JERZY HERDZIK, Assoc.Prof, D.Sc., M.E.
Gdynia Maritime University
ANDRZEJ BALCERSKI, Prof., D.Sc., M.E.
Gdańsk University of Technology
Polish Naval University, Gdynia

A method for determination of fuel oil consumption savings by stepwise differentiating loads on ship diesel engines running in parallel

SUMMARY

In the paper presented is a method for determination of the savings in fuel oil consumption of ship diesel engines co-operating with a common ship electric network, which result from differentiation of their loads and application of a step-by-step load changing method. If fuel oil consumption characteristics of particular diesel engines as well as an operational load distribution histogram are known, it is possible to assess savings in fuel oil consumption of the engines in question.

INTRODUCTION

During operation of ship diesel engines different forms of their fuel consumption characteristics, as well as further differentiating of the characteristics with time is observed [1 , 2]. In the case of the engines running in parallel the load sharing by using the stepwise differentiating of the loads may appear favourable from the point of view of total fuel oil consumption [3]. The principles of the method were presented in the previous issue of this journal.

PRINCIPLES OF THE METHOD OF STEP-BY-STEP DIFFERENTIATING ENGINE'S LOADS

The princples consist in :

- linear interpolation of fuel oil consumption between set points on fuel oil consumption characteristics
- determination of fuel oil consumption increments in the above mentioned intervals for all engines of a given power system
- choice of a number of operating engines for an assumed load, and next choice of a group of engines, complying with the condition of the lowest fuel oil consumption
- distribution of load among cooperating engines in accordance with the following principle : an appropriate load is added onto the engine whose fuel oil consumption increase is the lowest, and an appropriate load is removed from the engine whose fuel oil consumption increase is the greatest.

The schematic diagrams explaining the way of differentiating loads on two engines working in parallel under increasing load are given in Fig.1. In a given load increment interval the increment is taken over by the engine whose ratio of the increment of fuel oil consumption and the increment of load is lower. When approaching the total rated load the loads applied to particular engines become closer and closer to each other.

Such differentiating is possible only within the partial load range. In Fig.1c presented are values of differentiated loads put on the engines as well as the hypothetical savings in fuel oil consumption, ΔB, resulting from the load differentiation.

METHOD FOR DETERMINATION OF FUEL OIL CONSUMPTION SAVINGS

The assessment of fuel oil consumption savings can concern both absolute and relative values. The following is necessary to determine such values :

- absolute values of savings in fuel oil consumption of the engines being elements of a given power system working in a determined state of operation, obtained with application of the load differentiation method
- total fuel oil consumption of the system's engines working in this state of operation, determined without application of the load differentiation method.

In order to determine absolute values of savings in fuel oil consumption of the engines with application of the method it is necessary to know :

- values of the fuel oil consumption savings ΔB_j for an assumed number of load intervals ΔN_j or dN_j within the operational load range of the considered set of engines, $[N_{min}, N_{max}]$. They are determined as the difference between the total fuel oil consump-

