Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

SELECTED ASPECTS OF DETERMINING THE RELIABILITY OF THE PUMP SUBSYSTEMS WITH REDUNDANCY, USED IN MAIN ENGINE AUXILIARY SYSTEMS

Roman Liberacki

Gdansk University of Technology
ul. Narutowicza 11/12, 80-950 Gdańsk, Poland
tel.: +48 58 3471850, fax: +48 58 3472430
e-mail: romanl@pg.gda.pl

Abstract

The rules of classification societies require the use of redundancy in the systems essential for the safety of the ship. Duplication of pumps in the main engine auxiliary systems like cooling water system, lubricating oil system, fuel oil system is a good example here. Therefore, in the author's opinion, some attention should be paid to this issue. Two important questions arise here. Does duplication of pumps in marine systems make sense? What impact does the use of redundancy on the reliability of the system? To answer these questions, it is necessary to adequately assess the reliability of subsystems with redundancy. But it is not so simple. The first problem is gathering the reliability data. The second problem is the so-called human factor. The third problem, widely discussed in this article, is to adopt the appropriate reliability model.

Key words: *redundancy, reliability model, pumping systems.*

1. The idea of redundancy

In technical systems redundancy means the duplication of critical elements of a system. The idea of redundancy is to increase reliability of the whole system. In case of failure of one component, the second (redundant) component takes over its function. In complex systems, the best results are achieved through the duplication of the most unreliable elements, as shown in Fig.1. Duplication of item 2 with the lowest reliability gives the highest reliability of the system.

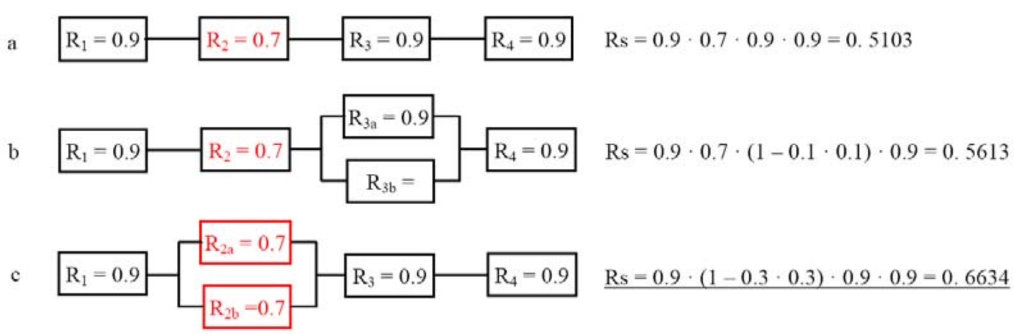

Fig. 1. The idea of redundancy in complex systems; a) system without redundancy, b) system with redundancy of item 3 with high reliability level c) system with redundancy of item 2 with low reliability level, R_i- reliability of the item "i", R_s – reliability of the whole system

2. Redundancy in main engine auxiliary systems

Reliability of the main engine is extremely important for ship's safety. But the proper operation of the main engine depends on the reliable operation of its auxiliary systems (cooling water system, lubricating oil system, fuel oil system). That's why the Ship Classification Societies like: Lloyd Register of Shipping, Det Norske Veritas, Germanischer Lloyd, American Bureau of Shipping, Polish Register of Shipping etc. require redundancy in the most important systems on ships. One of them is the fuel oil system. As we can see in Fig .2. the pumps and the filters are doubled.

