JÓZEF DROZDOWSKI, D.Sc.,M.E.
ADAM KOMOROWSKI, M.Sc.,M.E.
Maritime University of Szczecin
Institute of Basic Technical Sciences

Exploitation reliability characteristics of ship impeller pumps

SUMMARY

Results of exploitation reliability investigations of the impeller pumps installed on some ships of Polish Steamship Company, Szczecin, are presented. On their basis elements of durability distribution functions of the pumps working in usual exploitation conditions were determined. The obtained results can be useful for both manufacturers and users of the pumps.

INTRODUCTION

Failures of ship equipment, inclusive of the impeller pumps, can make fulfilling to some ship tasks impossible or impair effectiveness of her exploitation, endanger ship operation safety especially in bad weather [7]. Statistical investigations carried out on ships in service provide credible information for determining reliability and durability characteristics of ship equipment.

The investigations in question were performed on 10 sea-going ships owned by Polish Steamship Company, Szczecin. The water impeller pumps selected as the objects of the investigation operated from the moment of their installation onboard till the first failure [6]. The aim of the investigations was to preliminarily determine reliability characteristics of the pumps [3].

Operational reliability of the pump and its elements can be characterized by :

→ failure-free operation
→ durability
→ repairability.

The (n,B,n) test program [6], i.e. that without replacement of failed elements, was assumed to estimate the pump reliability characteristics. To estimate pump durability the relationships between reliability states of the object and environmental stress on it were searched for.

COURSE OF INVESTIGATIONS

The pump was considered as a system consisting of such elements that a failure of any of them caused the entire system's failure [2]. The notion „**reliability of a pump**" is meant as its ability to maintain the properties necessary to fulfil its tasks in assumed operation conditions and time.

During routine ship exploitation the following sea water and fresh water pumps were investigated : 400 WOC (sea water), 40 WOC (sea water), 250 WOC (fresh water), 40 WOC (fresh water), S-41c, QVP 3,5/300, 160 WZB, 63 WPS. The pumps were divided into the groups consisting of the pumps most frequently applied on the ships of Polish Steamship Company. Main particulars of three pump types, considered representative, are given in Tab.1. The given ratings are continuous duty data for clear water at 20°C.

Tab.1. Main particulars of three representative pump types

Pump size & type	Capacity	Uplift revolutions	Shaft power	Manufacturer
	m^3/h	rpm	kW	
400 WOC sea water pump	400	1450	43	GZUT Gliwice, Poland
40 WOC main engine sea/fresh water pump	40	2900	4.6	GZUT Gliwice, Poland
160 WZB ballast and bilge pump	160	1450	18.8	GZUT Gliwice, Poland

Investigation results were recorded on failure sheets which were verified to check their filling correctness and to standardize failure types and causes on the basis of failure description according to the applied investigation method [5].

Statistical estimation of the results were calculated by means of a computer program in accordance with Polish standards [6].

On this basis the following empirical statistical functions and parameters were calculated :

- the reliability function $R^*(m,n)$
  where: n – number of investigated objects
  m – number of failed objects

- ➢ the mean operation time-to-first-failure $\bar{t}$
- ➢ the mean operation time standard deviation s
- ➢ the limits of the mean time confidence interval : $\bar{t}_{dd}$, $\bar{t}_{dg}$
- ➢ the failure intensity function $\lambda^*(t)$

In result of their analysis, the obtained empirical operation time distribution of the investigated pumps appeared similar to the exponential and Weibull distributions. Therefore the following characteristics of the appropriate theoretical distributions were estimated :

For exponential distribution :

- ▪ the distribution parameter Θ^*
- ▪ the reliability function $R(t)$
- ▪ the probability distribution density function $f(t)$
- ▪ the failure intensity function $\lambda(t)$

For Weibull distribution :

- the distribution parameters : b^*, a^*
- the reliability function $R(t)$
- the probability distribution density function $f(t)$
- the failure intensity function $\lambda(t)$
- the mean operation time-to-first-failure $\bar{t}$

Also, Kolmogorov and chi-square tests were performed to check the stated hypotheses [4].

In Fig.1,2,3 and 4 the reliability characteristics of 400 WOC pump are shown [1]. The appropriate Weibull distribution parameters as well as results of the Kolmogorov and chi-square tests are simultaneously presented in Tab.2a and b.