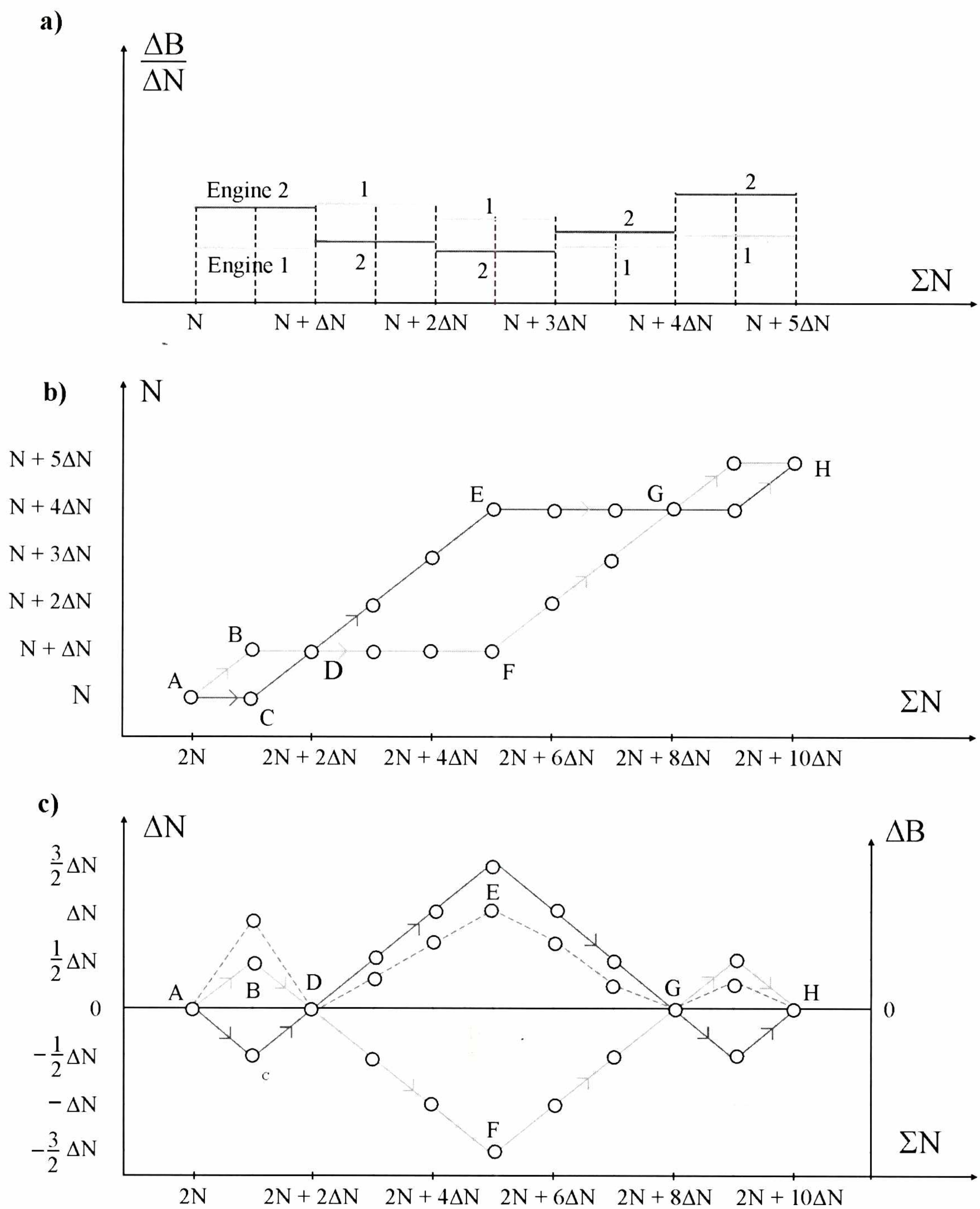

Fig.1. *Schematic diagrams for explaining the way of differentiating the loads put on two engines working in parallel under increasing load :* ***a)*** *the diagram of fuel oil consumption increments within load intervals* ***b)*** *the way of loading both engines* ***c)*** *the way of differentiating the loads on both engines*

tion of the engines working under proportional loads and that of the engines working under so differentiated loads as to obtain the consumption dropping

★ statistical distribution (histogram) of operational loads on the considered set of engines, in function of the time *t*. Such distributions can be determined by analyzing the instantaneous operational loads recorded in engine room logs, or by analyzing results of systematical measurements of operational loads. The performed investigations indicate that such distributions may be described by means of a truncated normal distribution [4 , 5].

The parameters N_r^m and σ_{N_r} of the truncated normal distributions of relative loads on the system's elements for different types of ships and their different operational states, obtained as a result of the performed investigations, are contained in the data base [5]. A scheme for determining the savings in fuel oil consumption is shown in Fig.2.

For j-th operational load interval the fuel oil consumption saving ΔG_j amounts to :

$$\Delta G_j = \Delta B_j \cdot p_j \cdot t \qquad (1)$$

and for the whole time *t* the absolute fuel oil consumption savings amount to :

$$\Delta G = t \cdot \sum_{j=1}^{m} \Delta B_j \cdot p_j \qquad (2)$$

or

$$\Delta B = t \cdot \sum_{j=1}^{m} \Delta B_j \cdot p_j$$

and the sum of probabilities is equal to 1 :

$$\sum_{j=1}^{m} p_j = 1$$

To determine the total fuel oil consumption G of the power system's engines a method which makes it possible to calculate the fuel oil consumption when a type of statistical load distribution is unknown, can be used [1].