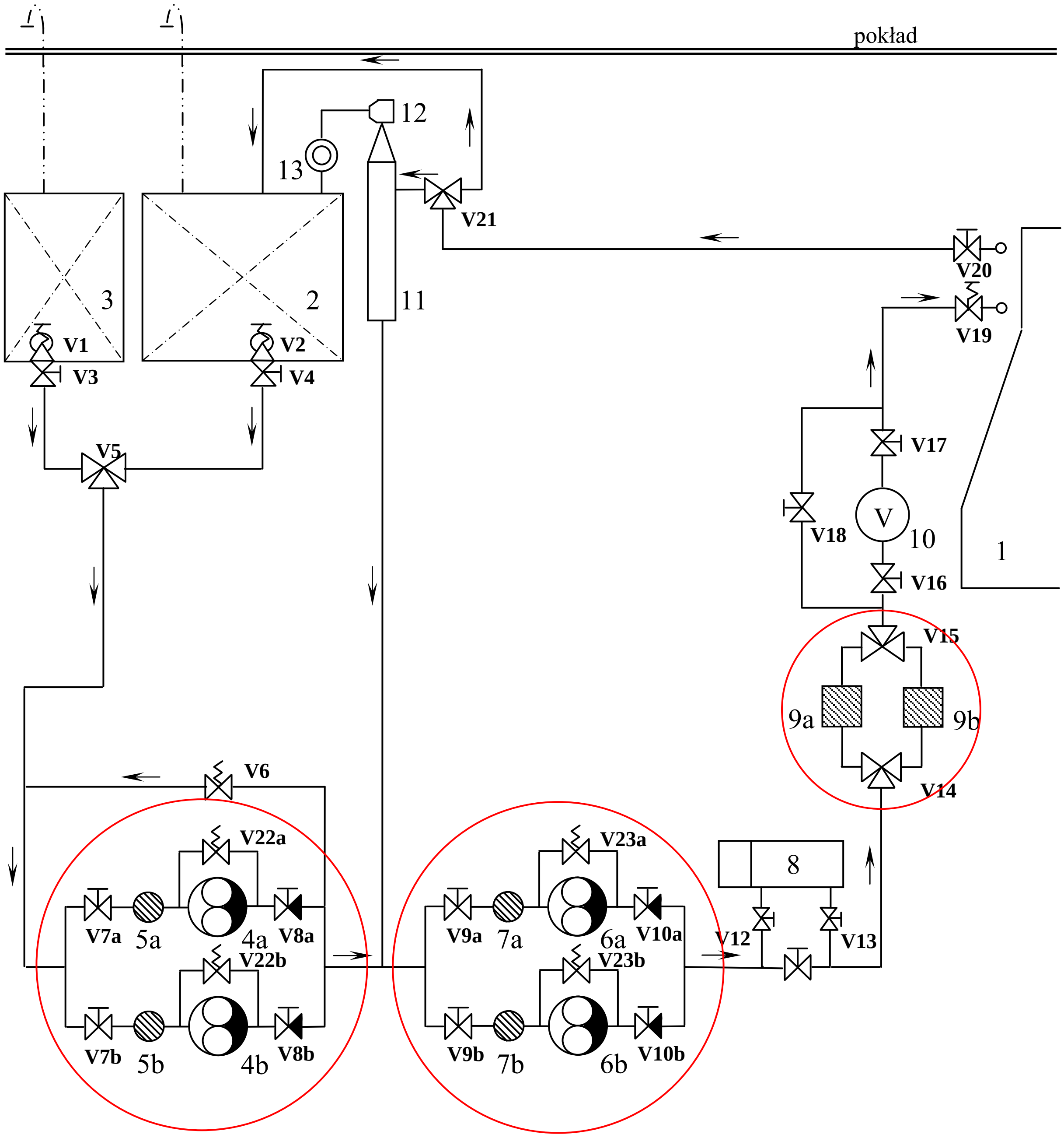

Fig. 2. Fuel oil system for the MAN MC – type diesel engine [1];
1 – main engine; 2 – HFO service tank; 3 – MDO service tank; 4a, 4b – fuel oil supply pumps; 5a, 5b – filters; 6a, 6b – fuel oil circulating pumps; 7a, 7b – filters; 8 – fuel oil pre-heater; 9a, 9b – fuel oil duplex filter; 10 – Viscometer; 11 – venting box, 12 – automatic de-aerating valve, 13 – sight glass, V – valves

3. Does duplication of pumps make sense?

As it has been stated in the second paragraph of the article - ship classification societies require, inter alia, redundancy of pumps in main engine auxiliary systems. For example, the requirements of Polish Register of Shipping are as follows [2]: "Sea-water cooling system of one main engine shall be provided with two pumps, one of which shall be a stand-by pump..."; "In machinery installations where one main engine is fitted at least two lubricating oil pumps of equal capacity shall be provided..."; At least two power-driven pumps shall be provided for fuel transfer...".

