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CHERNOBYL ACCIDENT: ASSESSING THE DATA

ENERGY SERIES NO. 15

by Bent Sørensen

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Abstract: *Data presented in the official Soviet report to the IAEA on the Chernobyl reactor accident are critically assessed. Special attention is given to the derivation of release fractions from fallout measurements, a procedure which is demonstrated to involve large elements of uncertainty. Further comments relate to estimates of plume rise and deposition velocity. A comparison is made with the predictions of previously published theoretical reactor safety studies.*

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The first comprehensive Soviet report on the Chernobyl accident[1] estimates that noble gasses plus 3.5±1.75% of the remaining core inventory escaped to the environment. The isotopic composition of the release is reproduced in Table 1. The report states that total release for each isotope has been obtained on the basis of integrated fallout data for the entire European territory of the Soviet Union. Neither primary nor regionally aggregated fallout data are presented in the report. It is of interest to assess the accuracy of this procedure for estimating the total release fractions, by performing the same kind of integration for the measured fallout outside the Soviet territory. National data have been collected and published by the WHO[2].

Figures 1 and 2 show the results of applying this procedure for the two significant isotopes ^{131}I and ^{137}Cs. National data are reported to the WHO in somewhat different formats, involving in some cases incremental fallout between successive days and in other cases only accumulated values. In some cases, fallout data have already been averaged over a number of regional measuring stations. The spot values included in Figures 1 and 2 represent accumulated values for single locations or locally averaged data. All data have been corrected for radioactive decay, so that they pertain to the time of the accident start, 26. April 1986 at 1:24h local time.

The isotopic deposition data have been further averaged over each 10 deg latitude by 20 deg longitude quadrant, and integrated. Figures 1 and 2 give integrated values for each quadrant and for the entire area outside the Soviet Union. The latter estimate is 10^{18} Bq of ^{131}I and 6×10^{16} Bq of ^{137}Cs. The corresponding values for the Soviet territory, similarly referred back to the accident start, are 742×10^{15} Bq of ^{131}I and 37×10^{15} Bq of ^{137}Cs. Thus the Soviet estimate of the total release fraction for iodine and cesium may be low by a factor of two or more.

The deposition estimates are uncertain at each step of the calculation: a) The local data may not be representative. b) The measuring stations are not uniformly spaced and thus the integration without any weight factor describing the density of measurements may be biased. c) Similarly, the large scale quadrant averaging may conceal areas without data, which might have altered the integrated totals if such data had been available.

By considering the spot data of Figures 1 and 2 as being representative for smaller and larger regions around the measurement location, the totals for deposition outside the Soviet Union can be made to range from about 5 times less than the quoted values to about twice these values.

This indicates that the sampling of areas underlying the estimates of Figures 1 and 2 might have involved a bias in the upward direction for the total fallout outside the Soviet Union. There are no reasons for assuming that the uncertainties involved in the intra-Soviet evaluation have been any smaller than the ones described above. If the Soviet handling of their fallout data involved a downward bias for the totals, then the true ratio between fallout outside and inside the Soviet Union could be smaller than the value near unity found in this study.

In all these cases, the combined fallout within and outside the Soviet Union would be considerably larger than the release values estimated by the Soviet report[1], indicating that the correct release fraction could be about twice the one quoted in the Soviet report, or 7% of the core minus noble gases.

Comparing Chernobyl releases and reactor safety studies

Along with the Soviet estimates of accumulated fractions of the reactor core inventory, which escaped to the atmosphere during the first 10 days of the Chernobyl accident[1], Table 1 shows the accident category that would be assigned to the accident on the basis of release fractions, by the Rasmussen study[3] and by the Birkhofer study[4], both pertaining to light water reactors (PWRs or BWRs). In other words, the model category indicated for each reactor safety model study is the one calculated to give rise to release fractions similar to those observed (or rather those inferred from the Soviet fallout data, as discussed above). For different isotope groups, Chernobyl is seen to correspond to one among the 3 most severe accident categories, except for the Chernobyl release of plutonium and other actinides, which exceeds the worst possible case in the reactor safety studies by a factor 10.