In Fig. 5,6,7 and 8 and Tab.3a and b the relevant statistical data for 40 WOC seawater pump are given, and for 160 WZB pump – in Fig. 9,10,11 and 12 and Tab.4a and b.

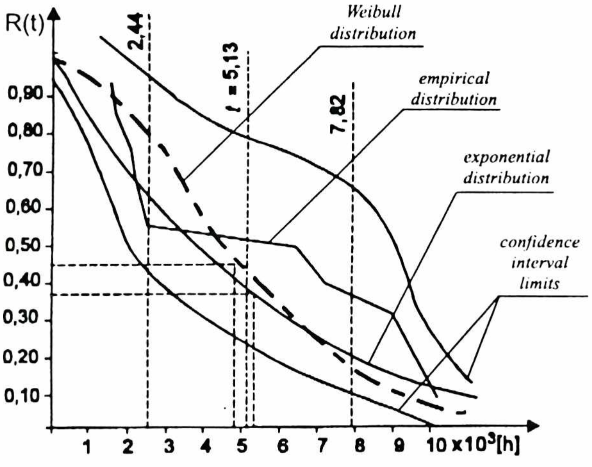

Fig.1. Empirical distribution of failure-free operation probability, its confidence interval limits, and relevant reliability functions for 400 WOC pump

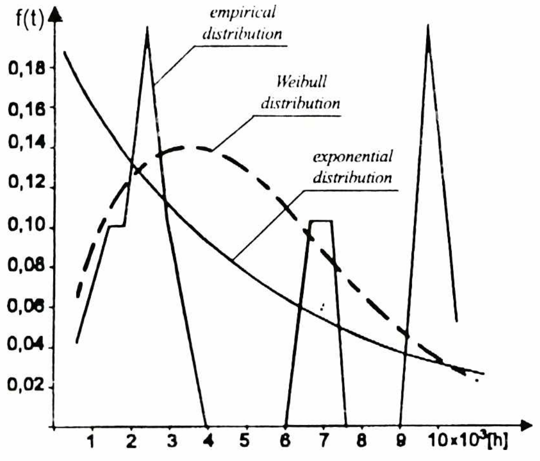

Fig.2. The probability distribution density functions for 400 WOC pump

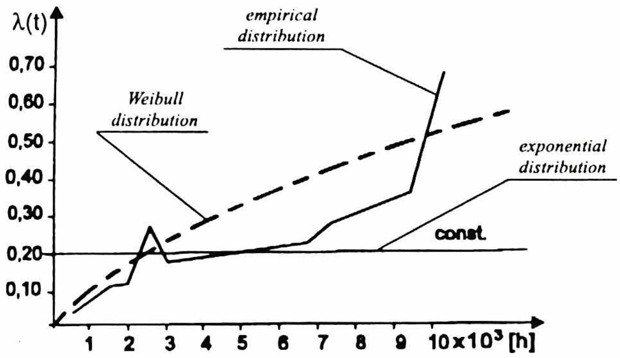

Fig.3. The failure intensity functions for 400 WOC pump

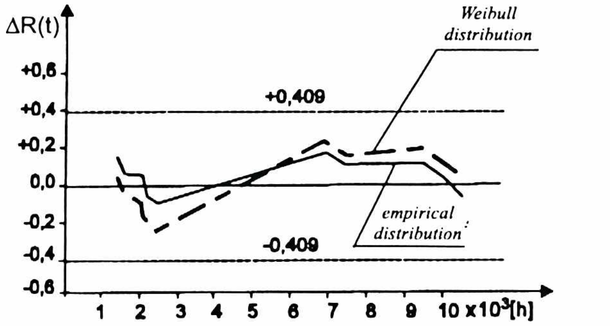

Fig.4. The differences between values of the empirical and theoretical reliability functions for 400 WOC pump (Kolmogorov test results)