Why the pumps? To answer the question we have to look at reliability indicators of components of cooling water system, lubricating oil system and fuel oil system. Those components are mostly: vessels, pumps, filters, heat exchangers, valves, pipe straight sections, control systems. A good source of reliability data is OREDA [3]. The objective of the handbook is to collect reliability data from offshore drilling and production operations. Unfortunately it is very hard to find such a data for the ship installation. So, the only possible solution for now is to use a set of data from OREDA. The reliability data collected in OREDA has a form of the failure rate λ given by the formula:

$$\lambda = \frac{n}{\tau}[h^{-1}]; \tag{1}$$

where:
n [–] - number of failures,
τ [h] - aggregated time in service [h].

According to OREDA [3] the sum of critical failure rates of selected components are, respectively:

Pumps:	$\lambda = 106.03 \cdot 10^{-6}\ h^{-1}$,
Vessels:	$\lambda = 17.46 \cdot 10^{-6}\ h^{-1}$,
Valves:	$\lambda = 12.39 \cdot 10^{-6}\ h^{-1}$,
Heat exchangers:	$\lambda = 6.03 \cdot 10^{-6}\ h^{-1}$.

The critical failure means a failure which causes immediate and complete loss of a system's capability of providing its function.

The above presented set of data clearly shows, that pumps are characterized by the highest failure rate. Therefore, they are the most unreliable elements of the systems under consideration. So according to the rule, that the best results are achieved through the duplication of the most unreliable elements, we can say that duplication of pumps makes sense.

4. Reliability model of redundant subsystems with pumps

The second problem, what impact the use of redundancy does on the reliability of the system - still remains open. To solve this problem, it is necessary to build an adequate reliability model. The essence of redundancy is to create a parallel reliability structure in place of a serial structure. Using a simple example with cooling water pumps let's consider, whether the subsystems with duplicated pumps create purely parallel reliability structure, as it has been shown in Fig. 3.

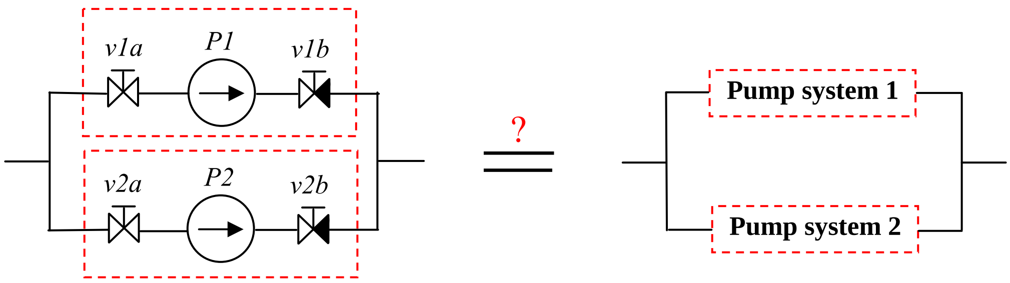

Fig. 3. Parallel reliability structure of pump subsystem

At the first glance the answer is yes. Such approach can be found in books [4, 5]. But in real systems, in the opinion of the author, the problem is more complicated. First of all, not only pump is duplicated. Shut – off valves are duplicated too. Their task is to cut off the flow through the pump unfit. But some failures of those valves have an impact on the work of both pumps. To explain this, we have to review possible failure modes of valves. In Tab.1. there are given critical failure modes of valves based on the OREDA handbook [3].