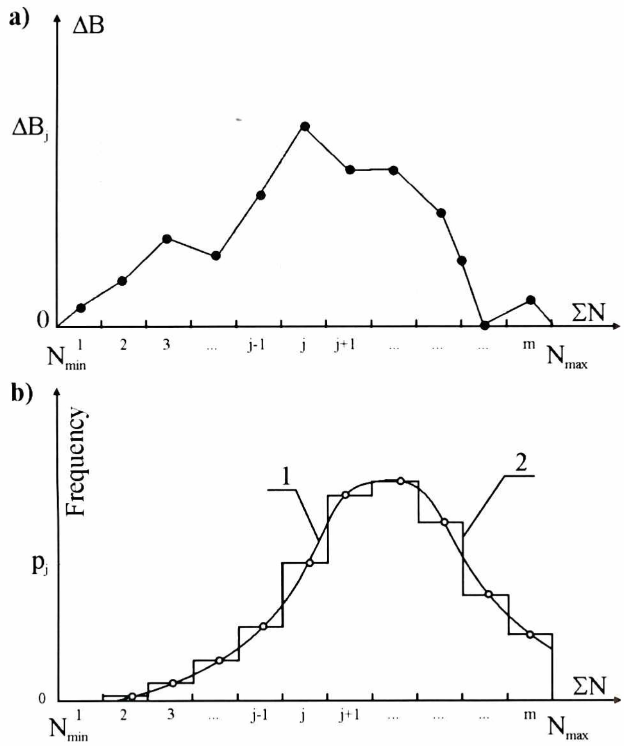

Fig.2. Schematic diagram for determining the savings in fuel oil consumption of the set of engines :
***a)** the diagram of decreasing the fuel oil consumption within intervals in function of loading*
***b)** the operational load distribution :*
1 – probability density function
2 – statistical distribution histogram

To apply the method the following should be known :

- the relationships of the relative fuel oil consumption and the relative load on the set of engines in question :

$$B_r^c = f(N_r)$$

$$B_r = a \cdot N_r^2 + b \cdot N_r + c$$

where :

a, b, c – constants
N_r – a parameter corresponding to relative load on the set of engines

- values of the rated hourly fuel oil consumption B_{nom} of the set of engines
- a statistical distribution of relative operational loads during operation of the set of engines within the time *t* (Fig.3).

The operation time of the engine under the load ΔN_{rj} can be expressed as follows :

$$\Delta t_j = t \cdot f(N_r^m)_j \cdot \Delta N_{rj}$$

The fuel oil consumption at the interval's mean load $(N_r^m)_j$ can be determined from the relationship :

$$B_{rj} = c + b \cdot (N_r^m)_j + a \cdot (N_r^m)_j^2$$

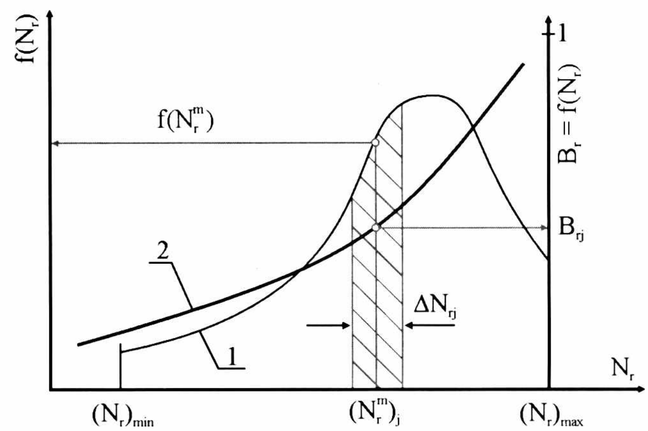

Fig.3. Schematic diagram for determining the total fuel oil consumption :
1 – statistical operational load distribution
2 – characteristics of the total relative hourly fuel oil consumption

and when the number of intervals m → ∞ then :

$$G = t \cdot B_{nom} \int_{N_{min}^r}^{N_{max}^r} B_r \cdot f(N_r)\, d N_r \qquad (3)$$

making use of the previously given relationships one can write as follows :

$$\int_{N_{min}^r}^{N_{max}^r} B_r \cdot f(N_r) d N_r = c \int_{N_{min}^r}^{N_{max}^r} f(N_r) d N_r +$$