The possible upwards revision of the release fractions discussed above would for some isotope groups move the accident up to the next, more severe accident category.

The duration of the radioisotope release at Chernobyl was longer than expected, and the rate of decay heat release correspondingly lower. However, the burning of 250 t of graphite over 10 days gave an average heat release of about 8.5 MW, similar to that of 'category 2' accidents in Table

1.

The frequency of accidents with radionuclide releases similar to those from Chernobyl is estimated to be about one in a million reactor-years (Birkhofer study[4]) and up to ten in a million reactor-years (Rasmussen study[3]). The reactor study accidents with releases similar to those from Chernobyl all involve core meltdown. The Soviet report[1] concludes, based on its own model calculations, that the temperature was never high enough for the core to melt. Yet the radionuclide release fractions strongly suggest that a level of core degradation similar to a meltdown must have occurred. This conclusion is also reached by other recent studies, one on the basis of the analysis of "hot spot" particles observed in Sweden[5], the other by interpreting the origin of ^{110m}Ag fallout in Holland and elsewhere[6].

Plume rise, dispersion and deposition of radioactivity

Following the Chernobyl accident, radioactive depositions and activity in air have been measured in all parts of Europe and at some locations outside Europe. The WHO summary of these data were used in Figures 1 and 2. In order to understand the atmospheric transport and deposition pattern, model calculations have been performed[7-9]. These serve not only to test the model assumptions, but also allows estimation of fallout in areas where observations are missing. If the models compare well with measurements in the regions where measurements have been performed, the model results for other regions gain credibility. The model efforts published so far do exhibit a general resemblance to the data, but no detailed agreement.

Reasons for the discrepancies are to be sought in the poor knowledge of the source term, particularly as regards the detailed time dependence of the release. The models used are trajectory models, which under the meteorological conditions prevailing during the critical periods of the accident exhibit strong sensitivity to the 'effective height' of the release (plume rise), to timing of the release sequence, and to deposition velocities for wet and dry deposition on surfaces of varying roughness.

Plume rise. The model of Briggs and Gifford[10] predicts a transitional plume rise (i.e. disregarding the initial jet stage/explosion) comprising a momentum, a buoyancy and a radioactivity part. In the first hour, each of these parts would in isolation lead to predicted plume rises of 200-600 m, 1200 m and about 50 m, respectively. In obtaining these estimates, a source area of 300 m^2, an initial vertical plume velocity of $(0.14\ \Delta T)^{1/2}$ ms^{-1} and an average wind speed of 5 ms^{-1} have been assumed. The release temperature increase ΔT (relative to ambient) has been taken from a calculation made in the Soviet report[1]. It starts at 1500 deg, declines to 600 deg but then rises sharply to 1900 deg on the sixth day, after which it slowly diminishes. The combined plume rise of 1000-1500 m is dominated by the effect of the burning graphite.

The Soviet report indicates a measured plume height exceding 1200 m on the second day, but claims that it diminished to below 400 m the following days. Although the lower part of the plume may have been close to the ground at this time (as suggested by measurements of sharply rising dose rates in the nearby town of Pripyat[1]), the much higher altitudes implied by continuing graphite burning appear consistent with the pattern of transport of radioactivity to other parts of Europe[7-9].

A part of the plume could have reached still higher altitudes, notably during the initial, explosive release, and later because of variations in discharge rate ('bursts'), low wind velocities or exceptionally stable atmospheric conditions that allow plume rise to continue beyond the assumed 1 h period. Indeed, a tail of the plume must have reached heights above 5000 m in order to account for the observed fallout in Japan and in the USA[7].

