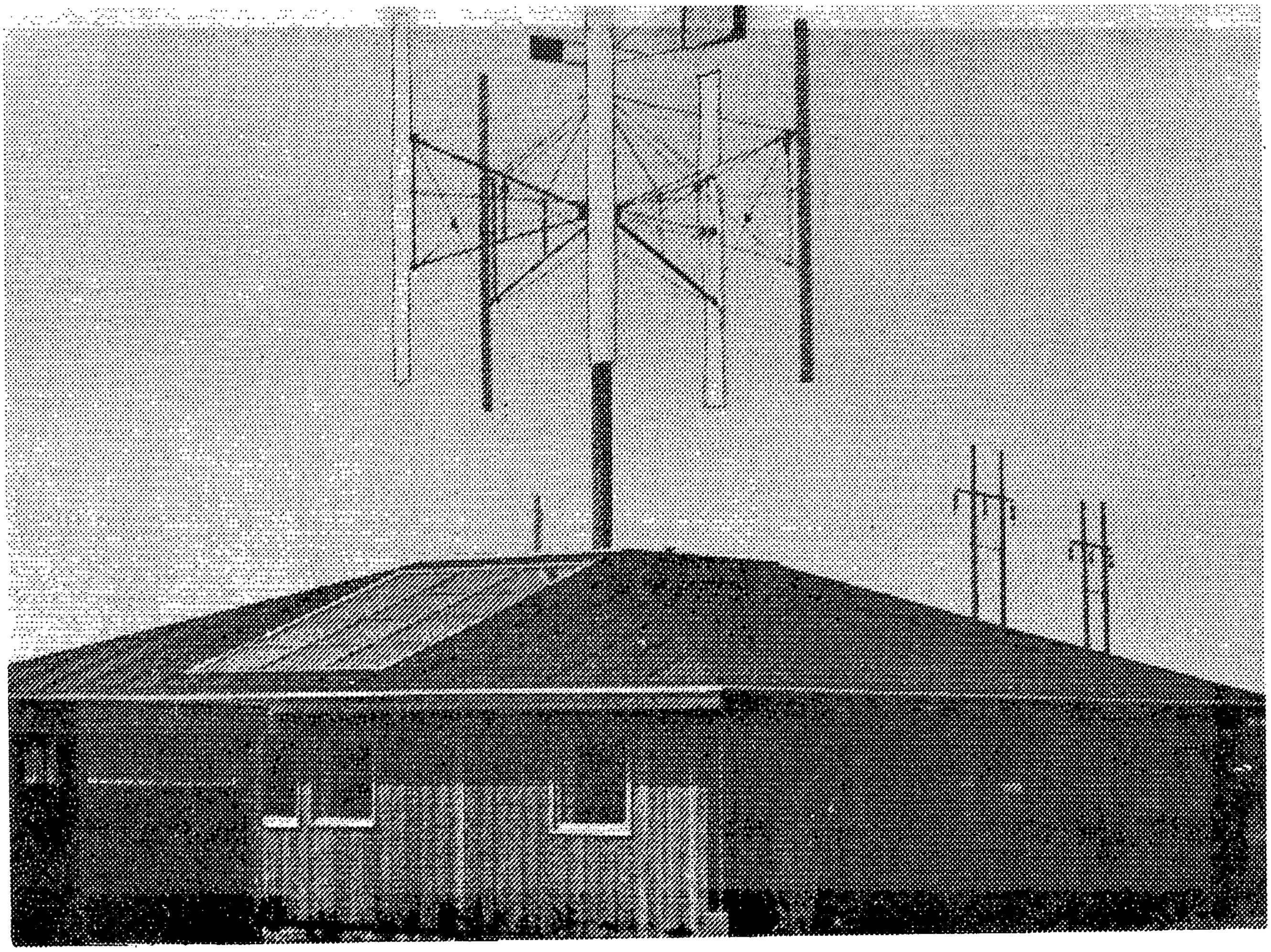