$$+ b \int_{N_{min}^r}^{N_{max}^r} N_r \cdot f(N_r) d N_r + a \int_{N_{min}^r}^{N_{max}^r} N_r^2 \cdot f(N_r) d N_r$$

the total fuel oil consumption G within the time *t* for an arbitrary load distribution $f(N_r)$ can be determined from :

$$G = t \cdot B_{nom} [c + b \cdot N_r^m + a \cdot (N_r^m)^2 + \sigma_{N_r}^2]$$

or

$$B = B_{nom} \cdot [c + b \cdot N_r^m + a \cdot (N_r^m)^2 + \sigma_{N_r}^2]$$

where :

N_r^m – mean value of the relative load distribution for the considered set of engines operating within the time t
σ_{N_r} – standard deviation of the relative load distribution, N_r .

It is easy to apply the method because the operational time *t* of the system of elements in a considered operational state, as well as its rated fuel oil consumption is known.

By using the above given relationships, the relative saving in fuel oil consumption of a considered system of elements within the time *t* can be expressed as follows :

$$\Delta G_r = (\Delta G / G) \cdot 100 \quad [\%]$$

EXAMPLE APPLICATION OF THE METHOD

The data obtained from measurements of the fuel oil consumption of the main electric generating sets (diesel-electric propulsion system) of a fishing trawler (Tab.1) were used to exemplify the method and to assess fuel oil consumption savings by differentiating loads on diesel engines running in parallel.

Tab.1. Fuel oil consumption characteristics of the main electric generating sets [$B_{GS} = a_1$] :

$$B_{GS} = a_1 \cdot N_{GS}^2 + b_1 \cdot N_{GS} + c_1 \quad [kg/h]$$

or

$$B_{GS}^r = a_2 \cdot (N_{GS}^r)^2 + b_2 \cdot N_{GS}^r + c_2 \quad [-]$$

Generating set's number	B_{nom} [kg/h]	Coefficients of index 1			Coefficients of index 2		
		a_1	b_1	c_1	a_2	b_2	c_2
GS1	183.26	8E-5	0.1434	33.246	0.2460	0.5753	0.1787
GS2	193.41	2E-4	0.1171	25.891	0.4235	0.4451	0.1314
GS3	185.32	4E-5	0.1801	33.595	0.1036	0.7144	0.1820
GS4	187.01	6E-5	0.171	28.066	0.1818	0.6721	0.1461

For calculations of fuel oil consumption savings in the operational state „operation at fishing ground" the following assumptions were made :

⇨ continuous operation of four main electric generating sets,
⇨ the time of operation in that state, t_f = 203 days / year [4].

The total distribution of the demanded power for driving the propeller motor and for ship's general and technological purposes is characterized by the following parameters [4] :

- the mean relative power demand $(N_{EL}^m)_{rf} = (N_{GS}^m)_{rf} = 0.574$;
- the relative standard deviation [coefficient of variance] $(\nu_{N_r})_{rf} = (\sigma_{EL})_f / (N_{EL}^m)_{rf} = 0.101$; which – at the total rated power of the 4 main electric generating sets – yield the mean power demand $(N_{EL}^m)_{rf} = 0.574 \cdot 4 \cdot 735 = 1687.56$ kW and the standard deviation $(\sigma_{EL})_f = 0.101 \cdot 1687.56 = 170.44$ kW.

By using the above given data as well as those of Tab.1. and the relationships (2) and (3) the total fuel oil amount consumed by the 4 generating sets running in parallel is of the following value :

$$(G_{GS})_f = 2\,098\,146 \text{ kg} \cong 2\,098.1 \text{ tons}$$

The way of load differentiating among four main generating sets running in parallel as well as relevant savings in their fuel oil consumption are presented in Fig.4. In accordance with the above given data the load frequency distribution is presented in Fig.5.