Deposition. Dry and wet (rain-related) deposition rates are in most model calculations determined by a single parameter each. For dry deposition it is the ratio of the deposition rate and the radionuclide concentration in air. This number v_d is found in experiments to depend strongly on particle size[11,12]. The Chernobyl data should provide new information on v_d and particle size spectrum. Outside the USSR, data from Southern UK[13] lead to values of $v_d = 3 \times 10^{-3}$ ms^{-1} for ^{131}I and $v_d = 4 \times 10^{-4}$ ms^{-1} for ^{137}Cs, which would suggest particles of diameter below 1 µm (the reactor safety studies[3,4] both used $v_d = 10^{-2}$ ms^{-1}). Spherical particles of diameter around 1 µm were in Sweden found in 'hot spot' fallout of unusual composition[5]. Generally, one expects larger particles to deposit closer to the release point. Unfortunately, the Soviet report does not disclose figures that would allow the deposition velocity closer to Chernobyl to be extracted.

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Table 1 Chernobyl radionuclide release fractions, and the accident category of two reactor safety studies, predicted to give releases similar to those observed. The lowest category number generally corresponds to the most severe accident. Also indicated are release characteristics and calculated accident frequencies.

Isotope group	Chernobyl[1]	Birkhofer[4]	Rasmussen[3]	
Xe-Kr	1	FK1-4	PWR1	BWR1
I-Br	0.20	FK2	PWR3	BWR1
Cs-Rb	0.10-0.13	FK2	PWR3	BWR1-3
Te-Sb	0.15	FK2	PWR3	BWR2-3
Ba-Sr	0.04-0.056	FK1-2	PWR2	BWR1-2
Ru-Mo	0.023-0.029	FK1-2	PWR1-2	BWR3
Ce	0.023-0.028	10×FK1	10×PWR1	6-10×BWR1
Pu, Cm, Np	0.030-0.032			
Release duration(h)	240	1-3	0.5-3	2-3
Heat release(MW)	8.5	150 (FK1)	150 (PWR1)	40 (BWR1)
		4 (FK2)	50 (PWR2)	9 (BWR2)
Calculated probability ($10^{-6}y^{-1}$)		2 (FK1)	0.9 (PER1)	1 (BWR1)
		0.6 (FK2)	8 (PWR2)	6 (BWR2)
			4 (PWR3)	20 (BWR3)

Figure captions

Fig. 1 Summary of ^{131}I fallout measurements^{2}. The data have been accumulated and referred back to accident start on 26. April 1986 (i.e. disregarding decay). Unit: 10^{3}Bq m^{-2}. Boldface numbers indicate area integrated values for each quadrant. Unit: 10^{15} Bq. Their uncertainty is considerable.

Fig. 2 Same as Fig. 1 but for ^{137}Cs.