Tab. 1. Critical failure modes of valves [3]

Critical failure mode	Failure rate
delayed operation	$\lambda = 0.16 \cdot 10^{-6}\ h^{-1}$
external leakage to environment	$\lambda = 0.76 \cdot 10^{-6}\ h^{-1}$
fail to close (actuator failure)	$\lambda = 2.90 \cdot 10^{-6}\ h^{-1}$
fail to open (actuator failure)	$\lambda = 1.96 \cdot 10^{-6}\ h^{-1}$
internal leakage (non return valve)	$\lambda = 0.41 \cdot 10^{-6}\ h^{-1}$
leakage in closed position	$\lambda = 2.02 \cdot 10^{-6}\ h^{-1}$
plugged	$\lambda = 0.56 \cdot 10^{-6}\ h^{-1}$
the sum of others	$\lambda = 3.62 \cdot 10^{-6}\ h^{-1}$

Let's imagine now a following situation: pump *P1* is working, valve *v1b* failed. The failure event is an external leakage of medium to environment. In such a situation it doesn't matter which of pumps is working at the moment. Even if we stop the pump *P1* and use the pump *P2*, a part of medium still will be pumped outside through a leaky valve. Another situation will occur when a valve *v1a* will leak on the suction side of the pump. This time, the outside air will be sucked into the medium, regardless of which of the pumps is working. Certainly, a significant leakage to the environment and a lot concentration of air in pumped medium cause the system does not meet the requirements. Therefore, it must be concluded, that the structure of reliability model of pumping subsystem is not purely parallel. The structure is a serial – parallel.

5. The impact of redundancy on the system reliability

To assess the impact of redundancy on the reliability of the subsystem with pumps, shown in Fig. 3, two solutions will be compared: one without redundancy and the second with redundancy. Reliability data needed for pumps are presented in Tab. 2. As we can see those pumps were working in redundant structure, because the failure rates for calendar time are about 50 % of the failutre rates for operational time. This means that the pumps work alternately, each of them for half of calendar time.

Tab. 2. Critical failure modes of pumps [3]

Critical failure mode	Failure rate (calendar time)	Failure rate (operational time)
external leakage	$\lambda = 3.46 \cdot 10^{-6}\ h^{-1}$	$\lambda = 7.71 \cdot 10^{-6}\ h^{-1}$
failed to start	$\lambda = 26.66 \cdot 10^{-6}\ h^{-1}$ *	$\lambda = 60.26 \cdot 10^{-6}\ h^{-1}$ *
failed while running	$\lambda = 55.34 \cdot 10^{-6}\ h^{-1}$	$\lambda = 101.76 \cdot 10^{-6}\ h^{-1}$
low output	$\lambda = 5.87 \cdot 10^{-6}\ h^{-1}$	$\lambda = 20.49 \cdot 10^{-6}\ h^{-1}$
vibration	$\lambda = 5.6 \cdot 10^{-6}\ h^{-1}$	$\lambda = 10.86 \cdot 10^{-6}\ h^{-1}$
the sum of others	$\lambda = 9.37 \cdot 10^{-6}\ h^{-1}$	$\lambda = 16.01 \cdot 10^{-6}\ h^{-1}$

* probability of the event fail to start on demand is $P = 8.6 \cdot 10^{-4}$.

Using the OREDA database we have to notice, that one very important simplifying assumption has been made there. The life of a technical item may generally be split into three different phases: the burn - in phase, the useful life phase and the wear - out phase. The failure rate function has then a form of a so called "bath - tub" curve. The failure rate is decreasing in the burn - in phase, then is close to constant in the useful life phase and at the end is increasing in the wear - out phase. The main part of the failure events in the database come from the useful life phase. All the failure rate estimates presented in the book [3] are based on the assumption, that the failure rate is constant and independent of time, so the item is considered to be "as good as new" as long as it is functioning. Of course the assumption is not always true, but because of the simplicity is widely used in reliability analysis. According to the exponential low the reliability of the item is given by the formula 2.

$$R(t) = e^{-(\Sigma\lambda)\cdot t}; \qquad (2)$$

where:
$\Sigma\lambda$ – the sum of failure rates of item,
t – time to be taken account.

Now let's compare reliability of two solutions of pump system.

System without redundancy.

The failure event (so called top event) is a pump system failure during operation, which may make it necessary to stop the main engine. The reliability of the system means the ability of the engine to run on. Valves *v1a* and *v1b* are in open position. The pump *P1* is working. Operating time of the pump *P1* is close to the calendar time.