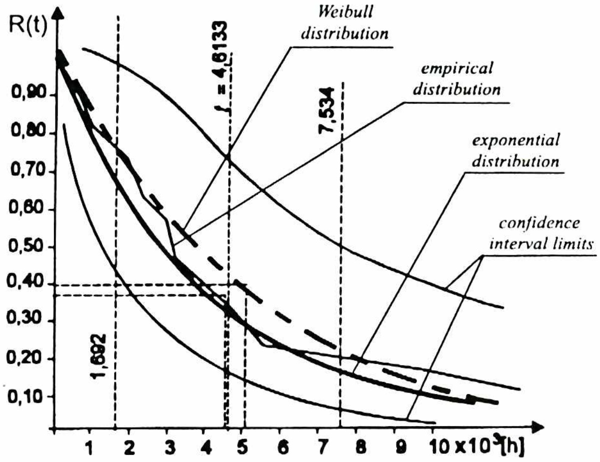

Fig.5. Empirical distribution of failure-free operation probability, its confidence interval limits, and relevant reliability functions for 40 WOC seawater pump

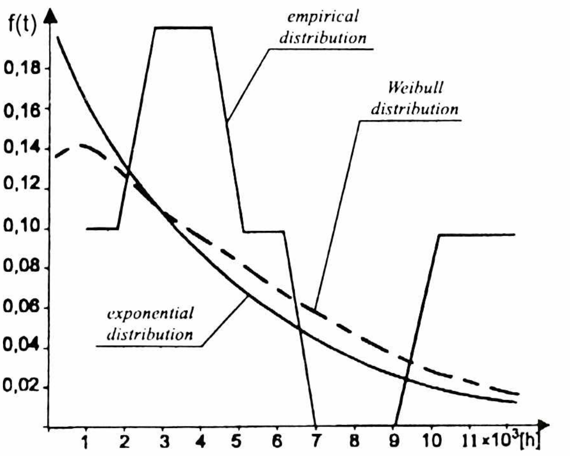

Fig.6. The probability distribution density functions for 40 WOC seawater pump

Tab.2a. Estimated reliability characteristics of 400 WOC pump (Weibull distribution)

$R^*(m,n)-R(t_i)$	$\frac{(m_i-np_i)^2}{np_i}$	$t\cdot10^3$ [h]	$R(t)$	$f(t)$
0.0053		1	0.9472	0.0878
– 0.0735	0.7764	2	0.8375	0.1269
– 0.1025		3	0.7014	0.1418
– 0.1909	2.8551	4	0.5598	0.1388
– 0.2448	1.0727	5	0.4276	0.1242
0.1966	3.1518	6	0.3134	0.1036
0.1387	1.3603	7	0.2208	0.0815
0.1805		8	0.1499	0.0608
0.0979	0.2469	9	0.0981	0.0433
0.0233	0.0309	10	0.0621	0.0295
	χ^2 9.4941			

$$\text{for :}\quad \left.\begin{matrix}\beta=0.95\\ k=4\end{matrix}\right\}\rightarrow \chi_0^2=9.488$$

$$D_{10}=-\,0.2448 \qquad D_{10}^0=0.4090 \qquad \bar{t}=4.91\cdot10^3[\mathrm{h}]$$

Tab.2b. Estimated reliability characteristics of 400 WOC pump (exponential distribution)

$R^*(m,n)-R(t_i)$	$\frac{(m_i-np_i)^2}{np_i}$	$t\cdot10^3$ [h]	$R(t)$	$f(t)$
0.1538		1	0.8229	0.1603
0.0789	0.1413	2	0.6773	0.1319
0.0579		3	0.5573	0.1086
– 0.0304	2.2422	4	0.4587	0.0894
– 0.0859	1.1789	5	0.3775	0.0736
0.1765	1.8170	6	0.3106	0.0605
0.1055	3.2241	7	0.2556	0.0498
0.1042		8	0.2104	0.0410
0.0201	1.1134	9	0.1731	0.0337
– 0.0567	0.2354	10	0.1425	0.0278
	χ^2 9.9523			

$$\text{for :}\quad \left.\begin{matrix}\beta=0.95\\ k=5\end{matrix}\right\}\rightarrow \chi_0^2=11.070$$

$$\lambda(t)=0.1949=\text{const}$$

$$D_{10}=0.1765 \qquad D_{10}^0=0.4090 \qquad \bar{t}=5.132\cdot10^3[\mathrm{h}]$$

Tab.3a. Estimated reliability characteristics of 40 WOC seawater pump (Weibull distribution)