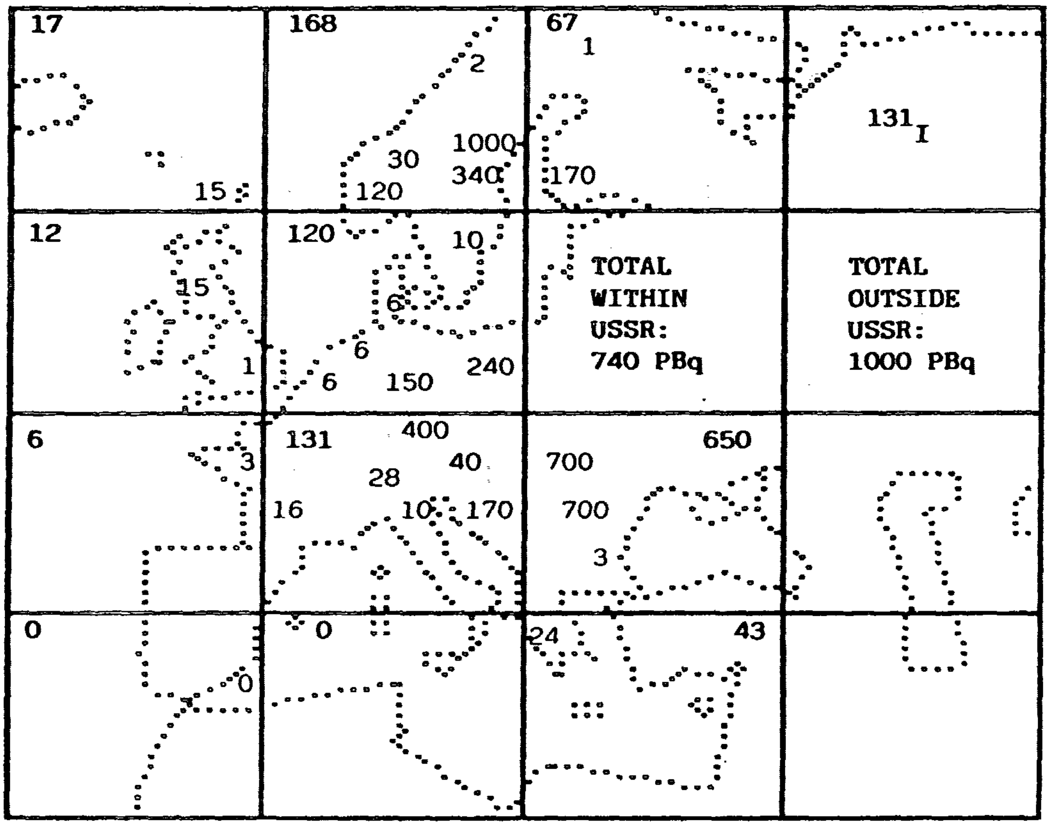
17
15
168
2
30
1000
340
120
67
1
170
131I
12
15
1
120
10
6
6
6
150
240
TOTAL WITHIN USSR: 740 PBq
TOTAL OUTSIDE USSR: 1000 PBq
6
3
131
400
40
28
16
10
170
700
650
700
3
0
0
0
24
43

Fig. 1

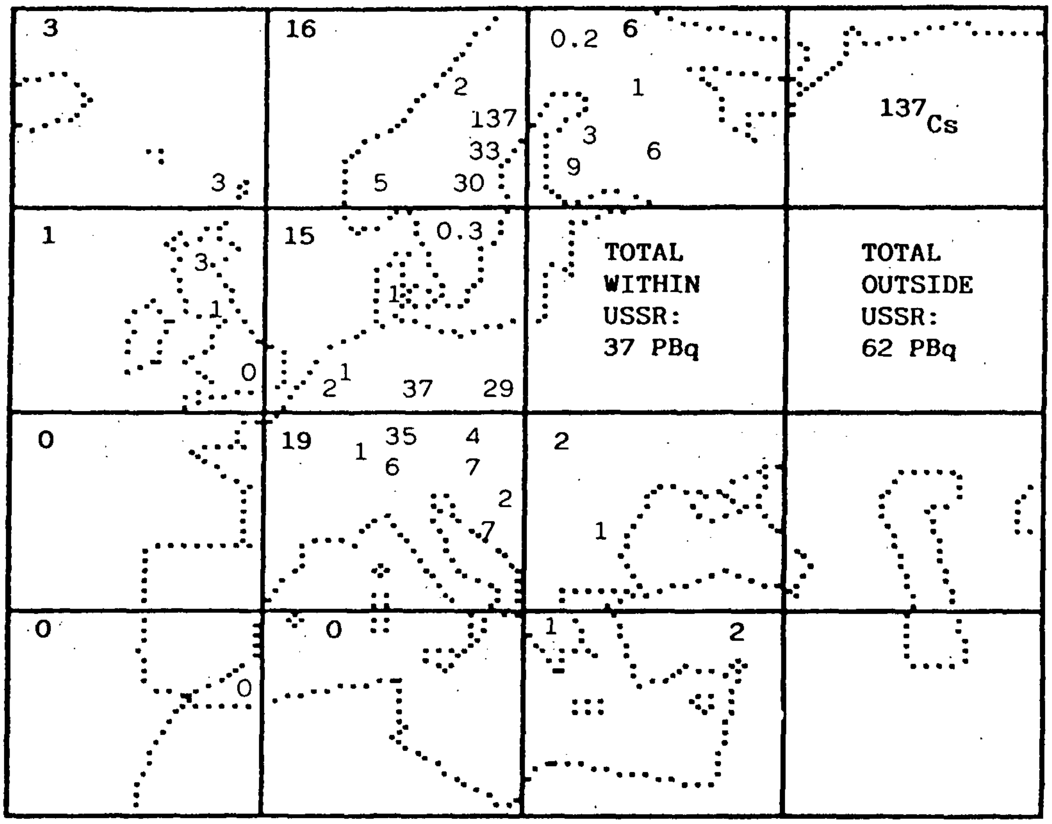
3
3
16
2
137
33
5
30
0.2
6
1
3
9
6
^{137}Cs
1
3
1
0
15
0.3
1
2
1
37
29
TOTAL WITHIN USSR: 37 PBq
TOTAL OUTSIDE USSR: 62 PBq
0
19
1
35
6
4
7
2
7
2
1
0
0
0
1
2