The reliability structure of pump system without redundancy is shown in Fig.4. The reliability of the system is given by the formula (3). The calculations of reliability of items and whole pump system are given in Tab. 3.

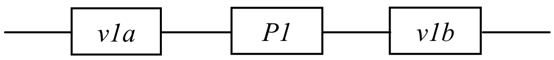

Fig. 4. Reliability structure of pump system without redundancy

$$R_s(t) = R_{v1a}(t) \cdot R_{P1}(t) \cdot R_{v1b}(t), \qquad (3)$$

where:
$R_{v1a\_1}(t)$ – reliability of item *v1a* versus failure mode *_1*,
R_{P1} (t) – reliability of item *P1*versus failure modes *_1* till *_5*,
$R_{v1b\_1}(t)$ – reliability of item *v1b* versus failure mode *_1*,
t [h] – time to be taken into account.

Tab. 3. Reliability of pump system without redundancy

Item	Failure mode critical for the system	λ [h^{-1}]	$\Sigma\lambda$ [h^{-1}]	Reliability of item $R_i(t)$			
				t = 2500 h	t = 5000 h	t = 7500 h	t = 10000 h
v1a	_1 external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v1b	_1 external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
P1	_1 external leakage _2 failed while running _3 low output _4 vibration _5 others	$7.71 \cdot 10^{-6}$ $101.76 \cdot 10^{-6}$ $20.49 \cdot 10^{-6}$ $10.86 \cdot 10^{-6}$ $16.01 \cdot 10^{-6}$	$156.83 \cdot 10^{-6}$	0.67565	0.45651	0.30844	0.20840
		Reliability of system $R_s(t)$		0.67309	0.45305	0.30494	0.20526

System with redundancy.

The reliability of the system, as stated above, means the ability of the engine to run on. Valves *v1a, v1b, v2a, v2b* are in open position. One of the two pumps is working, the second is a stand-bye pump. But during the time taken into account the pumps work alternately, each of them for half of calendar time. So operational time of one pump is a half of calendar time.

The reliability structure of the pump system with redundancy is given in Fig .5. The reliability of the system is given by the formula (4). The calculations of reliability of items and whole pump system are given in Tab. 4.

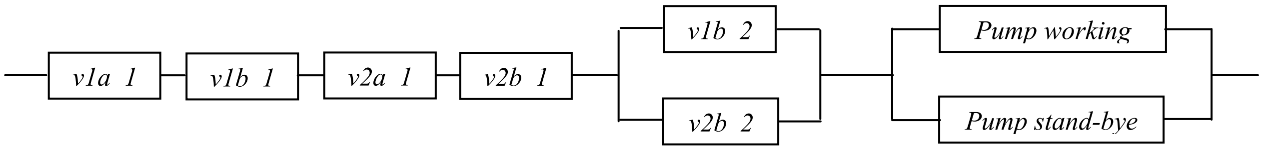

Fig. 5. Reliability structure of pump system with redundancy

$$R_s(t) = R_{v1a\_1}(t) \cdot R_{v1b\_1}(t) \cdot R_{v2a\_1}(t) \cdot R_{v2b\_1}(t) \cdot \left\{ 1 - [1 - R_{v1b\_2}(t)] \cdot [1 - R_{v2b\_2}(t)] \right\} \cdot \\ \left\{ 1 - [1 - R_{Pw}(t)] \cdot [1 - R_{Psb}(t)] \right\}; \tag{4}$$

where:

$R_{v1a\_1}(t)$ – reliability of item *v1a* versus failure mode *_1*,
$R_{v1b\_1}(t)$ – reliability of item *v1b* versus failure mode *_1*,
$R_{v2a\_}(t)$ – reliability of item *v2a* versus failure mode *_1*,
$R_{v2b\_1}(t)$ – reliability of item *v2b* versus failure mode *_1*,
$R_{v1b\_2}(t)$ – reliability of item *v1b* versus failure mode *_2*,
$R_{v2b\_2}(t)$ – reliability of item *v2b* versus failure mode *_2*,
$R_{Pw}(t)$ – reliability of item P_w versus failure modes*_1* till *_5*,
$R_{sb}(t)$ – reliability of item P_{sb} versus failure modes *_6* till*_7*,
t [h] – time to be taken into account.