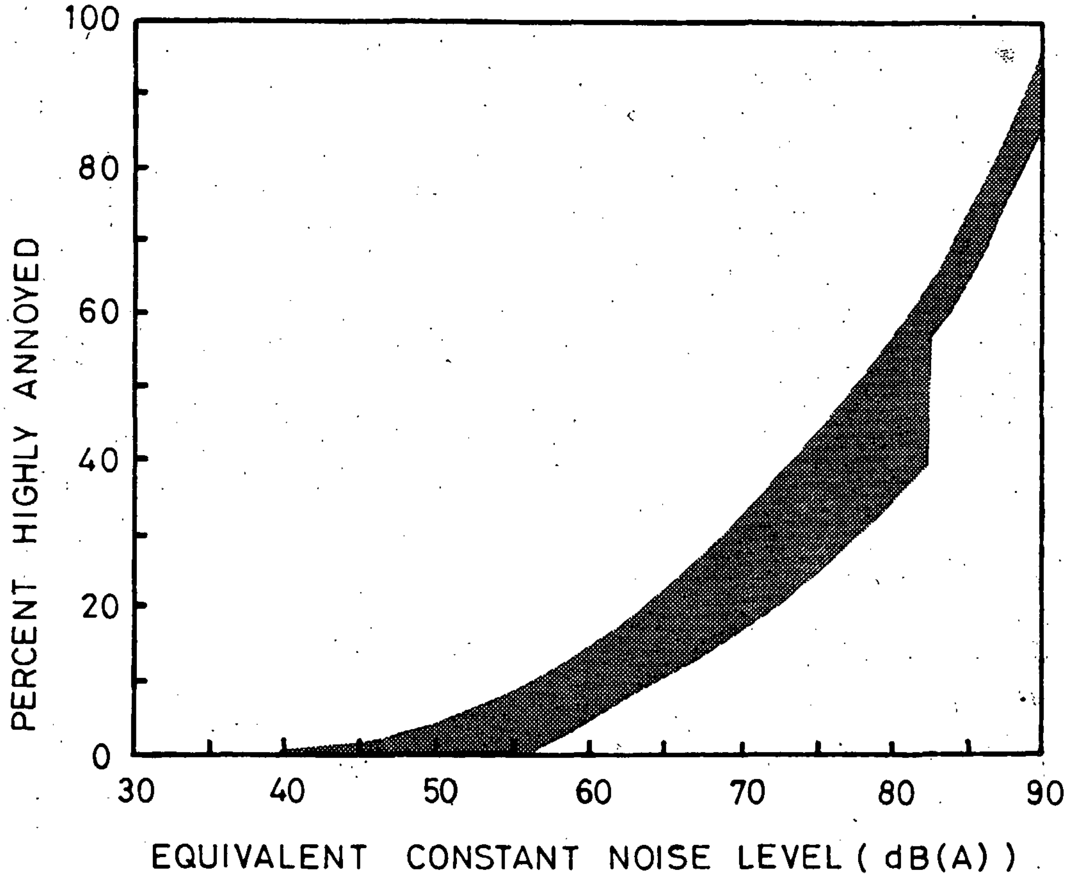