$R^*(m,n)-R(t_i)$	$\frac{(m_i-np_i)^2}{np_i}$	$t\cdot10^3$ [h]	$R(t)$	$f(t)$
– 0.0210	0.1296	1	0.8639	0.1440
– 0.0270	0.0269	2	0.7245	0.1331
0.0055	0.0444	3	0.5995	0.1166
– 0.0025	0.0353	4	0.4915	0.0995
– 0.0098		5	0.4001	0.0836
– 0.0877	1.1068	6	0.3238	0.0694
– 0.0535	0.0507	7	0.2607	0.0571
– 0.0792	0.1857	8	0.2090	0.0466
0.0359	0.5454	9	0.1669	0.0378
0.0231	0.1444	10	0.1328	0.0306
	χ^2 2.2692			

$$\text{for :}\quad \left.\begin{matrix}\beta=0.95\\ k=6\end{matrix}\right\}\rightarrow \chi_0^2=12.592$$

$$D_{10}=-\,0.0877 \qquad D_{10}^0=0.4090 \qquad \bar{t}=5.15\cdot10^3[\mathrm{h}]$$

Tab.3b. Estimated reliability characteristics of 40 WOC seawater pump (exponential distribution)

$R^*(m,n)-R(t_i)$	$\frac{(m_i-np_i)^2}{np_i}$	$t\cdot10^3$ [h]	$R(t)$	$f(t)$
0.0196	0.01	1	0.8051	0.1745
0.0355	0.0043	2	0.6482	0.1405
0.0819	0.1013	3	0.5219	0.1131
0.0758	0.0272	4	0.4202	0.0911
0.0659		5	0.3383	0.0733
– 0.0126	1.2167	6	0.2723	0.0590
0.0103	0.0170	7	0.2193	0.0475
– 0.0237	0.3265	8	0.1765	0.0383
0.0567	0.2968	9	0.1421	0.0308
0.0295	0.0504	10	0.1144	0.0248
	χ^2 2.0502			

$$\text{for :}\quad \left.\begin{matrix}\beta=0.95\\ k=7\end{matrix}\right\}\rightarrow \chi_0^2=14.067$$

$$\lambda(t)=0.2168=\text{const}$$

$$D_{10}=0.0819 \qquad D_{10}^0=0.4090 \qquad \bar{t}=4.613\cdot10^3[\mathrm{h}]$$

***Tab.4a.** Estimated reliability characteristics of 160 WZB pump (Weibull distribution)*

$R^*(m,n)-R(t_i)$	$\frac{(m_i-np_i)^2}{np_i}$	$t\cdot10^2$ [h]	$R(t)$	$f(t)$
– 0.0087	0.0385	1	0.9791	0.4243
– 0.0364	0.2143	2	0.9161	0.8226
– 0.0450	0.0381	3	0.8178	1.1238
0.0076	0.1319	4	0.6957	1.2933
– 0.1157	0.1553	5	0.5638	1.3246
– 0.0256	0.0440	6	0.4348	1.2372
0.0173	0.0854	7	0.3190	1.0673
– 0.0411	1.4019	8	0.2227	0.8571
– 0.0741	0.3061	9	0.1477	0.6435
0.0234	0.9498	10	0.0932	0.4533
		11	0.0558	0.3003
	χ^2 3.3653			

$$\text{for}: \left.\begin{matrix}\beta=0.95\\ k=7\end{matrix}\right\} \rightarrow \chi_0^2=14.067$$

$$D_{10}=-\,0.0741 \qquad D_{10}^0=0.4090 \qquad \bar{t}=581\,[\mathrm{h}]$$

***Tab.4b.** Estimated reliability characteristics of 160 WZB pump (exponential distribution)*

$R^*(m,n)-R(t_i)$	$\frac{(m_i-np_i)^2}{np_i}$	$t\cdot10^2$ [h]	$R(t)$	$f(t)$
0.2100	1.3413	1	0.8346	1.509
0.2000	0.0451	2	0.6966	1.259
0.1855	0.0729	3	0.5814	1.051
0.1939	0	4	0.4852	0.877
0.1420	0.9541	5	0.4049	0.732
0.0938	0.7644	6	0.3380	0.611
0.0685	0.1804	7	0.2821	0.426
– 0.0068	4.5663	8	0.2354	0.355
– 0.0699	1.9360	9	0.1965	0.296
– 0.0552	0.9143	10	0.1640	0.247
	χ^2 10.774			

$$\text{for}: \left.\begin{matrix}\beta=0.95\\ k=8\end{matrix}\right\} \rightarrow \chi_0^2=15.507$$