Tab. 4. Reliability of pump system with redundancy

Item	Failure mode critical for system	λ [h^{-1}]	Σ λ [h^{-1}]	Reliability of item $R_i(t)$			
				t = 2500 h	t = 5000 h	t = 7500 h	t =10000 h
v1a	_1external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v1b	_1external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v2a	_1external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v2b	_1external leakage	$0.76 \cdot 10^{-6}$	$0.76 \cdot 10^{-6}$	0.99810	0.99621	0.99432	0.99243
v1b	_2 internal leakage	$0.41 \cdot 10^{-6}$	$0.41 \cdot 10^{-6}$	0.99898	0.99795	0.99693	0.99591
v2b	_2 internal leakage	$0.41 \cdot 10^{-6}$	$0.41 \cdot 10^{-6}$	0.99898	0.99795	0.99693	0.99591
Pw 1)	_1 external leakage _2 failed while running _3 low output _4 vibration _5 others	$7.71 \cdot 10^{-6}$ $101.76 \cdot 10^{-6}$ $20.49 \cdot 10^{-6}$ $10.86 \cdot 10^{-6}$ $16.01 \cdot 10^{-6}$	$156.83 \cdot 10^{-6}$	0.82198	0.67565	0.55537	0.45651
Psb	_6 fail to start on demand _ 7 fail after starting	2) 3)	- $156.83 \cdot 10^{-6}$	0.99914 0.99671	0.99914 0.99671	0.99914 0.99671	0.99914 0.99671
		Reliability of system $R_s(t)$ =		0.99170	0.98359	0.97565	0.96786

Remarks to Tab. 4.

1) Operational time of working pump is a half of callendar time "t" so $R_{Pw}(t) = e^{-(\Sigma\lambda) \cdot t/2}$.
2) The probability that the stand-bye pump will fail to start on demand, according to OREDA [3], is equal 0.00086, so the probability that the failure event will not occure is 0.99914.
3) The probability, that the stand-bye pump will fail after starting, before the first pump will be repaired, was calculated assuming that the repair time is 21 hours. The mean value of repair time is based on OREDA [3].

The results of calculations are presented in Fig. 6.