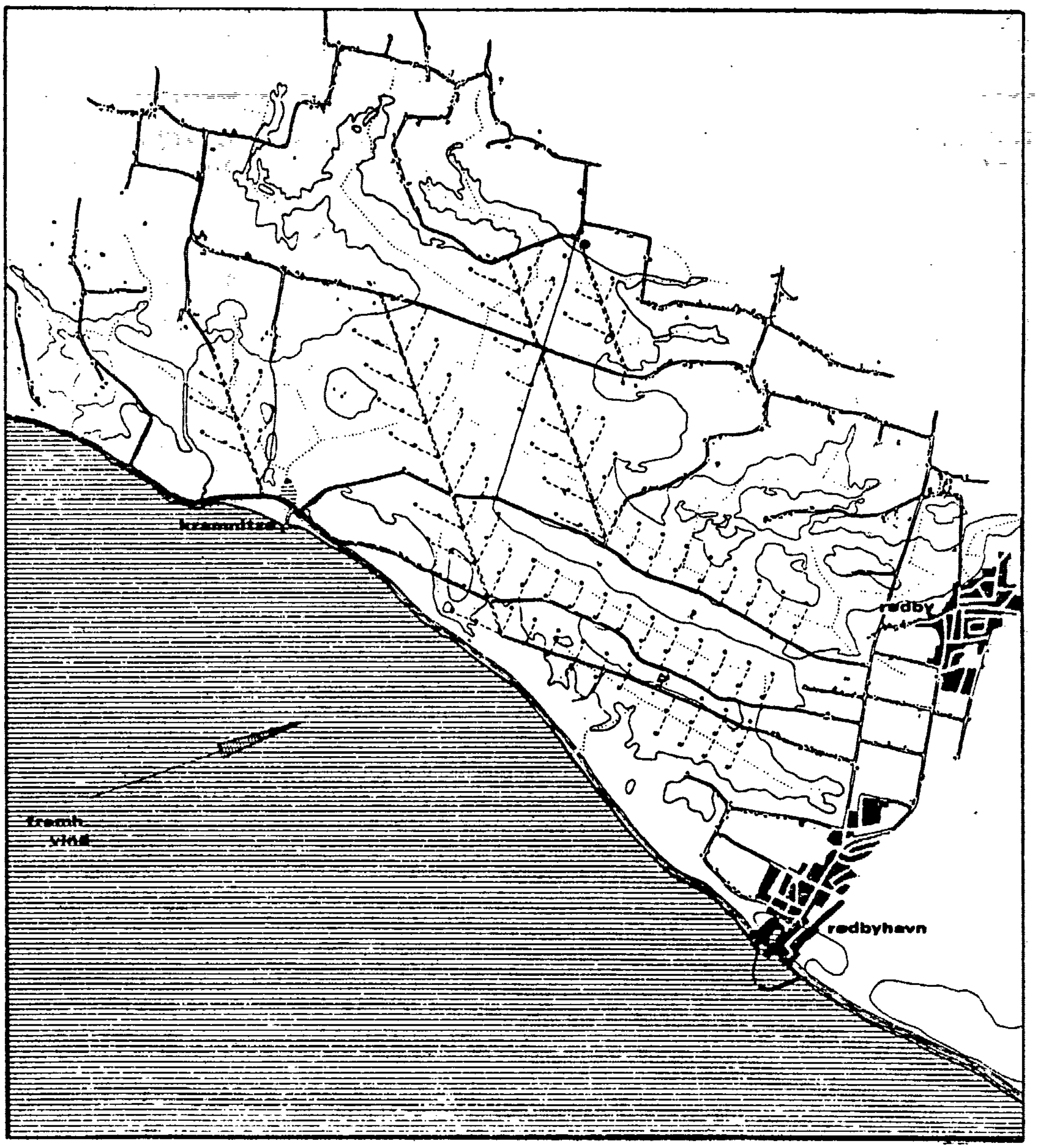