$$\lambda(t)=1.808=\text{const}$$

$$D_{10}=0.2100 \qquad D_{10}^0=0.4090 \qquad \bar{t}=553\,[\mathrm{h}]$$

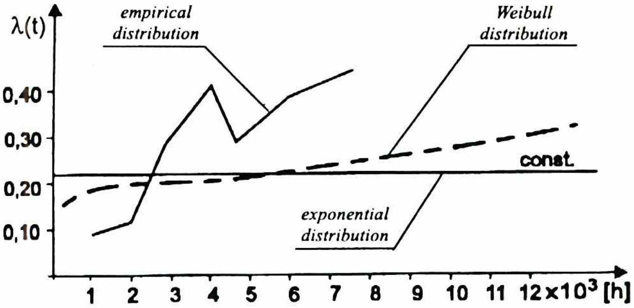

***Fig.7.** The failure intensity functions for 40 WOC seawater pump*

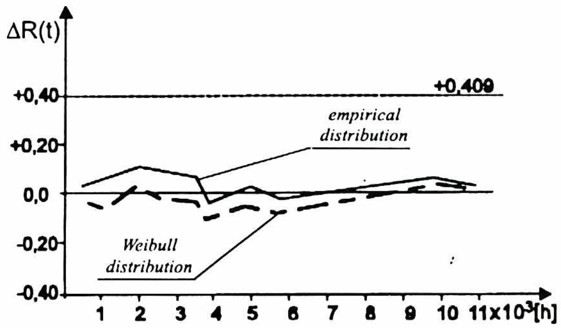

***Fig.8.** The differences between values of the empirical and theoretical reliability functions for 40 WOC seawater pump (Kolmogorov test results)*

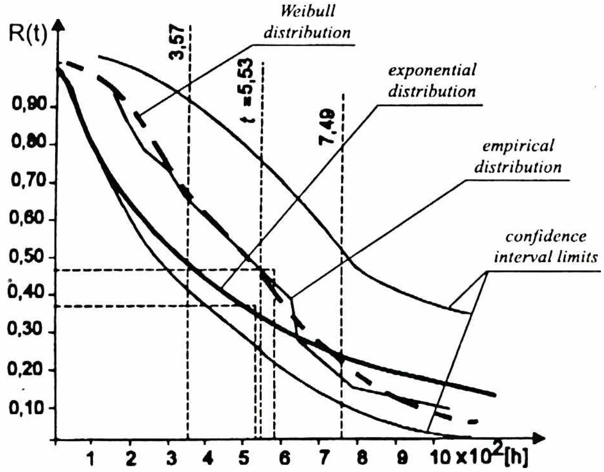

***Fig.9.** Empirical distribution of failure-free operation probability, its confidence interval limits, and relevant reliability functions for 160 WZB pump*