The hourly saving this way assessed amounted to $(\Delta B_{GS})_f = 11.01$ kg/h (2.61 %). The total absolute saving was :

$$(\Delta G_{GS})_f = 53\,640.72 \text{ kg} \cong 53.6 \text{ tons}$$

FINAL REMARKS

For the assumed operational conditions of the selected fishing trawler, namely „operation at fishing ground", the following results were obtained :

❍ the total saving in fuel oil consumption of the set of diesel engines working in parallel under step-by-step differentiated load amounts to about 53.6 tons (2.61% of the total consumption)
❍ the fuel oil consumption saving makes it possible to extend the time of ship's operation at fishing ground by about 8 days per year of operation
❍ it should be observed that in the considered example – as it results from Fig.4 and 5 – the savings in fuel oil consumption will be significantly greater if the histogram of fuel oil consumption decrease within load intervals is more similar in shape to the load frequency distribution.

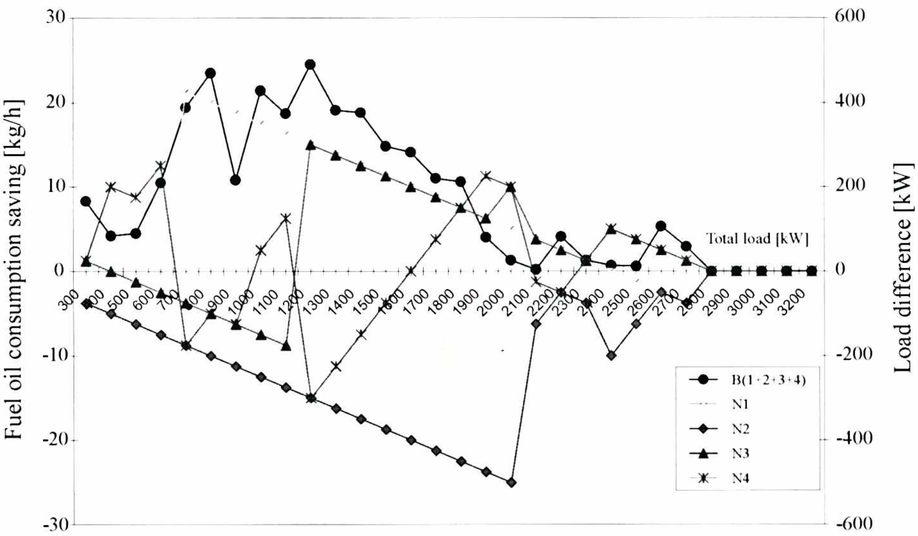

Fig.4. The way of load differentiating among four main generating sets running in parallel and the relevant savings in their fuel oil consumption

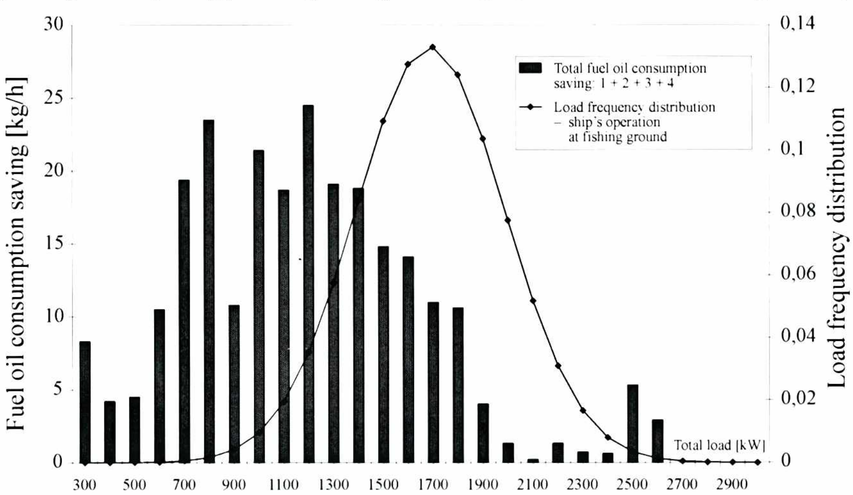

Fig.5. The diagram of the saving in fuel oil consumption of four main generating sets, and the load frequency distribution during ship's operation at fishing ground

Recapitulating, the presented method of stepwise differentiating loads on diesel engines running in parallel leads to fuel oil consumption savings. In general, to apply the method no investment outlays are required, and the savings in the order of 1÷5% may encourage to its application.

Appraised by Romuald Cwilewicz, Assoc.Prof.,D.Sc.