Fig. 2

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Projektrapport af: Hanne Lisbet Andersen, Torben J. Andreasen, Svend Åge Houmann, Helle Glerup Jensen, Keld Fl. Nielsen, Lene Vagn Rasmussen.
Vejleder: Klaus Grünbaum og Anders Hede Madsen.

71/83 "PIGER OG FYSIK"
- et problem og en udfordring for skolen?
Af: Karin Beyer, Sussanne Blegaa, Birthe Olsen, Jette Reich og Mette Vedelsby.

72/83 "VERDEN IFØLGE PEIRCE" - to metafysiske essays, om og af C.S Peirce.
Af: Peder Voetmann Christiansen.

73/83 ""EN ENERGIANALYSE AF LANDBRUG"
- økologisk contra traditionelt.
ENERGY SERIES NO. 9
Specialeopgave i fysik af: Bent Hove Jensen.
Vejleder: Bent Sørensen.

74/84 "MINIATURISERING AF MIKROELEKTRONIK" - om videnskabeliggjort teknologi og nytten af at lære fysik.
Projektrapport af: Bodil Harder og Linda Szkotak Jensen.
Vejledere: Jens Højgaard Jensen og Bent C. Jørgensen.

75/84 "MATEMATIKUNDERVISNINGEN I FREMTIDENS GYMNASIUM"
- Case: Lineær programmering.
Projektrapport af: Morten Blomhøj, Klavs Frisdahl og Frank Mølgaard Olsen.
Vejledere: Mogens Brun Heefelt og Jens Bjørneboe.

76/84 "KERNEKRAFT I DANMARK?" - Et høringssvar indkaldt af miljøministeriet, med kritik af miljøstyrelsens rapporter af 15. marts 1984.
ENERGY SERIES No. 10
Af: Niels Boye Olsen og Bent Sørensen.

77/84 "POLITISKE INDEKS - FUP ELLER FAKTA?"
Opinionsundersøgelser belyst ved statistiske modeller.
Projektrapport af: Svend Åge Houmann, Keld Nielsen og Susanne Stender.
Vejledere: Jørgen Larsen og Jens Bjørneboe.

78/84 "JÆVNSTRØMSLEDNINGSEVNE OG GITTERSTRUKTUT I AMORFT GERMANIUM".
Specialrapport af: Hans Hedal, Frank C. Ludvigsen og Finn C. Physant.
Vejleder: Niels Boye Olsen.

79/84 "MATEMATIK OG ALMENDANNELSE".
Projektrapport af: Henrik Coster, Mikael Wennerberg Johansen, Povl Kattler, Birgitte Lydholm og Morten Overgaard Nielsen.
Vejleder: Bernhelm Booss.

80/84 "KURSUSMATERIALE TIL MATEMATIK B".
Af: Mogens Brun Heefelt.