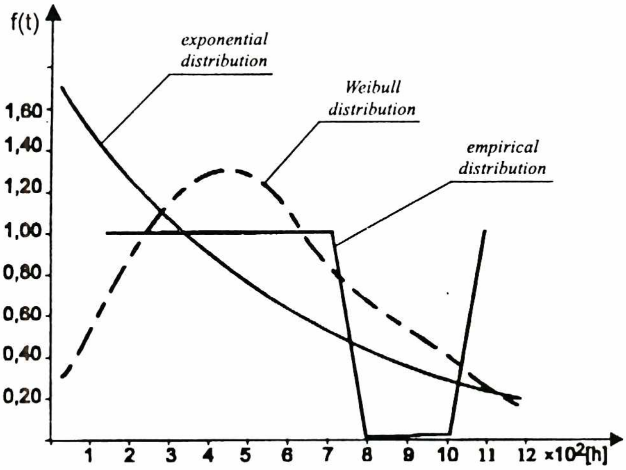

***Fig.10.** The probability distribution density functions for 160 WZB pump*

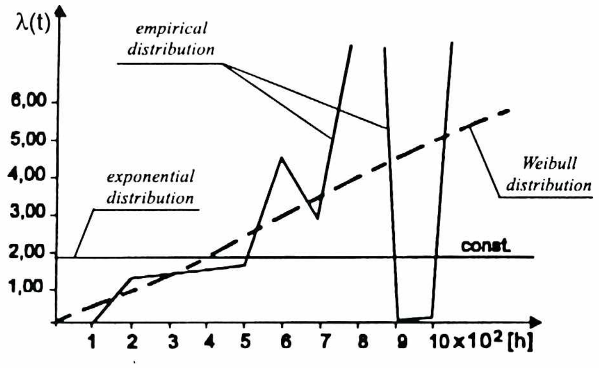

Fig.11. The failure intensity functions for 160 WZB pump

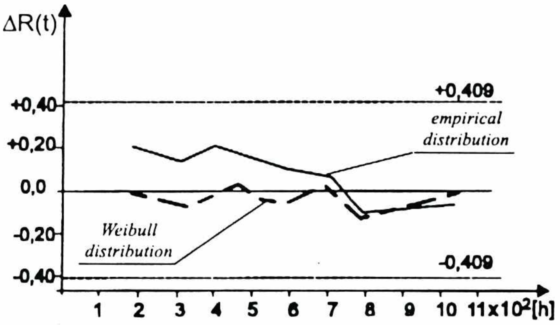

Fig.12. The differences between values of the empirical and theoretical reliability functions for 160 WZB pump (Kolmogorov test results)

The summary results of statistical estimation are presented in Tab.5.

CONCLUSIONS

The following conclusions can be stated on the basis of the performed statistical investigations :

- The mean operation time values of the particular pumps are contained within running repair time limits and also within capital repair time limits in some cases (e.g. 250 WOC and 40 WOC fresh water pumps).
- The mean failure-free operation time of 40 WOC sea water pump is much shorter than that of the fresh water pump of the same design.
- It appeared from reliability characteristics analysis of the pumps that :
    - The random variable assumed as the failure-free operation time of the pumps can be approximated by both exponential and Weibull distributions.
    - Weibull distribution is the best approximation of the short operation time of heavy service pumps, e.g. 160 WZB bilge/ ballast pump.
    - The failure intensity is different depending on a pump type and it highly increases at operation time values exceeding about 7500 h.
    - The failure probability distribution density function *f(t)* is different for different pump types, and not always contained within the running repair time limits provided in manufacturer's maintenance guidelines.
    - The exploitation investigation results confirmed that the time schedules for running and capital repairs established by pump manufacturers are appropriate.
- The exploitation investigations confirmed also that the failure-free operation time of the pump was highly influenced by a pumped medium type.
- The information collected in result of the investigations can be useful for both manufacturers and users of the pumps, namely :

Tab.5. Estimated statistical distribution parameters for the investigated impeller pumps

Distribution	Parameter	Pump type							
		400 WOC sea water	250 WOC fresh water	40 WOC* fresh water	40 WOC sea water	S-41c fresh water	QVP 3.5/300	160 WZB	63 WPS
Empirical	$\bar{t}$ x10^3 [h]	5.13	8.43	10.11	4.61	3.57	4.23	0.553	0.416
	$\Delta\bar{t}_d^g$ x10^3 [h]	2.69	2.16	3.78	2.92	1.33	1.23	0.196	0.154
	s x10^3 [h]	3.56	2.87	5.01	3.87	2.78	2.56	0.260	0.204
	$\bar{t}_{dd}$ x10^3 [h]	2.45	6.27	6.33	1.69	2.24	3.00	0.357	0.262
	$\bar{t}_{dg}$ x10^3 [h]	7.82	10.59	13.89	7.53	4.90	5.46	0.749	0.570
Exponential	Θ^* x10^3 [h]	5.13	8.43	10.11	4.61	3.57	4.23	0.553	0.416
	χ^2	9.952	12.150	6.021	2.050	3.969	9.525	10.775	9.988
	χ_0^2	11.070	12.592	14.067	14.067	15.507	12.592	15.507	12.592
Weibull	a^*	5.50	9.36	11.17	5.40	4.21	4.71	0.656	0.475
	b^*	1.71	3.49	2.34	1.14	1.33	2.07	2.05	2.23
	$\bar{t}$ x10^3 [h]	4.91	8.42	9.90	5.15	3.88	4.17	0.581	0.421
	χ^2	9.494	5.079	5.539	2.269	3.575	3.458	3.365	4.376
	χ_0^2	9.488	11.070	12.592	12.592	14.067	11.070	14.067	11.070

- ❖ The manufacturer should pay more attention to appropriate choice of materials and their processing as e.g. 40 WOC sea water pump and that of the same design but used for fresh water revealed very different failure-free operation time values : 4613 h and 10 110 h respectively.
- ❖ The user can utilize the information in overhaul and repair planning.