NOMENCLATURE

a, b, c	- coefficients of square polynomial
B	- hourly fuel oil consumption, B_{nom} - rated fuel oil consumption
B_r	- relative hourly fuel oil consumption
G	- fuel oil consumption
ΔG	- fuel oil consumption saving
ΔG_r	- relative fuel oil consumption saving
GS	- main electric generating set
m	- number of intervals (j = 1 , 2 , 3 , ...)
N	- power of engine, total power of engines
N_{min}	- minimum power of engine, N_{max} - maximum power of engine
N_{min} - N_{max}	- range (interval) of total operational load on a set of engines
N_r	- relative power of engine
N_r^m	- relative mean power of engine
N_{rj}^m	- relative mean power in j-th load interval
N_{rt}^m	- mean value of statistical distribution of relative load on a considered set of engines during their operation within the time *t*
$(N_{EL}^m)_{rf}$	- mean relative electric power demand in the state of ship's operation at fishing ground
dN	- step of load differentiation
ΔN_i	- differentiation of power load on i-th engine
ΔN_{rj}	- j-th load interval of relative engine's power
p_j	- occurrence probability of load interval ΔN_j , occurrence frequency
t	- time of engine's operation
t_f	- operational time in the state of ship's operation at fishing ground
Δt_j	- operational time within the load interval ΔN_{rj}
σ_{N_r}	- standard deviation of statistical distribution of the relative load N_r
$(\sigma_{EL})_f$	- standard deviation of electric power demand in the state of ship's operation at fishing ground
$(\nu_{N_r})_{rf}$	- relative standard deviation of statistical distribution of the relative load N_r in the state of ship's operation at fishing ground.

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Conference

KONBiN 2003

The 3rd International Safety and Reliability Conference KONBiN'03 had place in Gdynia on 27-30 May 2003. It was organized by the following scientific institutions :

- Air Force Institute of Technology
- Committee of Transport, Polish Academy of Sciences
- Faculty of Transport, Warsaw University of Technology
- Gdynia Maritime University
- Polish Safety and Reliability Association.

The Conference aroused a great interest worldwide as over 140 papers were prepared by 117 Polish authors and 106 scientists from 19 European countries as well as China, Japan and Thailand. Most papers, as it can be seen, was elaborated by two or three persons.

The scientific program of the Conference was realized during 4 plenary sessions, 18 topical sessions, one poster session and two workshops on :

★ *Safety at sea*
★ *Human and organizational factors in risk analysis and safety management.*

The following papers were presented during the plenary sessions :

- *Trends in theory and engineering of reliability applied to the NBIC technology* – by Dariusz Caban and Wojciech Zamojski (Poland)
- *Safety and reliability of industrial products, systems and structures* – by Carlos Guedess Soares (Portugal)
- *Dynamic systems modelling by using stochastic Petri nets and Monte Carlo simulation* – by Yves Dutuit and Jean-Pierre Signoret (France)
- *Integrated safety and reliability transport management systems* – by Krzysztof Kołowrocki (Poland).

The topical sessions were divided into 10 blocks :

1. *Hazard, risk and safety analysis and prediction* (20 papers)
2. *Accident and pollution investigations* (24 papers)
3. *Standards and regulations in safety and reliability* (9 papers)
4. *Mathematical foundations of safety and reliability* (18 papers)
5. *Hardware and software reliability* (5 papers)
6. *Expert methods in uncertainty and sensitivity analysis* (5 papers)
7. *Human factors in safety and reliability* (10 papers)
8. *Reliability and safety optimization* (8 papers)
9. *Data bases and reliability and safety management* (14 papers)
10. *Miscellaneous and integrated approaches to safety and reliability* (28 papers).

Excepting the last block which contains individual papers on different themes, the greatest interest was paid to the issues covered by blocks : 2, 1, 4 and 9, that has revealed the areas on which the current scientific efforts have been focussed worldwide.

The this-year Conference was organized with a great flourish as the participants had the opportunity :

- to take part in Demonstration of the newest life saving appliances at Baltic Sea
- to be acquainted with : ER-SIM ship power plant simulator, FULL MISSION BRIDGE, VISUAL SYSTEM simulator, ECDIS Laboratory, GMDSS Laboratory, Radar/ARPA Laboratory
- to visit the sailing ship – museum Dar Pomorza.

Moreover, informal social meetings gave occasion to renew old personal contacts or to establish new ones, which to a large extent facilitates international scientific cooperation.