81/84 "FREKVENSAFHÆNGIG LEDNINGSEVNE I AMORFT GERMANIUM".
Specialerapport af: Jørgen Wind Petersen og Jan Christensen.
Vejleder: Niels Boye Olsen.

82/84 "MATEMATIK - OG FYSIKUNDERVISNINGEN I DET AUTOMATISEREDE SAMFUND".
Rapport fra et seminar afholdt i Hvidovre 25-27 april 1983.
Red.: Jens Højgaard Jensen, Bent C. Jørgensen og Mogens Niss.

83/84 "ON THE QUANTIFICATION OF SECURITY":
PEACE RESEARCH SERIES NO. I
Af: Bent Sørensen
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84/84 "NOGLE ARTIKLER OM MATEMATIK, FYSIK OG ALMENDANNELSE".
Af: Jens Højgaard Jensen, Mogens Niss m. fl.

85/84 "CENTRIFUGALREGULATORER OG MATEMATIK".
Specialerapport af: Per Hedegård Andersen, Carsten Holst-Jensen, Else Marie Pedersen og Erling Møller Pedersen.
Vejleder: Stig Andur Pedersen.

86/84 "SECURITY IMPLICATIONS OF ALTERNATIVE DEFENSE OPTIONS FOR WESTERN EUROPE".
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Af: Bent Sørensen.

87/84 "A SIMPLE MODEL OF AC HOPPING CONDUCTIVITY IN DISORDERED SOLIDS".
Af: Jeppe C. Dyre.

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89/84 "FJERNVARMEOPTIMERING".
Af: Bjarne Lillethorup og Jacob Mørch Pedersen.

90/84 "ENERGI I 1.G - EN TEORI FOR TILRETTELÆGGELSE".
Af: Albert Chr. Paulsen.

91/85 "KVANTETEORI FOR GYMNASIET".
1. Lærervejledning
Projektrapport af: Biger Lundgren, Henning Sten Hansen og John Johansson.
Vejleder: Torsten Meyer.

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Projektrapport af: Biger Lundgren, Henning Sten Hansen og John Johansson.
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Af: Peder Voetmann Christiansen.

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Projektrapport af: Morten Blomhøj, Klavs Frisdahl og Frank M. Olsen.
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Af: Bjarne Lilletorup.
Vejleder: Bent Sørensen.

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Af: Jeppe C. Dyre.

98/85 "VALGMULIGHEDER I INFORMATIONSALDEREN".
Af: Bent Sørensen.

99/85 "Der er langt fra Q til R".
Projektrapport af: Niels Jørgensen og Mikael Klintorp.
Vejleder: Stig Andur Pedersen.

100/85 "TALSYSTEMETS OPBYGNING".
Af: Mogens Niss.

101/85 "EXTENDED MOMENTUM THEORY FOR WINDMILLS IN PERTURBATIVE FORM".
Af: Ganesh Sengupta.

102/85 OPSTILLING OG ANALYSE AF MATEMATISKE MODELLER, BELYST VED MODELLER OVER KØERS FODEROPTAGELSE OG - OMSÆTNING".
Projektrapport af: Lis Eilertzen, Kirsten Habekost, Lill Røn og Susanne Stender.
Vejleder: Klaus Grünbaum.

103/85 "ØDSLE KOLDKRIGERE OG VIDENSKABENS LYSE IDEER".
Projektrapport af: Niels Ole Dam og Kurt Jensen.
Vejleder: Bent Sørensen.

104/85 "ANALOGREGNEMASKINEN OG LORENZLIGNINGER".
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105/85 "THE FREQUENCY DEPENDENCE OF THE SPECIFIC HEAT AF THE GLASS TRANSITION".
Af: Tage Christensen.

"A SIMPLE MODEL AF AC HOPPING CONDUCTIVITY".
Af: Jeppe C. Dyre.
Contributions to the Third International Conference on the Structure of Non - Crystalline Materials held in Grenoble July 1985.