NOMENCLATURE

a^*, b^* - Weibull distribution parameters
D_{10}, D^0_{10} - difference values of the reliability functions $[R^*(m,n) - R(t_i)]$ in Kolmogorov test
$f(t)$ - probability distribution density function
k - number of failures
m - number of failed objects
m_i - number of failed objects within the time t_i
n - number of investigated objects
p_i - probability of the event that an object will fail within $< 0, t >$ time interval
$R^*(m,n)$ - empirical reliability function
$R(t)$ - theoretical reliability function
$R(t_i)$ - theoretical reliability function of i-th element (pump)
s - mean operation time standard deviation
t - time of operation
$\bar{t}$ - mean operation time-to-first-failure
$\bar{t}_{dd}$ - lower confidence interval limit of the object operation time
$\bar{t}_{dg}$ - upper confidence interval limit of the object operation time
t_i - time-to-first-failure of i-th element (pump)
β - confidence level index
$\Delta\bar{t}^g_d$ - limits of the mean time confidence interval
Θ^* - exponential distribution parameter
$\lambda(t)$ - failure intensity function for Weibull and exponential distributions
$\lambda^*(t)$ - empirical failure intensity function
χ^2, χ^2_0 - chi-square distribution test values

Appraised by Bolesław Kuźniewski, Assoc.Prof.,D.Sc.

Miscellanea

FATIGUE OF STRUCTURES

The Topic Group on „Fatigue of Structures" acts within the Section on „Fatigue of Materials and Structures", Mechanical Engineering Committee, Polish Academy of Sciences. It was initiated by the Faculty of Ocean Engineering and ShipTechnology, Technical University of Gdańsk. The Group headed by Prof. K.Rosochowicz., the Dean of the Faculty, consists of 30 specialists of several Polish universities and scientific research centres as well as of industrial enterprises.

The Group's area of interest covers fatigue processes of complex large-size structures such as ships, aircraft, road and railway vehicles and heavy-duty machines. Within the confines of seminar meetings of the Group its members, although coming from different scientific and industrial circles, have an oportunity to exchange their research and production experience and initiate common undertakings.

Scientific and application aspects of the research projects underway are discussed just at the research stands. In this way some fatigue problems of the ship structures and aircraft fuselage and drive were considered at the Faculty of Ocean Engineering and Ship Technology, Technical University of Gdańsk, and in the Air Force Technical Institute and Aviation Institute (twice) in Warszawa.

The so directed activity of the Group meeting wide acceptance contributes to tightening connections between different professional circles and integrating the scientific development in the area of structural fatigue.

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Miscellanea

POLISH SOCIETY ON SAFETY AND RELIABILITY

In the 1980s and 1990s in Poland the seminars and scientific conferences under the headings :

„Reliabilty Problems in Transport"
and **„Safety of Systems"**

were organized independent of each other. The situation reflected modes of activity of the scientists practically working in the same institutions and research groups, but treading more or less separately in spite of both areas of activity mainly dealing with transport problems. That state lasted for 12 years. As late as in 1997 the initiative was undertaken to join together both activity areas and expanding its interest onto safety and reliability problems of man-technology-environment systems.

In result in February 1998 The Polish Society on Safety and Reliability was established (PTBiN), headed by Prof. Alfred Brandowski, with its headquarters at the Faculty of Ocean Engineering and Ship Technology, Technical University of Gdańsk.

PTBiN is an inter-disciplinary, scientific society generally aimed at developing, applying and publishing the scientific research results on the safety problems arising from hazards due to technology and nature as well as the reliability problems of the systems joining together the man, technology and environment.

Hence the following tasks of the Society arise, a.o. :

- ⇨ development of safety and reliability engineering
- ⇨ integration and promotion of activities directed at determining rational safety and reliability levels
- ⇨ submitting official proposals in this respect to the administrative bodies
- ⇨ influencing safety and reliability management.

In this year PTBiN has a very important task to organize I National Conference on Safety and Reliability (KONBiN '99) to be held on 22 to 25 November in Zakopane. It is intended to be the broad forum devoted to both theoretical and practical aspects of safety, reliability, serviceability and maintainability.

KONBiN'99