FIG 4



100
80
60
40
20
0
PERCENT HIGHLY ANNOYED
30
40
50
60
70
80
90
EQUIVALENT CONSTANT NOISE LEVEL (dB(A))

FIG 5



1:75.000.

FIG 6

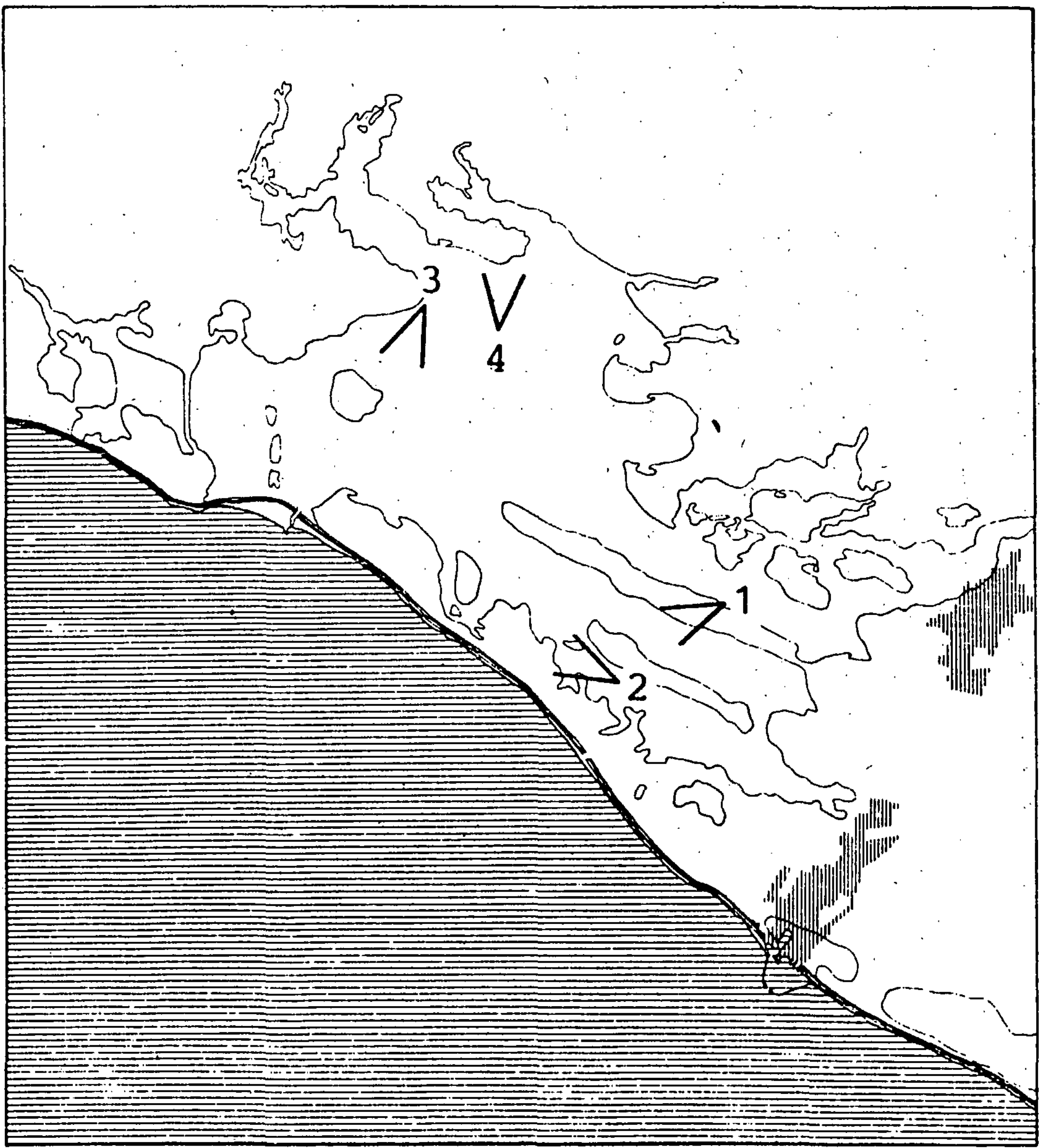


FIG 7

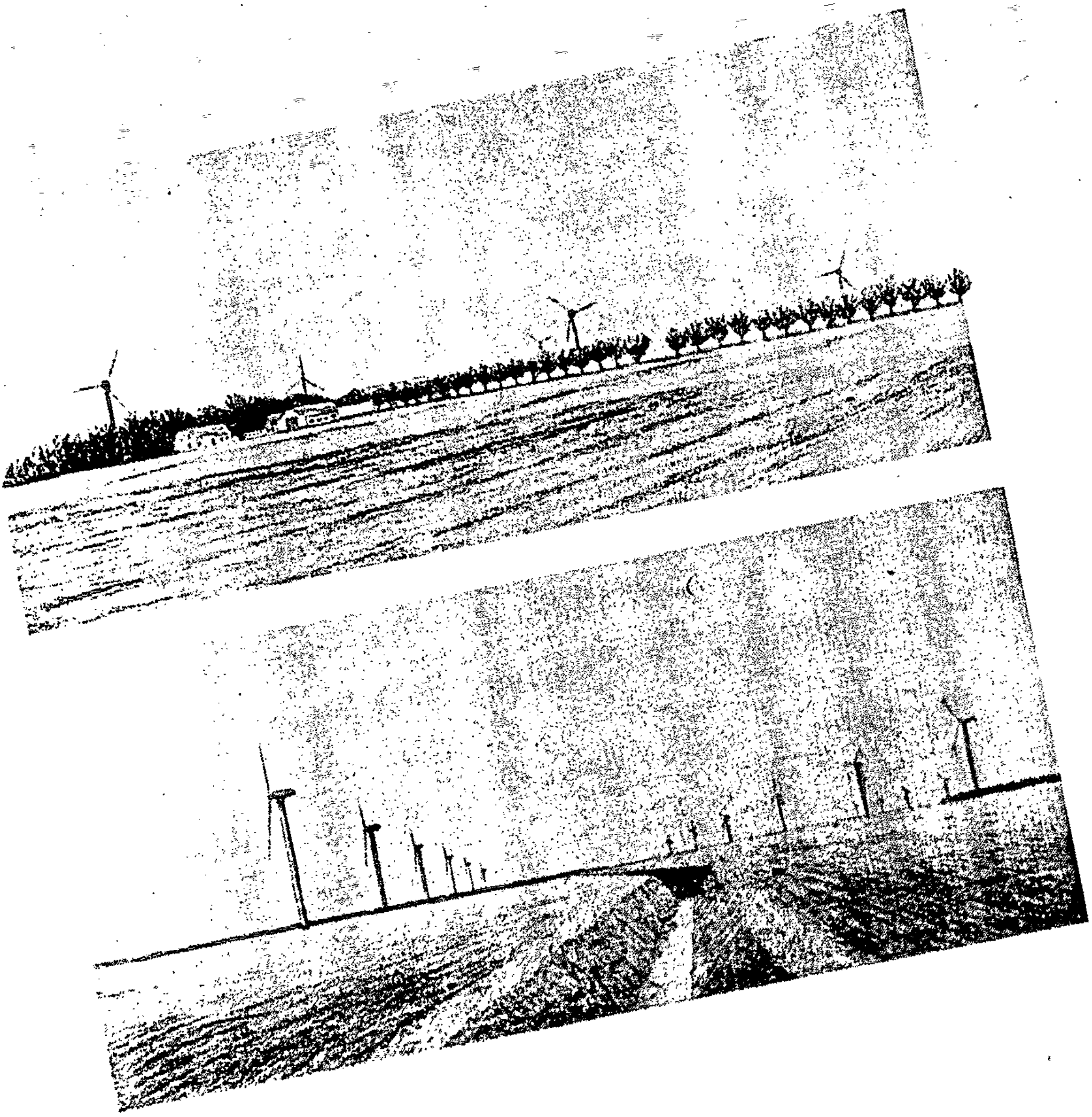


FIG 8

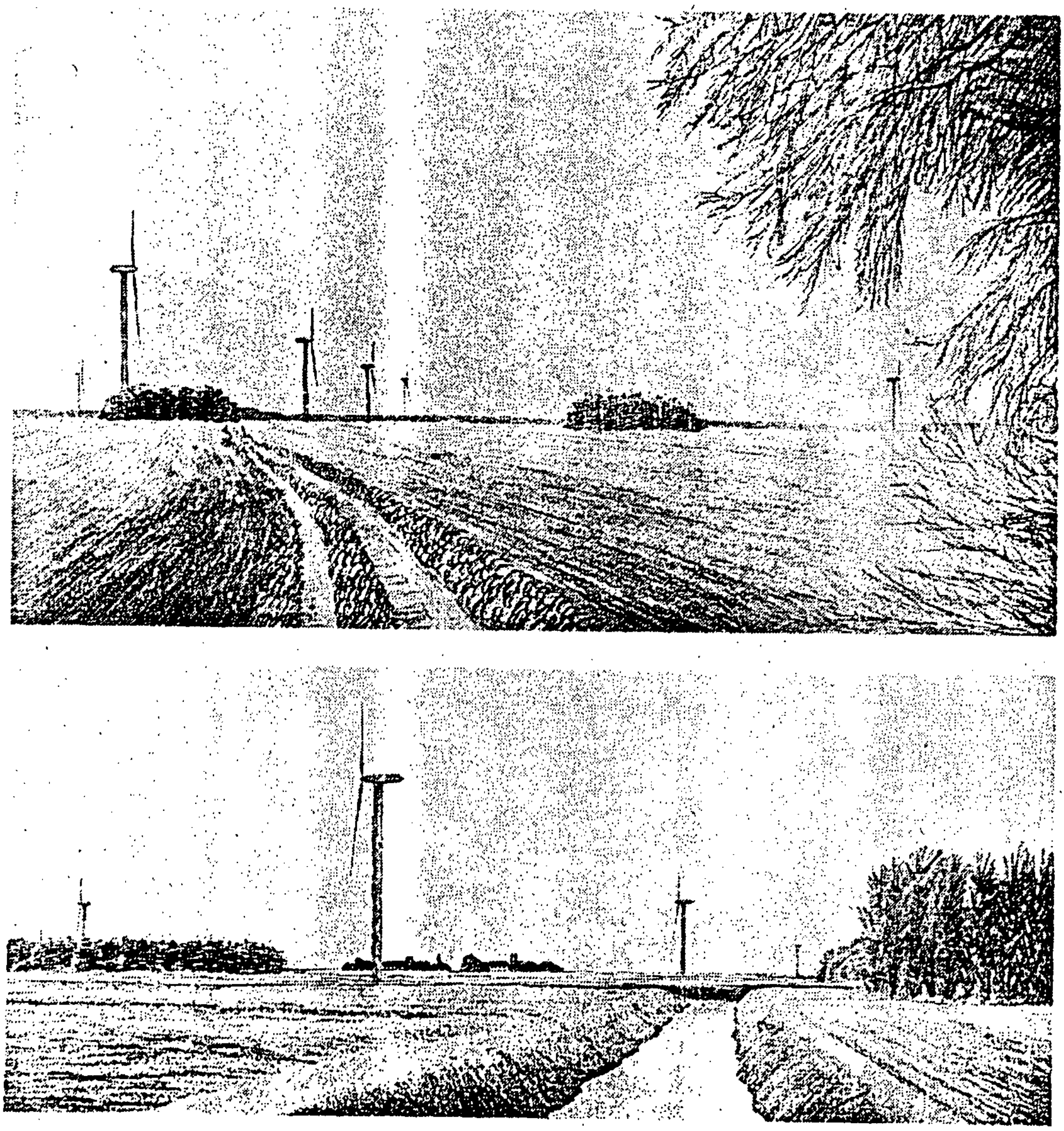


FIG 9

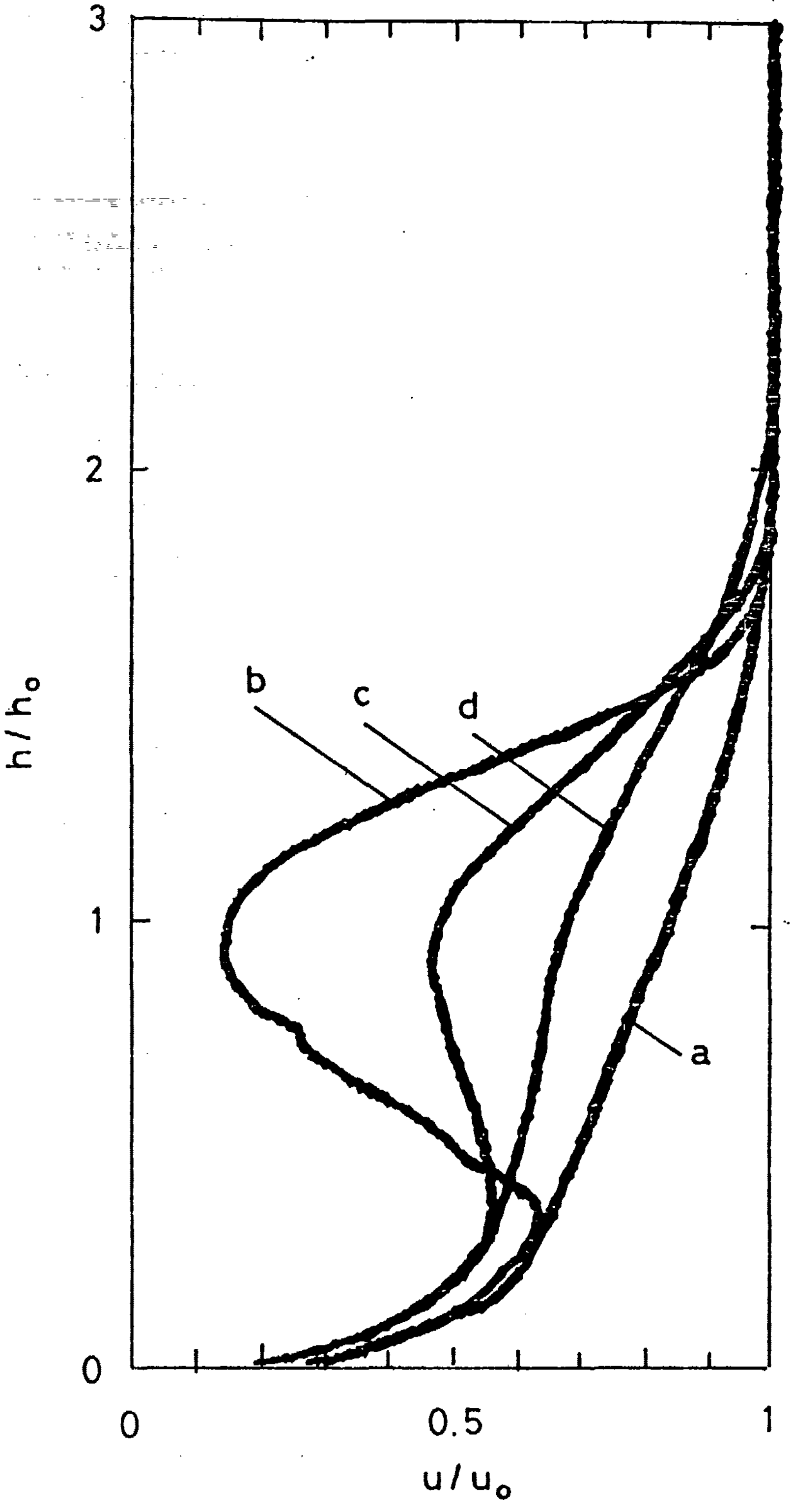


FIG 10

TEKSTER fra IMFUFA Roskilde universitetscenter.

1/78 "TANKER OM EN PRAKSIS" - et matematikprojekt
Anne Jensen, Marianne Kesselhahn, Lena Lindenskov og Nicolai Lomholt.
Vejleder: Anders Madsen.

2/78 "OPTIMERING" - Menneskets forøgede beherskelsesmuligheder af natur og samfund.