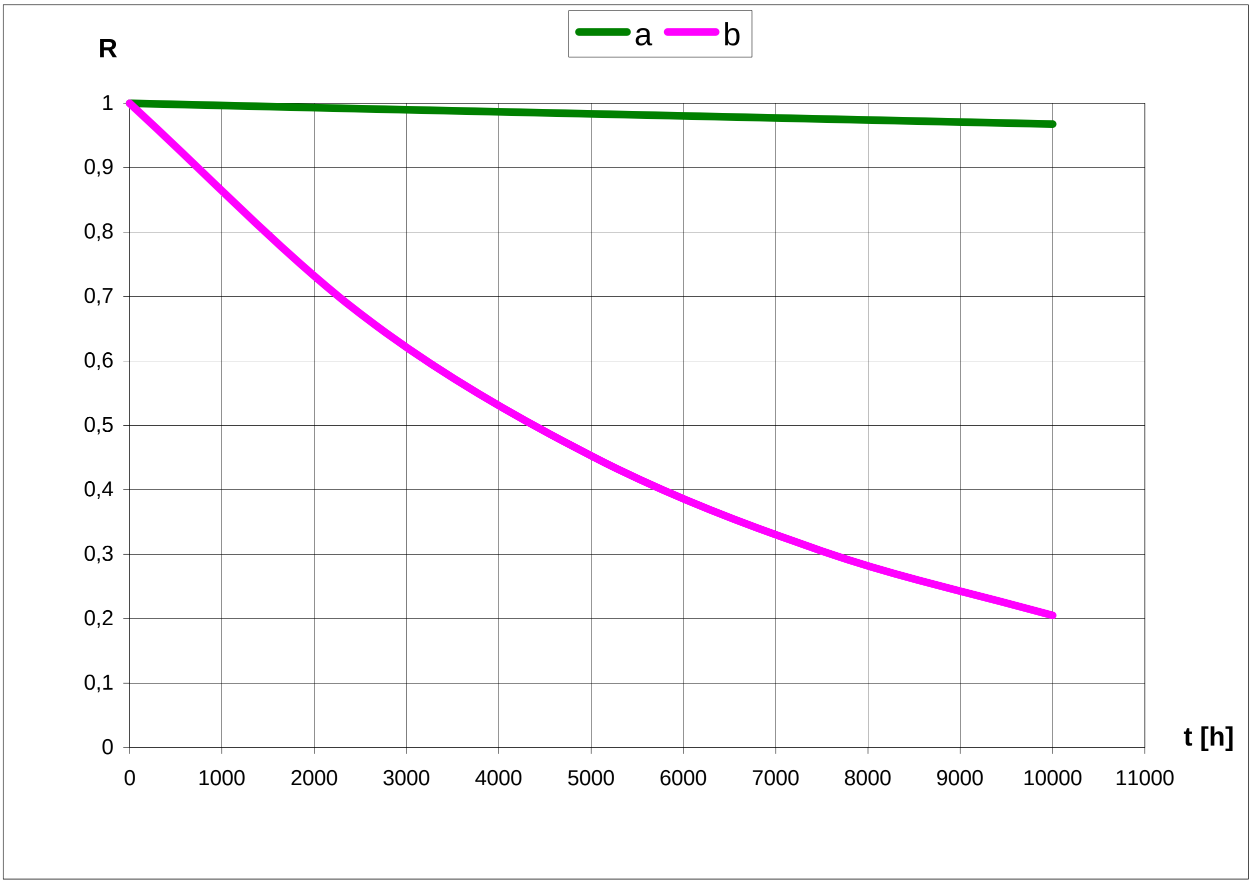

Fig. 6. Reliability function of pump system a) with redundancy b) without redundancy

6. Final remarks

Duplication of pumps makes sense. Reliability of pumps is very low compared with the reliability of other system components. In practice, the reliability of pumps determines the reliability of the whole subsystem, as we can see in Tab. 3. and Tab. 4. Possible failure events of valves reduce system reliability, but very little in comparison with pumps. But it is worthy to note, that relatively new system have been considered there. In the old pipe systems the failures of pipes and valves occur much more frequently.

The reliability structure of pump subsystem with redundancy is not clearly serial, but mixed. Fortunately the serial part of the structure is created by valves (with low failure rates). The parallel structure is created by pumps (with high failure rates). As we can see in Fig. 6. redundancy of pumps gives a very high reliability level of the whole subsystem. First, due to the creation of partially parallel reliability structure. Secondly, due to the fact, that active work time of each of two pumps is a half of active work time in the case of one pump installed in the system. It is clear, that the pumps working alternayively wear up more slowly than a pump that runs continuously.

A question of keeping the redundancy by the crew is still open. In a case of one pump failure the system is not redundant until the pump is repaired. In the above calculations an assumption has been made, that the fitness pump recovery time is 21 hours. However, in practice, the crew can did not make the repair at all, for various reasons.

The issue of redundancy in marine systems is more complex than it seems to be. The author believes it is necessary to pay more attention to this matter. The first step has been done in the article.

References

[1] MAN: Engine Selection Guide Two – stroke MC/MC-C Engines. 6th Edition, January, 2002.
[2] PRS: Rules for the Classification and Construction of Sea-going Ships. Part VI, Machinery Installations and Refrigerating plants. Gdansk. 2009.
[3] OREDA: Offshore Reliability Data Handbook. 3rd Edition. DNV, Trondheim 1997.
[4] Modarres M.: What Every Engineer Should Know about Reliability and Risk Analysis. New York, 1993.
[5] Czajgucki J. Z.: Niezawodność spalinowych siłowni okrętowych. Gdańsk 1984.