106/85 "QUANTUM THEORY OF EXTENDED PARTICLES".
Af: Bent Sørensen.

107/85 "EN MYG GØR INGEN EPIDEMI".
- flodblindhed som eksempel på matematisk modellering af et epidemiologisk problem.
Projektrapport af: Per Hedegård Andersen, Lars Boye, CarstenHolst Jensen, Else Marie Pedersen og Erling Møller Pedersen.
Vejleder: Jesper Larsen.

108/85 "APPLICATIONS AND MODELLING IN THE MATEMATICS CURRICULUM" - state and trends -
Af: Mogens Niss.

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Projektrapport af: Mikael Wennerberg Johansen, Poul Katler og Torben J. Andreasen.
Vejleder: Jørgen Larsen.

110/85 "PLANNING FOR SECURITY".
Af: Bent Sørensen

111/85 "JORDEN RUNDT PÅ FLADE KORT".
Projektrapport af: Birgit Andresen, Beatriz Quinones og Jimmy Staal.
Vejleder: Mogens Niss.

112/85 "VIDENSKABELIGGØRELSE AF DANSK TEKNOLOGISK INNOVATION FREM TIL 1950 - BELYST VED EKSEMPLER".
Projektrapport af: Erik Odgaard Gade, Hans Hedal, Frank C. Ludvigsen, Annette Post Nielsen og Finn Physant.
Vejleder: Claus Bryld og Bent C. Jørgensen.

113/85 "DESUSPENSION OF SPLITTING ELLIPTIC SYMBOLS 11".
Af: Bernhelm Booss og Krzysztof Wojciechowski.

114/85 "ANVENDELSE AF GRAFISKE METODER TIL ANALYSE AF KONTIGENSTABELLER".
Projektrapport af: Lone Biilmann, Ole R. Jensen og Anne-Lise von Moos.
Vejleder: Jørgen Larsen.

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Vejleder: Bent Sørensen

118/85 "TILFÆLDIGHEDEN OG NØDVENDIGHEDEN IFØLGE PEIRCE OG FYSIKKEN".
Af: Peder Voetmann Christiansen

119/86 "DET ER GANSKE VIST - - EUKLIDS FEMTE POSTULAT KUNNE NOK SKABE RØRE I ANDEDAMMEN".
Af: Iben Maj Christiansen
Vejleder: Mogens Niss.

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Af: Jørgen Larsen

121/86 "SIMULATION I KONTINUERT TID".
Af: Peder Voetmann Christiansen.

122/86 "ON THE MECHANISM OF GLASS IONIC CONDUCTIVITY".
Af: Jeppe C. Dyre.

123/86 "GYMNASIEFYSIKKEN OG DEN STORE VERDEN".
Fysiklærerforeningen, IMFUFA, RUC.

124/86 "OPGAVESAMLING I MATEMATIK".
Samtlige opgaver stillet i tiden 1974-jan. 1986.

125/86 "UVBY,β - systemet - en effektiv fotometrisk spektralklassifikation af B-,A- og F-stjerner".
Projektrapport af: Birger Lundgren.

126/86 "OM UDVIKLINGEN AF DEN SPECIELLE RELATIVITETSTEORI".
Projektrapport af: Lise Odgaard & Linda Szkotak Jensen
Vejledere: Karin Beyer & Stig Andur Pedersen.

127/86 "GALOIS' BIDRAG TIL UDVIKLINGEN AF DEN ABSTRAKTE ALGEBRA".
Projektrapport af: Pernille Sand, Heine Larsen & Lars Frandsen.
Vejleder: Mogens Niss.

128/86 "SMÅKRYB" - om ikke-standard analyse.
Projektrapport af: Niels Jørgensen & Mikael Klintorp.
Vejleder: Jeppe Dyre.

129/86 "PHYSICS IN SOCIETY"
Lecture Notes 1983 (1986)
Af: Bent Sørensen

130/86 "Studies in Wind Power"
Af: Bent Sørensen