Projektrapport af Tom J. Andersen, Tommy R. Andersen, Gert Kreinøe og
Peter H. Lassen. Vejleder: Bernhelm Booss

3/78 "Opgavesamling", breddekursus i fysik.
Lasse Rasmussen, Aage Bonde Kræmmer, Jens Højgaard Jensen.

4/78 "Tre essays" - om matematikundervisning, matematiklæreruddannelsen og
videnskabsrindalismen.
Mogens Niss.

5/78 "BIBLIOGRAFISK VEJLEDNING til studiet af DEN MODERNE FYSIKS HISTORIE"
Helge Kragh.

6/78 "Nogle artikler og debatindlæg om - læreruddannelse og undervisning i fysik,
og - de naturvidenskabelige fags situation efter studenteroprøret"
Karin Beyer, Jens Højgaard Jensen, Bent C. Jørgensen.

7/78 "Matematikkens forhold til samfundsøkonomien"
B.V. Gnedenko.

8/78 "DYNAMIK OG DIAGRAMMER". Introduktion til energy-bond-graph formalismen.
Peder Voetmann Christiansen.

9/78 "OM PRAKSIS' INDFLYDELSE PÅ MATEMATIKKENS UDVIKLING"
Motiver til Kepler's: "Nova Stereometria Doliorum Vinarioum"
Projektrapport af Lasse Rasmussen.
Vejleder: Anders Madsen.

10/79 "TERMODYNAMIK I GYMNASIET"
Projektrapport af Jan Christensen og Jeanne Mortensen
Vejledere: Karin Beyer og Peder Voetmann Christiansen.

11/79 "STATISTISKE MATERIALER"
red. Jørgen Larsen.

12/79 "Lineære differentialligninger og differentialligningssystemer"
Mogens Brun Heefelt.

13/79 "CAVENDISH'S FORSØG I GYMNASIET". Projektrapport af Gert Kreinøe.
Vejleder: Albert Chr. Paulsen.

14/79 "Books <u>about</u> Mathematics: History, Philosophy, Education, Models, System
Theory, and Works of Reference etc. A Bibliography".
Else Høyrup.

15/79 "STRUKTUREL STABILITET OG KATASTROFER i systemer i og udenfor
termodynamisk ligevægt". Specialeopgave af Leif S. Striegler.
Vejleder: Peder Voetmann Christiansen.

../.

16/79 "STATISTIK I KRÆFTFORSKNINGEN". Projektrapport af Michael Olsen og Jørn Jensen.
Vejleder: Jørgen Larsen.

17/79 "AT SPØRGE OG AT SVARE i fysikundervisningen"
Albert Christian Paulsen.

18/79 "MATHEMATICS AND THE REAL WORLD", Proceedings of an International Workshop, Roskilde university centre (Denmark), 1978. Preprint.
Bernhelm Booss & Mogens Niss (eds.).

19/79 "GEOMETRI, SKOLE OG VIRKELIGHED".
Projektrapport af Tom J. Andersen, Tommy R. Andersen og Per H.H. Larsen.
Vejleder: Mogens Niss.

20/79 "STATISTISKE MODELLER TIL BESTEMMELSE AF SIKRE DOSER FOR CARSINOGENE STOFFER".
Projektrapport af Michael Olsen og Jørn Jensen.
Vejleder: Jørgen Larsen.

21/79 "KONTROL I GYMNASIET - FORMÅL OG KONSEKVENSER".
Projektrapport af Crilles Bacher, Per S. Jensen, Preben Jensen og Torben Nysteen.

22/79 "SEMIOTIK OG SYSTEMEGENSKABER (1)". 1-port lineært response og støj i fysikken.
Peder Voetmann Christiansen.

23/79 "ON THE HISTORY OF EARLY WAVE MECHANICS - with special emphasis on the role of relativity".
Helge Kragh.

24a/80 "MATEMATIKOPFATTELSER HOS 2.G'ERE" 1. En analyse.
24b/80 "MATEMATIKOPFFATTELSE HOS 2.G'ERE" 2. Interviewmateriale.
Projektrapport af Jan Christensen og Knud Lindhardt Rasmussen.
Vejleder: Mogens Niss.

25/80 "EKSAMENSOPGAVER" Dybdemodulet/fysik 1974-79.

26/80 "OM MATEMATISKE MODELLER". En projektrapport og to artikler.
Jens Højgaard Jensen m.fl.

27/80 "METHODOLOGY AND PHILOSOPHY OF SCIENCE IN PAUL DIRAC's PHYSICS"
Helge Kragh.

28/80 "DIELEKTRISK RELAXATION - et forslag til en ny model bygget på væskernes viscoelastiske egenskaber".
Projektrapport, speciale i fysik, af Gert Kreinøe.
Vejleder: Niels Boye Olsen.

29/80 "ODIN - undervisningsmateriale til et kursus i differentailligningsmodeller"
Projektrapport af Tommy R. Andersen, Per H.H.Larsen og Peter H. Lassen.
Vejleder: Mogens Brun Heefelt.

30/80 "FUSIONSENERGIEN - - - ATOMSAMFUNDETS ENDESTATION".
Oluf Danielsen.

31/80 "VIDENSKABSTEORETISKE PROBLEMER VED UNDERVISNINGSSYSTEMER BASERET PÅ MÆNGDELÆRE"
Projektrapport af Troels Lange og Jørgen Karrebæk.
Vejleder: Stig Andur Pedersen.

32/80 "POLYMERE STOFFERS VISCOELASTISKE EGENSKABER - BELYST VED HJÆLP AF MEKANISKE IMPEDANSMÅLINGER OG MÖSSBAUEREFFEKTMÅLINGER".
Projektrapport, speciale i fysik, af Crilles Bacher og Preben Jensen.
Vejledere: Niels Boye Olsen og Peder Voetmann Christiansen.

33/80	"KONSTITUERING AF FAG INDEN FOR TEKNISK-NATURVIDENSKABELIGE UDDANNELSER: I-II." Arne Jakobsen.
34/80	"ENVIRONMENTAL IMPACT OF WIND ENERGY UTILIZATION". ENERGY SERIES NO.1. Bent Sørensen.
35/80	"HISTORISKE STUDIER I DEN NYERE ATOMFYSIKS UDVIKLING". Helge Kragh.
36/80	"HVAD ER MENINGEN MED MATEMATIKUNDERVISNINGEN ?" Fire artikler. Mogens Niss.
37/80	"RENEWABLE ENERGY AND ENERGY STORAGE". ENERGY SERIES NO.2. Bent Sørensen.